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The Scientific Diving Experience

NTNU – Trondheim
Norwegian University of
Science and Technology

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Thesis for the degree of Doctor Philosophiae
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DIVING IN EXTREME ENVIRONMENTS:

The Scientific Diving Experience

by

Michael A. Lang

Thesis for the degree of Doctor philosophiae in Environmental Physiology (Diving)
April 2012

NORWEGIAN UNIVERSITY OF SCIENCE AND TECHNOLOGY
Faculty of Medicine
Department of Circulation and Medical Imaging

Thesis Advisor: Alf O. Brubakk, MD, PhD, Professor of Applied Physiology (Emeritus),
Department of Circulation and Medical Imaging, NTNU

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Kandidat: Michael Andreas Lang
Institutt: Institutt for sirkulasjon og bildediagnostikk
Veileder: Professor emeritus Alf O. Brubakk

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Dykking i Ekstreme Omgivelser: Erfaring med Vitenskapelig Dykking

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Executive Summary

The scope of extreme-environment diving defined within this work encompasses diving modes outside of the generally accepted no-decompression, open-circuit, compressed-air diving limits on self-contained underwater breathing apparatus (scuba) in temperate or warmer waters. Extreme-environment diving is scientifically and politically interesting. The scientific diving operational safety and medical framework is the cornerstone from which diving takes place in the scientific community. From this effective baseline, as evidenced by decades of very low DCS incidence rates, the question of whether compressed air is the best breathing medium under pressure was addressed with findings indicating that in certain depth ranges a higher fraction of oxygen (while not exceeding a PO_2 of 1.6 ATA) and a lower fraction of nitrogen result in extended bottom times and a more efficient decompression. Extreme-environment diving under ice presents a set of physiological, equipment, training and operational challenges beyond regular diving that have also been met through almost 50 years of experience as an underwater research tool. Diving modes such as mixed-gas, surface-supplied diving with helmets may mitigate risk factors that the diver incurs as a result of depth, inert gas narcosis or gas consumption. A close approximation of inert gas loading and decompression status monitoring is a function met by dive computers, a necessity in particular when the diver ventures outside of the single-dive profile into the realm of multi-level, multi-day repetitive diving or decompression diving. The monitoring of decompression status in extreme environments is now done exclusively through the use of dive computers and evaluations of the performance of regulators under ice have determined the characteristics of the next generation of life-support equipment for extreme-environment diving for science. These polar, deep and contaminated water environments require risk assessment that analyzes hazards such as cold stress, hydration, overheating, narcosis, equipment performance and decompression sickness. Scientific diving is a valuable research tool that has become an integral methodology in the pursuit of scientific questions in extreme environments of polar regions, in contaminated waters, and at depth.

Keywords: extreme environments, polar diving, contaminated water diving, under-ice regulator performance, dive computer, nitrox, DCS incidence rates, risk assessment.

1. Introduction

This thesis synthesizes our current state of knowledge of diving in extreme environments based on the experiences from a controlled, supervised, and highly trained scientific diving community.

The scope of extreme-environment diving defined within this work encompasses diving modes outside of the generally accepted no-decompression, open-circuit, compressed-air diving limits on self-contained underwater breathing apparatus (scuba) in temperate or warmer waters. Lessons learned from the outer edge of diving often further refine and improve our operational knowledge and facilitate advances in equipment technology and training. This trickle-down effect benefits millions of scuba divers diving worldwide in the recreational diving environment.

The diving universe examined here is the scientific diving community. Since 1978, this is the model from which my experience base is derived. A synthetic review of the scientific diving medical and safety procedures characterizes the capabilities of the diver examined, i.e., the diving scientist, and the framework within which scientific missions are successfully conducted with a remarkably high margin of safety. The main findings between extreme-environment diving and recreational or ubiquitous scientific diving validate the increased level of operational diving skill, knowledge and training required to conduct these activities within acceptable degrees of safety.

Extreme-environment diving is scientifically and politically interesting. Polar environmental factors are biological, geological, physical and sociological in nature. Studies of Arctic-Antarctic marine faunal comparisons and adaptations are receiving much interest in the fields of medicine, physiology, fisheries and ecology. Research on carbon dioxide levels, temperatures, greenhouse gases, and climate change centers on polar regions because of their global importance. Human impacts and their ethical and economic considerations are integral to the conservation efforts of these pristine ecosystems. Ocean circulation and heat release, sea level rise and the extent of sea ice cover are topics that currently receive much attention due to their direct impacts on the climatic effects on coastal zones where human populations reside. Reductions in sea-ice coverage have improved the accessibility to poorly studied above- and under-ice environments, especially in the Arctic and the Antarctic Peninsula, where much research has revealed that the forces of climate change are having a measurable impact. Polar marine ecosystems possess unique features such as temperature extremes, variable photoperiod and a frequent sea-surface boundary layer of sea ice. Endemic Antarctic organisms and their biomass abound, having been shielded from biological invasions primarily due to long-term, stable oceanographic conditions and isolationist temperature barriers and currents. Sea-ice dynamics make polar habitats particularly challenging for studying benthic or under-ice plants and animals. Polar scientific diving has over a 50-year period yielded a wealth of scientific information and proven to be a unique sampling and observational technique, irreplaceable by exclusively mechanical or remote methods. The International Polar Diving Workshop (Lang and Sayer, 2007) in Ny-Ålesund, Svalbard, resulted in findings on ice-diving equipment, cold-water decompression, and scientific ice diving operational procedures. Lang and Robbins (2007) detailed the U.S. ice diving experience from the National Science Foundation's U.S. Antarctic Program (USAP) Scientific Diving Program. Since 1989, USAP diving activities have annually averaged 700 ice dives, 36 scientific divers, 41-minute dive times and dive profile depths shallower than 40 m.

Political interest in polar regions and the desire to increase national capabilities was highlighted on December 1, 2009 in celebration of the 50th anniversary of the signing of the Antarctic Treaty (Berkman *et al*., 2011). Twelve nations had come together in 1959 to adopt the Antarctic Treaty in the interests of all mankind. The simple fourteen articles contained therein formed the basis for the governance of this vast international space that comprises nearly 10% of the Earth for peaceful purposes only. An international agreement on governance of the Arctic does not exist and thus cannot set aside territorial claims or provide a mechanism for nations to consult on matters of common interest such as commercial fisheries quotas, law enforcement and maritime rescue, or mineral extraction. However, lessons learned from fifty successful years of international governance of an entire continent will hopefully provide a template for a peaceful governance structure of an ocean surrounded by continents.

The commonality between poles and tropics is their shared remoteness, removed from the immediate thoughts of society. Diving in the tropics is unquestionably simpler and many risk factors do not feature prominently in hazard analyses. Notwithstanding the potential for sunburn and interactions with hazardous marine life, perhaps the greatest similarity in diving preparedness centers on method of transport and evacuation time to a recompression facility following decompression accidents due to the remote nature of the dive site and the urgency with which recompression treatment is needed to effect a positive outcome. However, more divers are venturing into extreme-environment diving as evidenced by the increase in dive tour operators offering unique, adventure-diving experiences in polar regions (e.g., International Association of Antarctic Tour Operators). Specialized ice-diving equipment and training of divers, supervisors and medical personnel must feature prominently in preparation for the operational logistics of such diving. Traditional dive plan models do not cater well to extreme-environment diving where the margins of error are much narrower. Extra preparation for decompression illness management and conduct of the diving operation as a remote-environment activity increases the probability of successful diving missions. Gas management planning and potential incident management in extreme-environment diving require special consideration.

Diving under polar ice clearly is an exemplar of such extreme-environment diving because of the multitude of physiological, equipment and training parameters that impact the diver such as, for example, regulator performance and thermal protection. When scuba regulators are dived in polar regions there is a chance that first- or second-stage regulators will malfunction due to the accumulation of ice in or around the regulator, yielding complete occlusion of air flow or a massive freeflow that rapidly expends a diver's air supply. Factors influencing regulator freeze-up are design and configuration (determined by the manufacturer), quality control (individual regulator), depth (due to increased gas density), mass flow (depth and respiratory minute volume), time, and temperature. Full-face masks have been used successfully by the Norwegian Polar Institute (Hop and Pavlova, 2007) and the British Antarctic Survey. Sayer *et al.* (2007) describes operation and maintenance of full-face AGA masks with manual bail-out side valve connected to a rear-mount pony cylinder but Robbins (2006) cautions about the higher failure rate of full-face masks (AGA, Heliox 18, and Superlite 17 helmets) in the -1.86°C waters of McMurdo Sound, approximately 2°C colder than those of the Arctic, Antarctic Peninsula, and perennially ice-covered lakes of the Antarctic Dry Valleys. However, diving modes such as mixed-gas, surface-supplied diving with helmets may mitigate risk factors that the diver incurs as a result of depth, inert gas narcosis or gas consumption.

Enriched-air nitrox (EAN; popularly named nitrox) has proven to be an effective method to greatly extend bottom times in certain depth ranges. Nitrox also increases offgasing efficiency on ascent by creating a large diffusion gradient between the elevated oxygen partial pressure in the lungs and the dissolved inert gas tensions within the body. The use of nitrox has vested itself as a mainstream diving breathing gas since it was first introduced to recreational divers in 1985. Although nitrox tables were first published by the National Oceanic and Atmospheric Administration (NOAA) and used by the scientific diving community in 1979, as with any emerging technology that has found a broader market appeal, controversies invariably arose. Ignorance, myths and misconceptions often fueled opposite views. An evaluation of the available nitrox operational and physiological data, risk management, equipment and training parameters was in order to disseminate credible diving safety information (Lang, 2006). An approximation of the magnitude of nitrox consumption was essential and seemed achievable by our ability to provide a denominator of nitrox divers and nitrox dives, as a sub-set of the overall level of recreational diving activity. Many other discussions of nitrox topics flowed from these numbers, *e.g.,* nitrox DCS incidence rates compared to air, and nitrox training, certifications and equipment sales growth. Physiological issues such as carbon dioxide retention and oxygen toxicity were also in need of critical examination. Nitrox training and equipment issues were examined to comprehensively address risk management and legal considerations regarding the use of nitrox.

A close approximation of inert gas loading and decompression status monitoring is a function met by dive computers, a necessity in particular when the diver ventures outside of the single-dive profile into the realm of multi-level, multi-day repetitive diving or decompression diving. These polar, deep and contaminated water environments require risk assessment that analyzes hazards such as cold stress, hydration, overheating, narcosis and decompression sickness. Based on that assessment, safety is the judgment of the acceptability of that risk, which is a compound measure of probability and severity of harm to human health. We accept that there are degrees of risk and, therefore, degrees of safety. Estimating the risk of an extreme-environment diving operation is an objective and probabilistic pursuit, a scientific activity. Whether that risk is acceptable is a personal or social judgment, a political activity. No matter how much we analyze or prepare for a high-risk, extreme-environment dive, we acknowledge that nothing is absolutely free of risk.

Contaminated water diving resonates with many individuals as an extreme-environment diving activity because of the chemical (hydrocarbons, solvents, PCBs, heavy metals, tributyl-tin fluorides, pesticides, oxidants), biological (sewage, bacterial pathogens, viruses, protozoans, microorganism toxins), or radiological substances that pose a chronic or acute health risk to exposed personnel. Protective equipment for divers and tenders and efficient decontamination procedures are essential to safeguarding personnel from incidental exposure and subsequent adverse health effects. Marine disasters have a lasting, devastating effect on individual lives, communities and ecosystems. Among the worst oil spills in maritime history are the 1978 *AMOCO CADIZ* spill of 1.6 million barrels of crude oil on the Breton coast of France and the 1989 *EXXON VALDEZ* spill of 240,000 barrels of crude oil in Prince William Sound, Alaska, arguably attributed to human error. In 2010, *DEEPWATER HORIZON,* an ultra-deepwater, dynamically positioned, semi-submersible offshore oil drilling rig discharged 4.9 million barrels of oil into the Gulf of Mexico 400 km southeast of Houston, Texas, after an explosion and fire caused the rig to collapse and sink in approximately 1,300 m of water. These oil-spill triggers activate a number of responding diving operations in their aftermath: commercial divers, search and rescue divers, resource management divers, law enforcement divers, journalist divers/underwater photographers, and scientific divers. Minimization of risk to all dive team members is a priority consideration. Exemplars of contaminated water diving from the U.S. Antarctic Program, the Smithsonian Tropical Research Institute Oil Spill Project and the Smithsonian Environmental Research Center Marine Bioinvasions Program are highlighted as extreme-environment diving operations that can be successfully managed within acceptable risk parameters.

The sole purpose of a scientific diving project is the advancement of science performed by divers who make observations, gather data and use their scientific expertise in studying the underwater environment. Scuba diving conducted by scientists places the trained scientific eye under water and provides research value and flexibility that unmanned systems often do not. Scientific diving is a valuable research tool that has become an integral methodology in the pursuit of scientific questions in extreme environments of polar regions, in contaminated waters, and at depth (Lang *et al.,* 2012).

2. The Scientific Diving Management Model: Medical and Safety Experience

A baseline understanding of the structure of scientific diving is provided to put its management model into context compared to recreational, commercial and military diving programs. Much of this information is from the U.S.-based scientific diving community, with references to the European Scientific Diving Panel and international programs where appropriate. The scientific diving community has effectively used self-contained underwater breathing apparatus (scuba) as a research tool since 1951 when the first diving program was established at Scripps Institution of Oceanography in San Diego, California. One metric used to validate the effectiveness of diving programs is decompression sickness (DCS) incidence rates. From 1965 to 1982, scientific diving compared favorably by registering a rate that was by a factor of 10 lower than recreational and commercial diving DCS rates (Lang and Vann, 1992). A recent 10-year review (1998-2007) of scientific diving DCI rates with better reporting and analysis recorded DCI hits at 0.245/10,000 person-dives, also a favorable comparison to earlier rates (Dardeau *et al*., 2012). This safety record is partially attributable to thorough medical, training and operational standards and programmatic supervision of relatively conservative diving activities. Safety considerations are of primary concern for diving programs and their effectiveness is reflected in the diving regulations that are promulgated by the underwater scientists who live by them.

This community has also been proactive since 1988 in addressing diving physiological and operational questions that directly impact the safety and health of the scientific diver. The results of the scientific diving safety projects have benefited the recreational diving community in many ways as evidenced by the incorporation of consensus guidelines and operational practices into recreational diver training curricula. There has also been much interaction and transfer of operational knowledge from commercial and military diving, to the benefit of the scientific diving community (Lang and Smith, 2006).

Research objectives, whether through mensurative or manipulative experiments, in many instances could not have been accomplished without scientific diving techniques, as evidenced in materials and methods sections of peer-reviewed published scientific literature. An effort to highlight scientific results from research diving activities was made by the Smithsonian Institution, the National Science Foundation and the National Research Council at the 2010 symposium “Research and Discoveries: The Revolution of Science through Scuba” (Lang *et al*., 2012). At some point in the future, decompression, diver training, and medical issues may become a minor concern to scientists, as emerging technologies develop and the level of maturity of the scientific diving program management model becomes evident based on over 60 years of experience. The incidents that do occur may then reasonably be characterized as probabilistic events. While a zero incident rate is desirable, it is realistically not achievable. In the mean time, many topics of current scientific interest, including polar marine biodiversity, coral reef health, fisheries, sea-level change and global warming impacts are to a large degree dependent on placing the trained scientific eye under water to record, interpret and sample the marine environment.

General

The purpose of a research diving project is the advancement of science. Divers use their scientific expertise to study the underwater environment. The tasks of a scientific diver are to make observations and gather data, which are usually disseminated in a technical document or peer-reviewed research publication. Scientific diving is performed solely as a necessary part of a scientific, research, or educational activity by employees whose sole purpose for diving is to perform scientific research tasks and does not include performing any tasks usually associated with commercial diving such as placing or removing heavy objects under water, inspection of pipelines and similar objects, construction, demolition, cutting or welding, or the use of explosives.

The scientific diving programs in the United States can be broadly categorized into three entities: research institutions, public and private universities; museums and aquaria (predominantly education, teaching, and research); and, consulting companies (predominantly contractual environmental, geological and archaeological investigations). The current scientific diver population in the United States is estimated at 4,000 individuals based on American Academy of Underwater Sciences (AAUS) programmatic reporting requirements. A minority of these individuals are long-term, career scientific divers (*e.g.,* federal employees, university professors, professional scientists) who may be considered on average in the 40+ year age category. At the university level the turn-over of scientific divers can be rather high as evidenced by undergraduate students enrolled in diving courses, research technicians on grant funds or students in Master’s degree or Ph.D. curricula. This population tends to be in the 18-34 year age category. An upper age limit for scientific diver certification does not exist; the lower limit is generally 18 years of age.

The American Academy of Underwater Sciences publishes *Standards for Scientific Diving* (AAUS, 2010). The purpose of this document is to ensure that all scientific diving is conducted in a manner that will maximize protection of scientific divers from accidental injury and/or illness, and to set forth standards for training and certification that will allow a working reciprocity (mutual recognition of diving certifications) between organizational member programs that adhere to these standards. These standards for AAUS-recognized scientific diving programs prescribe the organization and conduct of these programs and the basic regulations and procedures for safety in scientific diving operations. The AAUS standards are generally considered the standard of practice for scientific diving in the U.S.

Diving Medical Surveillance

The employer determines that scientific divers who are exposed to hyperbaric conditions have passed a current diving medical evaluation and have been certified by the examining physician to be medically fit to engage in diving activities. All medical evaluations are performed by, or under the direction of, a licensed physician of the diver's choice, preferably one trained in diving/undersea medicine. The diver must be free of any acute or chronic disabling disease or conditions contained in the list of conditions by Bove (1998) for which restriction from diving may be recommended. There currently are no fitness standards *per se* for scientific divers other than during the initial scientific diver training course, which includes in-water time/distance parameters for swimming, or a stress tolerance test prescribed by a physician based on coronary artery disease risk factor screening (Vann and Lang, 2011).

Medical evaluations are completed before a diver may begin diving; thereafter, at 5 year intervals up to age 40, every 3 years after age 40, and every 2 years after age 60. Any major injury or illness, or any condition requiring hospital care, requires new diving medical clearance. If the injury or illness is pressure related, then the clearance to return to diving must be performed by a physician trained in diving medicine. Laboratory requirements for diving medical evaluations and intervals are age-dependent (Lang, 2005). Diving medical evaluations conducted initially and at the interval frequency specified above consist of the following: diving medical history, diving medical examination, and completion of a scientific diver medical certification by the examining physician.

Diver Training

Scientific Diving Authorizations

There are three types of scientific diving authorizations (AAUS, 2010): Diver-in-Training (diver has completed entry-level training requirements), Scientific Diver (diver is authorized to dive with compressed air within no-decompression limits of approved dive computer models, and Temporary Diver (diver has met scientific diver proficiency requirements and is authorized for a project-specific limited time).

Scientific Diver Training

The 100-hour scientific diver training course consists of theoretical training, practical skills training in confined water, and completion of 12 supervised open-water dives in a variety of dive sites for a minimum cumulative bottom time of 6 hours. An underwater swim for a distance of 25 m without surfacing, a 400 m swim in less than 12 minutes, a 10-minute water tread and the ability to transport another diver of equal size for a distance of 25 m in the water are prerequisites for training. Water skills remain a fundamental adjunct because divers cannot rely solely on equipment as a backup for safety. Experience has also shown that the individuals who are most comfortable and relaxed in the water progress more rapidly during scuba diver training than those who are not.

Continuation of Certification

Recreational diver certification cards have no expiration dates. Some individuals instinctively feel the need to participate in a refresher course if they have not been diving in some time. Diveboat charter operators often require presentation of dive log books to verify actual diving experience, in addition to a certification card. In recognition of the gradual deterioration of diving skills if not practiced regularly, each certified scientific diver must log a minimum of 12 dives during any 12-month period, including two dives within their certified depth range. If no dive is made for a 6-month period, performance of a check-out dive is required. The thorough entry-level diver training forms the baseline of scientific diving competency. The model is constructed so that if the scientific diver maintains the minimum diving and depth certification requirements, they remain on active status with little interference from the program, other than maintaining medical certification, submission of dive plans and dive computer profile downloads, and annual retraining in diving first aid (cardiopulmonary resuscitation, first aid, field neurological examination and oxygen administration).

Depth Certifications

The scientific diving community has long adhered to a progressive experience-accumulation schedule. Depth certifications provide a mechanism to incrementally gather diving experience under supervision of more experienced dive partners. This approach simultaneously serves as an apprenticeship period for extreme-environment diving projects for less experienced divers to become indoctrinated to higher-risk, more complex diving environments and equipment.

The scientific diver certification authorizes the holder to dive to a specific depth as indicated on the approved dive plan. Divers may exceed their depth certification by one step while accompanied by a diver certified to a greater depth. Diving with compressed air is not permitted beyond a depth of 58 msw (190 fsw). Depth certification requests need to be justified based on scientific need and there are relatively few individuals with certifications beyond 40 msw. The initial depth certification is to 9 msw (30 fsw) depth. Logging another 12 supervised dives between 9 and 18 msw allow the diver to request 18 msw (60 fsw) depth certification. Certification to 30 msw (100 fsw), 40 msw (130 fsw), 50 msw (150 fsw) and 58 msw (190 fsw) depths respectively may be obtained by logging four dives near the maximum depth, and successfully completing an approved check-out dive.

A mitigating factor that enables deep scientific dives is that they are planned and executed under close supervision of a scientific diver who has demonstrated knowledge of the special problems of deep diving, gas management, decompression strategies, and hazards of nitrogen narcosis and oxygen toxicity.

Diving Specialties

Diving beyond the ubiquitous science operations of no-decompression, open-circuit scuba on compressed air are considered specialties that require additional training and approval, such as: Decompression diving, surface-supplied diving, mixed-gas or oxygen-enriched air (nitrox) diving, semi- or closed-circuit rebreather diving, saturation diving, blue-water diving, drysuit diving, overhead environment (ice, cave or wreck) diving, and altitude diving. Extreme diving operations usually entail this type of additional training.

Diving Operations

Diving Supervision

For any scientific dive there exists a hierarchy of diving supervisory responsibilities. The Diving Control Board (DCB) is the policy-setting body of active scientific divers that establishes the program's diving regulations and to whom the Diving Officer (DO) has full responsibility and accountability in all operational, diving and safety matters. The DO is a recognized diving expert, appointed by the administration on the recommendation of the DCB, and is responsible for the conduct and supervision of the diving program and scientific diving activities. The Lead Diver submits a dive plan for DO approval prior to engaging in any diving activity and is present at the dive location during the entire diving operation. The Lead Diver is responsible for coordination, briefing, dive planning, and emergency equipment and procedures. Scientific dives are planned around the competency of the least experienced diver. Responsibilities of individual scientific divers include maintaining themselves in good physical condition and at a high level of diving proficiency commensurate with the frequency, scope, and type of diving activity being undertaken. In contrast to commercial diving, scientific divers have the right to refuse to dive without fear of recrimination or loss of pay if in their judgment the conditions are unsafe for the type of diving operations planned, for any reason they believe their diving participation might jeopardize human life, they are not in proper physical or mental condition, and/or, they believe the diving equipment to be used is not operating properly. Each scientific diver receives current diving first aid training, has an annual scuba equipment maintenance performed and conducts a pre-dive functional check of diving equipment. The diver is responsible for terminating the dive while there is sufficient cylinder pressure to permit a safe ascent to the surface, including a stop. The ultimate responsibility for personal safety and compliance with the diving safety regulations on a planned diving operation is borne by the diver.

In recreational diving this type of hierarchical diving supervision does not typically exist, other than during training courses. Divemasters may be present on a charter boat, but their function usually is to check divers in and out of the dive platform, provide dive site briefings, or if serving as dive guides, lead underwater tours. Much recreational diving is conducted in a less formally structured format, i.e., two divers walking into the water from a beach. Commercial and military diving is more structured and controlled with dive supervisors, crew chiefs, standby divers, and often medical support personnel or recompression chamber operators on site. Commercial diving, due to the nature of the activity, can be described as a more physiologically stressful type of exposure, physically hazardous and typically deep, mixed-gas, surface-supplied diving controlled from the surface. Military diving includes ship husbandry, explosive ordnance disposal, reconnaissance, diver delivery vehicles and a number of other activities that are not publicly disclosed. From a resource standpoint, the military diving community possesses more staff, equipment and capabilities to accomplish their mission when compared to scientific diving.

Diving Equipment

Each scientific diver wears the following equipment: mask and fins (snorkel is optional), regulator and alternate breathing source (e.g., octopus, AIRII or SS1 alternate breathing regulator), scuba cylinder, a dive computer approved by the DCB, and cylinder high-pressure gauge. A buoyancy compensator that provides the diver with the capability of attaining and maintaining positive buoyancy must be equipped with a low-pressure power inflator. A dive knife, sharp enough to cut through monofilament line, and appropriate thermal insulation must also be worn. Diving in extreme environments requires additional training in drysuit and ice diving techniques or fully protective contaminated water diving gear with positive-pressure full-face masks or surface-supplied diving helmets, and decontamination equipment and procedures for divers and tenders.

Diving Procedures

All scientific diving is planned and executed in a manner that ensures that every diver maintains constant, effective communication with at least one other comparably equipped, certified scientific diver in the water. This buddy system is based upon mutual assistance, especially in the case of an emergency. If loss of effective communication occurs within a buddy team, all divers surface to re-establish contact before continuing with the dive. A dive flag is displayed prominently whenever diving is conducted and an emergency oxygen/first aid kit and cell phone or radio is present at the dive location. Recompression chambers, as a rule, are not required at the dive site. Scientific diving profiles at remote sites are approached with a higher degree of conservatism relative to the evacuation time and distance to a recompression chamber facility. In the case of an asymptomatic diver diving within the dive computer no-decompression limits during the previous 48 hours, there should be a minimum 12-hour delay period with no diving prior to flying. The longer the diver delays an ascent to altitude, the lower the probability of onset of DCS symptoms (Sheffield and Vann, 2002).

All diving accidents requiring recompression or resulting in moderate or serious injury are reported to the DO. The DCB records and reports occupational injuries and illnesses as established by the U.S. Department of Labor, Occupational Safety and Health Administration: the occurrence of any diving-related injury or illness that requires any dive team member to be hospitalized for 24 hours or more, after an episode of unconsciousness related to diving activity, or after treatment in a recompression chamber following a diving accident.

Compressor Systems and Breathing Air Quality

Gas analyses and air tests are performed on each breathing air compressor at regular intervals of no more than six months or 100 hours of operation. Breathing air for scuba meets the Grade E specifications as set forth by the Compressed Gas Association (CGA Pamphlet G-7.1) and referenced in OSHA 29 CFR 1910.134. Equipment used with oxygen or mixtures containing over forty percent (40%) by volume oxygen are designed, dedicated and maintained for oxygen service. Components exposed to oxygen or mixtures containing over forty percent (40%) by volume oxygen are cleaned of flammable materials before being placed into service. Oxygen systems over 8.6 bar (125 psig) must be equipped with slow-opening shut-off valves.

Scientific Diving Safety

The scientific diving community has a traditional proactive record of furthering diving safety. The first scientific diving safety program was established at Scripps Institution of Oceanography in 1951, preceding the organization of national recreational scuba training agencies by seven years. Most scientific diving programs today trace their ancestry to common elements of the original Scripps diving program.

Diving safety programs can be generalized as fulfilling a two-fold purpose. The first serves as a research-support function that assists the diving scientist with specialized underwater equipment, advice, and diver support to assist in fulfilling the scientific objectives of the diving project. The second is a risk-management function that protects the safety and health of the individual scientist, and the employing organization from excessive liability exposure, by providing state-of-the-art diving equipment, breathing air, training and medical surveillance programs.

Scientific diving safety research by Lang and Hamilton (1989) considered a more effective means of decompression status monitoring using dive computers. DCB's approve specific makes and models of dive computers that may be used as a means of determining decompression status. All divers relying on a dive computer to plan dives and indicate or determine decompression status must have their own unit and pass a practical and written training session. On any given dive, both divers in the buddy pair follow the most conservative dive computer. If the dive computer fails at any time during the dive, the dive is terminated and appropriate surfacing procedures are immediately initiated. Divers are not allowed to dive for 18 hours before activating a dive computer to control their diving, and once in use, it is not switched off until complete outgasing has occurred. Multiple deep dives and/or decompression dives with dive computers require careful consideration. The future of dive computers and their development was discussed by Lang and Angelini (2009) with further elaboration in Chapter 6.a. (Risk Assessment, Decompression monitoring and dive computers).

The slowing of ascent rates and performance of safety stops to provide scientific divers with a greater margin of decompression safety was investigated by Lang and Egstrom (1990). It has long been the position of the American Academy of Underwater Sciences that the ultimate responsibility for safety rests with the individual diver. Scientific divers are trained to slow and control their ascents through correct buoyancy compensation, which can be a significant problem but is fundamental to safe diving practice. Before certification, the diver demonstrates proper buoyancy, weighting and a controlled ascent, including a "hovering" stop. Ascent rates are controlled at a maximum of 10 msw/min from 20 msw and are not to exceed 20 msw/min from depth, at the rate specified for the make and model of dive computer being used. Scientific diving programs require a stop in the 3 – 10 msw zone for 3-5 min on every dive. Scientific divers receive additional practical training in the use of drysuits, which must have a hands-free exhaust valve. Buoyancy compensators must be equipped with a reliable rapid exhaust valve that can be operated in a horizontal swimming position. A buoyancy compensator is required with drysuit use for ascent control and emergency flotation. Should a runaway ascent (blow-up) occur, current thinking is that breathing 100% oxygen above water is preferable to in-water air procedures for omitted decompression (Lang and Egstrom, 1990).

The third phase of this scientific diving safety project was to consider multi-day, repetitive diving physiological aspects (Lang and Vann, 1992). Although diving is a relatively safe activity, all persons who dive must be aware that they incur an inherent risk. In 1992, the risk of decompression illness in the United States was estimated at 1-2 incidents per 1,000-2,000 dives for the commercial diving sector, 2 incidents per 10,000 dives for recreational diving activities and 1 incident in 100,000 dives for the scientific diving community. Scientific diving programs provide continuous training, recertification and dive site supervision, which helps maintain established safe diving protocols. Recreational divers, who may lack such direct supervision, need to be aware of the need to stay within recommended protocols, especially when making repetitive dives over multiple days for which the risk of DCS may be higher. Increasing knowledge regarding the incidence of DCS indicates that our ability to predict the onset of DCS on multi-level, multi-day diving is even less sensitive than our ability to predict DCS on single square-wave profile dives. There appears to be good evidence that there are many variables that can affect the probability of the occurrence of DCS symptoms. The ability to mitigate these variables through education, good supervision and training appears to be possible for hydration, fitness, rate of ascent, fatigue, etc., and are continuously promoted. Scientific divers are subject to a host of specific conditions that may increase risk if precautions are not taken given the environments they dive in (blue-water, contaminated-water, under-ice, or other overhead environments). There is adequate technical support for the use of enriched-air nitrox and surface-oxygen breathing in scientific diving where higher gas loadings are anticipated in multi-level, multi-day dives. We must continue to remember that DCS is generally recognized as a probabilistic event, which tends encourages the scientific diving community to adopt a more conservative diving position.

The order of dive profiles was investigated by Lang and Lehner (2000), in part, because of the difficulty for scientific divers to adhere to the "dive progressively shallower" rule while on projects investigating coral reefs at varying transect depths. More importantly, the genesis and physiological validity of the "dive deep first" rule was in need of examination. Historically, neither the U.S. Navy nor the commercial sector has prohibited reverse dive profiles, which are acknowledged as being performed in recreational, scientific, commercial, and military diving. The prohibition of reverse dive profiles by recreational training organizations cannot be traced to any definite diving experience that indicates a measurable increase in risk of DCS for profiles conducted within the no-decompression limits. Lang and Lehner (2000) found no reason for the diving communities to prohibit reverse dive profiles for no-decompression dives less than 40 msw and depth differentials less than 12 msw.

Nitrox has been used in the scientific diving community since published by NOAA in 1979 and is discussed in a Chapter 4.b. (Deep Diving, Enriched-air nitrox). Operational guidelines for remote scientific diving operations were promulgated on a consensual basis by senior practicing scientific divers for blue-water diving (Haddock and Heine, 2005) and polar diving operations by Lang and Stewart (1992) and Lang and Sayer (2007). Further discussion in Chapter 4.a. (Deep Diving, Modes) focuses on modes of advanced scientific diving (Lang and Smith, 2006) in consideration of expanding the working envelope from 60 msw to 90 msw depth.

3. Polar diving

a. Introduction

Approximately five decades ago, scientists were first able to enter the undersea polar environment to make biological observations for a nominal period of time. The conduct of underwater research in this extreme environment required special consideration of diving physiology, equipment design, diver training, and operational procedures, all of which enabled this under-ice approach.

Milestones of U.S. Antarctic diving activities commence with the first dive by Americans in Antarctic waters made just after New Year's Day in 1947 as part of Operation Highjump, the United States' first major postwar Antarctic venture (Lang and Robbins, 2009). Lieutenant Commander Tommy Thompson and Chief Dixon used "Jack Brown" masks and Desco® oxygen rebreathers. Since 1963, early scuba divers braved McMurdo Sound's -1.8°C water with wetsuits and double-hose regulators. Equipment advances since then led to the use of variable volume drysuits, buoyancy compensators, and dive computers. Because of their resistance to freezing, however, double-hose regulators were used almost exclusively in the McMurdo area from 1963 until 1990 when they were replaced by freezing resistant single-hose regulators. From 1947 to 1967, research diving operations fell under the control of the U.S. Naval Support Force Antarctica and divers adhered to established U.S. Navy diving regulations. In 1967, James R. Stewart, Scripps Institution of Oceanography Diving Officer, established guidelines for the conduct of research diving in the polar regions for the National Science Foundation (NSF) Office of Polar Programs (OPP). Since 1995, Rob Robbins, Raytheon Polar Services Company, has served as onsite scientific diving coordinator. In 2001, Michael A. Lang, Director of the Smithsonian Scientific Diving Program, enacted an Interagency Agreement between the Smithsonian Institution and the NSF for the management of the U.S. Antarctic Program (USAP) scientific diving program. As NSF OPP Diving Safety Officer (DSO), these responsibilities included, with the USAP Diving Control Board, promulgation of diving safety standards and procedures, evaluation and training of prospective divers, and authorization of dive plans. A Polar Diving Workshop was convened by Lang and Stewart (1992), Svalbard ice-diving courses were conducted in 2003, 2005, and 2007, followed by the International Polar Diving Workshop, Svalbard (Lang and Sayer, 2007). These efforts further focused our attention on extreme-environment diving issues in need of resolution. The Smithsonian ice-diving regulator performance evaluation project was conducted during the 2008 and 2009 McMurdo field seasons (Lang and Clarke, 2012) and the Smithsonian diving thermal protection study was initiated in 2010.

The 4th International Polar Year (IPY) 2007-2009 was a global research effort to better understand the polar regions and their climatic effect on Earth. The research completed during IPY provided a baseline for understanding future environmental change. Previous IPYs were held in 1882-1883 and 1932-1933, and the International Geophysical Year in 1957-1958. A "*Vision for International Polar Year 2007-2009*" was published by the National Academy of Sciences' Polar Research Board. The first major IPY scientific symposium, "*Smithsonian at the Poles: Contributions to International Polar Year Science"* highlighted projects involving scientific diving of the National Museum of Natural History's U.S. Antarctic Program Invertebrate Collection, the U.S. Antarctic Program Scientific Diving Program, the Smithsonian Environmental Research Center's Antarctic Photobiology and Polar Invasions Biology Programs and the National Zoological Park's Weddell Seal Energetics Project (Krupnik *et al*., 2009).

Polar environmental factors that make these ecosystems unique are biological, geological, physical and sociological in nature. Studies of Arctic-Antarctic marine faunal comparisons and adaptations are receiving much scientific interest in light of climate change and marine bio-invasions. Research on carbon dioxide levels, temperatures, greenhouse gases, and climate change centers on the polar regions because of their global importance. Human impacts and their ethical and economic considerations are integral to the conservation efforts of these pristine ecosystems. The ability to maintain and advance underwater capabilities features strategically in national readiness plans. Ocean circulation and heat release, sea-level rise and the extent of sea-ice cover are topics that currently receive much interest due to their direct impacts on the climatic effects on locations where human populations reside.

The International Polar Diving Workshop, convened March 15-21, 2007 at the Arctic Marine Laboratory in Ny-Ålesund, Svalbard, promulgated consensus polar diving recommendations on ice-diving equipment, cold water decompression, and scientific ice diving operational procedures through the combined international, interdisciplinary expertise of participating polar diving scientists, equipment manufacturers, physiologists and decompression experts, and diving safety officers (Lang and Sayer, 2007). The U.S. ice diving experience is derived mainly from the National Science Foundation's USAP Scientific Diving Program whose activities since 1989 have averaged annually 700 ice dives, 36 scientific divers, 41-minute dive times and depths shallower than 40 m (Lang and Robbins, 2007). These scientific diving exposures, in support of underwater research, have enjoyed a remarkable safety record and high scientific productivity due to a significant allocation of logistical support and resources to ensure personnel safety.

The USAP *Standards for the Conduct of Scientific Diving* (USAP, 1991) reference the scientific diving standards published by the American Academy of Underwater Sciences (AAUS). The USAP researchers understand that polar diving demands the acceptance of responsibility for an increased level of risk and diver preparation. Polar conditions are more rigorous and demanding of scientific divers and their equipment than most other diving environments. Approximately 36 scientists dive each year through USAP and have logged more than 13,000 scientific ice dives since 1989. Average dive times are 41 minutes; generally, no more than two dives are made per day within the no-decompression limits. The USAP scientific diving authorization process requires submission of information on diver training and history, depth certification, diving first aid training and drysuit experience (Lang *et al*., 2007). Minimum qualification criteria for NSF diving authorization include: (a) a one-year diving certification; (b) 50 logged open-water dives; (c) 15 logged drysuit dives; (d) 10 logged drysuit dives in the past six months; and, e) 30 m depth certification. Somers (1988) described ice diver training curricula considerations. A pre-dive orientation and checkout dive(s) are done on site to ensure that divers exhibit a satisfactory level of comfort under the ice with their equipment. Divers new to the Antarctic program are usually accompanying experienced Antarctic research teams and are thus mentored in an “apprentice” mode. However, divers must become proficient with the gear and techniques they will be using prior to deployment.

In essence, the major transition from tropical reef scuba diving to extreme-environment polar diving entails mastering expertise in buoyancy control, i.e., managing the bubble in the drysuit. Operational issues are discussed below but predominantly have to do with being able to always have a controlled under-ice exit strategy while air supplies are sufficient. Drysuit diving courses within the scientific diving community encompass much of the material outlined below. The theoretical knowledge a drysuit diver must master involves several interrelated topics: physics (water properties, pressure, density, buoyancy effects); physiology (thermal effects, hypothermia); and equipment (diving suits, undergarment insulation, weight systems, maintenance.) Practical skills include drysuit diving procedures, i.e., pre-dive planning, drysuit donning, entry, leak check, buoyancy control, trim, descent and ascent control, neutrally buoyant safety stop, drysuit doffing, post-dive maintenance and emergency management).

Water exhibits a high specific heat value and conductivity. It absorbs body heat approximately 3,500 times greater than air of the same volume and conducts heat 25 times faster than air at the same temperature. Thus, body heat loss is faster than heat production even in 26°C water. Warmer water next to the skin flows away and is replaced by cold water. There is forced convection caused by currents or from moving through this liquid medium. Water is incompressible, approximately 800 times denser than air. The density of fresh water is 1.00 kg/l. At 40 ppm salinity the density of sea water is 1.03 kg/l but at a reduced salinity of 27 ppm sea water density is 1.0197 kg/l where 1 bar of pressure is exactly equivalent to 10 msw. When under water, vision, hearing, heat retention and movement are affected. At all depths the diver must compensate for the pressure exerted by the atmosphere, the water and the gases breathed under water.

Atmospheric pressure (air) exerted at sea level by the Earth's atmosphere and hydrostatic pressure (water) constitute absolute pressure (ATA). At sea level, the weight of a 1 cm by 1 cm column of air (extended to the edge of the atmosphere) = 1 kg or 1 atmosphere. Hydrostatic pressure is the constant weight of the accumulated water above the diver that increases at a rate of 0.1 kg/m in sea water (or 1 kg/10 m).

Density is measured as mass per unit volume leading to Archimedes' Principle: "An object wholly or partially immersed in a fluid is buoyed upward by a force equal to the weight of the fluid displaced." Therein lies the crux of drysuit diving: the issue of buoyancy and its control.

There are three states of buoyancy: positive, neutral and negative. Drysuit divers strive for a neutral state of buoyancy throughout the dive, i.e., maintaining the same volume throughout the dive that allows the diver to hover at any depth in the water column. A diver controls buoyancy primarily by the amount of weight worn (including diver's body weight and dive gear) and the amount of air in the drysuit and buoyancy compensator. The volume of buoyancy required depends on the diver's body size, thickness of suit, and dive gear. In extreme-environment diving, additional amounts of air are usually introduced into the drysuit as insulating gas to keep the diver warm, resulting in the need for additional weight.

Weighted neutral for sea water, the diver sinks in fresh water with the same amount of weight. Therefore, a buoyancy check is standard operating procedure if changing diving environments and is also affected by the amount of insulation, air in the drysuit, or gear that is worn. Neutral buoyancy beneath the surface is necessary for scientific diving efficiency and safety stops. Diving without proper buoyancy control is not advised and may become a leading trigger of drysuit diving accidents. A note of caution is appropriate here. Drysuit divers worry mainly about avoiding runaway ascents, i.e., rapid increase of buoyancy on ascent, also known as blowup, which propels a diver to the surface at excessive rates of speed. This can clearly compromise a diver and present itself as decompression illness or barotrauma. However, given the large amount of weights a drysuit diver must wear to compensate for the increased amount of air inside the drysuit, a runaway descent can prove to be irrecoverable and has in fact been the proximate cause of drowning in a series of drysuit diving fatalities. Once the diver initiates the descent, care must be taken to inflate the drysuit with enough air to maintain neutral buoyancy. If negative buoyancy prevails, the drysuit diver will sink faster and faster as suit and gas compression become more pronounced with increasing ambient pressure. At this point middle ear and sinus equalization issues may manifest themselves and the importance of dive fins with strong thrust potential are obvious. A further complication is that drysuit inflation under ice diving conditions must be done in short-burst depressions of the inflator button on the sternum. The probability of inflator freeze-up is otherwise increased and can result in the opposite effect, an uncontrolled blowup to the surface.

Boyle's Law describes the pressure/air volume relationship, which most directly affects buoyancy. "For any gas at a constant temperature, the volume of the gas is inversely proportional to the pressure." Thus, for a constant temperature: P1V1 = P2V2. A drysuit diver is surrounded by air, the volume of which changes as ambient water pressure changes. As the diver descends the pressure increases, the air compresses causing the volume to become smaller, the buoyancy decreases and the diver sinks even faster through the water column. As the diver ascends the pressure decreases, the air expands causing the volume to become larger, the buoyancy increases and the diver rises even faster. Therefore, either sinking too fast or ascending too fast because of lack of buoyancy control presents the extreme-environment drysuit diver with a significant safety issue.

b. Thermal protection and drysuits

Thermal protection

The drysuit, whether of trilaminate shell construction, vulcanized rubber or crushed neoprene, is conceptually like a rain coat, it keeps the diver dry while the undergarments provide a matrix to trap low-conductivity gas and thus provide warmth. The choice of drysuit underwear is perhaps more important than the choice of drysuit construction material, because it is the underwear that provides most of the thermal protection. Many divers wear an under-layer of expedition-weight polypropylene with an outer layer of 400 g Thinsulate®, which consists of many tissue-thin layers of polypropylene sheets covered by nylon fabric, is of light weight and dries quickly. It has excellent insulating properties, repels water and does not compress at depth. It is the most desirable undergarment to be wearing in the event of a complete drysuit flooding. Thinsulate is not easily machine washable and any detergent not rinsed away will reduce insulation properties. Regardless of the main undergarment that is used, it is recommended to wear a one-piece thin polypropylene layer next to the skin, which emits water vapor. Polypropylene is hydrophobic and 'wicks' this moisture away from skin, preventing a 'clammy' feeling. It further keeps the main undergarment clean. Layering garments can add insulation but can affect mobility and the effective migration of air within the suit. Cotton is not ideal because it readily absorbs moisture and loses insulation qualities, and materials that pill or shed fibers can easily clog valves.

The level of insulation (unaffected by depth) can be adjusted for different diving requirements and individual needs. The primary means of passive thermal protection is by trapping and stabilizing a low conductivity gas. For extreme-environment, remote polar scientific diving operations, active heating options that exist are not a good substitute for a highly effective passive system. An infinite energy source is not available on site that can deliver the needed 250-1000 W to the diver. Free-flooding hot-water suits require an infinite power source and, in general, water is not an optimal medium to work with in -40^{o}C polar environments. One particular exception is commercial diving construction work that is being performed seasonally at the USAP Palmer Station dock where divers are fitted with helmets and hot-water suits, facilitated by the close proximity to infrastructure at the laboratory. Liquid-heat transport garments also require energy sources that are difficult to provide in extreme diving environments.

A viable compromise may be a hybrid insulation system consisting of a high-efficiency passive undergarment with supplemental electrical heating of hands and feet. My current research objective for the 2012 Antarctic field season is to evaluate the operational reliability of electrically heated underwear, gloves and socks, a system designed by Diving Unlimited International, Inc. in San Diego, California. The drysuit is configured with zipseal drygloves and a sub-inflator mounted adapter with wet plugs that accepts power penetrations. This eliminates further through-hull perforations of the drysuit shell that may compromise its water-tight integrity. Highly efficient passive insulation, *e.g.,* Thinsulate, incorporates the wiring harness for a ventrally and dorsally electric-panel lined torso vest. Electrically heated glove and sock liners are on a separate circuit powered by a 50 W, compact rechargeable 6V Lithium battery system with ground-fault interrupter, screening and temperature control. Subjective impressions from a series of October 2010 test dives in San Diego, California in 30-m water depths at 14-17 are that the beneficial effects of warm hands throughout the dive are of prioritized importance compared to torso warming. Hands have been repeatedly noted as the dive-time limiting thermal factor in extreme-environment diving (Lang and Stewart, 1992; Lang and Sayer, 2007). Drygloves or mitts with an inner liner instead of wet gloves are now used with the drysuit. The DUI zipseal drygloves enjoy widespread use and are effective at warm air equalization from the drysuit into the glove at depth. A disadvantage of these dryglove systems is the complete lack of thermal protection if the gloves flood or are punctured, and the related inevitability of flooding the entire drysuit. Neoprene wetsuit gloves are wet gloves that are pulled over the tops of wrist seals and do not provide ideal insulation. Rubber drygloves are by far the warmest and connect to the suit with cuff rings or zipseals and insulation is provided by liner gloves worn underneath.

Inadequate thermal protection in extreme environments leads to progressive safety concerns including the distracting effect of cold, loss of manual dexterity, loss of cognitive functions, non-freezing cold injuries, and ultimately life-threatening hypothermia. Moreover, respiratory heat loss is approximately 10% of the diver's metabolic rate, influenced by atmospheric composition, temperature, water vapor content, and ambient pressure. Further heat loss results from the lungs warming and moisturizing the cold inhaled gas. The inability to complete underwater and post-dive tasks measurably impacts scientific productivity.

Matrix (undergarment) composition and selection for polar diving, including characteristics such as low conductivity under hydrostatic loads of 35 to 210 cmH_2O (0.5 to 3.0 psi), effectiveness when wet (hydrophobic characteristics) or immersed (flooded), conformity to the diver’s body, low conductivity to bulk ratio, materials, and construction costs were discussed by Stinton (2007). The diver's hands and feet are the factors limiting exposure time and efficiency in passive systems. Circulation to the hands can be improved by attaching ZipGloves™ by DUI, Inc. without a wrist seal to the drysuit. Medical examination gloves worn under insulation create a vapor barrier that keeps moisture out of the insulative matrix and vapor barrier socks worn on the feet perform the same function. The use of a gas interlayer by occasionally positioning the hands higher than the torso inflates the gloves and reduces the hydrostatic pressure on the hands. Twice the amount of insulation covering the legs should be used for insulating the feet, without impairing their circulation, and the use of tight fin pockets should be avoided.

Air has been the traditional drysuit inflation gas. The use of Argon, with lower conductivity than air, as a suit-inflation gas has become common in the technical diving community but not in recreational or scientific diving. However, its value has been debated following tests done by Risberg and Hope (2001) whose results from skin and core temperature monitoring during dives did not show a significant difference between air and Argon. Weinberg (1992) reported a 19% improvement in suit insulation using CO_2. Argon and CO_2 have conductivities that are comparatively close relative to air (Stinton, 2007). The difference in test results can possibly be explained by Risberg and Hope's utilization of a 6-mm foam neoprene drysuit with wooly bear undergarments where a large fraction of the total insulation is derived from the foam neoprene. The addition of Argon into the drysuit would not change the intrinsic insulation of the foam and at 9 m depth the foam still contributes a major portion of the total suit/system insulation. Weinberg used shell drysuits that had relatively little intrinsic insulation with the majority of insulation provided by the undergarments. Argon or possibly CO_2 are not a solution for an inferior insulation package. They are a means to gain additional performance when there is no more room in the drysuit for additional thermal layers. The effect of CO_2 use in suits at deeper depths is not known.

Aerogel is perhaps the most promising non-electrical matrix for thermal insulation for the future. It is silica-based and the world's lowest density solid consisting of 99.8% air, a density of 3 g/L, and an average particle size 2-5 nm. Current aerogel undergarment production challenges are the need for its encapsulated construction to control silica dust and reduction of the 5-fold increased cost over traditional insulation materials. We did test dive aerogel/thinsulate drygloves in Antarctica in 2009 and were subjectively impressed by the tremendous thermal protection quality, even with flooded gloves. However, manufacturing issues regarding silica dust control have appeared to slow its integration into commercially available products.

Drysuit

Drysuit choice depends on the diver's preference, the requirement for range and ease of motion, and the options available with each suit. Drysuits must be equipped with hands-free, automatic exhaust valves. Overinflation of the drysuit should never be used as a means to compensate for excess hand-carried weight.

A drysuit is a one-piece suit with a waterproof zipper, attached boots and seals at the diver's wrists and neck, which do not allow water to enter the suit. The type and amount of undergarments worn determine the level of insulation. Inflator and exhaust valves are installed to allow for inflation/deflation of the suit to maintain a constant volume.

Drysuits provide superior thermal protection regardless of depth, can isolate the diver from pollutants, and evoke a lessened diuresis effect. They are, however, more expensive, have increased weight and maintenance requirements, present difficulties in answering "nature's call," are bulkier than wetsuits, increase drag, require an inflator hose and larger fin pocket sizes, and their use mandates critical buoyancy control proficiency.

Of the various drysuit materials, neoprene stretches well and can be tailored to closely fit the body. It has good insulating properties, may require less or even no undergarments and is beneficial in the event of a leak. It is the only type of drysuit material that is inherently buoyant and is the most inexpensive type of suit. However, this suit loses buoyancy and insulation value as depth increases. It tends to develop leaks over time as cracks develop in the bubble layers and water migrates through the material making it difficult to patch and repair. This suit may not last as long as other types of drysuits. Crushed neoprene is very tough yet flexible and can be tailored into a suit of outstanding fit. It is good for swimming, has high insulation value and is long lasting. Crushed neoprene may be difficult to repair, may be heavier than suits made of other materials and is more expensive than foam neoprene. Urethane-coated nylon is composed of nylon to which urethane has been laminated to create a waterproof barrier. It is of light weight and low cost construction. There is minimal stretch and the suit's fit is loose and baggy. It is furthermore not as durable and is easily punctured. Trilaminate (TLS) drysuits are composed of two layers of tightly woven nylon with a layer of rubber in between. This is a light weight yet very strong suit of flexible material with little stretch and is easily repaired. TLS suits provide a great range of motion. Vulcanized rubber is available in several thicknesses (*e.g.,* Viking Sport, Pro, Commercial). It is easily repaired with a tire innertube-type patch and the exterior dries quickly resulting in the least amount of evaporative cooling. This suit is excellent for diving in contaminated waters because of its relative ease of decontamination. However, this suit is heavy and not as form-fitting or flexible as other suits.

The shoulder-entry suit design has the zipper located horizontally across the shoulders on the back, requires assistance to zip in, but is the least expensive to manufacture. The self-donning front diagonal suit requires no assistance in dressing, its telescoping torso allows easier entry into the neck seal and it improves flexibility and zipper durability. The wrap-around zipper between legs is an outdated 'Unisuit' style, originally developed for the Swedish military to allow toilet function without having to remove the suit, but assistance is required in closing the zipper. The wrap-around torso zipper is also an antiquated design because of the high stress it places on the zipper when the diver bends over.

Latex neck seals stretch easily, are more comfortable by putting less constrictive pressure on neck and wrists and are less likely to leak. However, latex is more easily punctured or torn by fingernails or jewelry during dressing/undressing, are susceptible to deterioration from oils, U/V radiation exposure, ozone and have a 1-2 year service life. Neoprene seals are rugged, harder to tear and longer lasting but are difficult to repair, do not stretch as well and may feel uncomfortable. Neoprene becomes permanently stretched and will thus fit loosely over time. Individuals with thin necks may have difficulty getting a proper seal because of the stretch required to pull the seal over the head.

Wet hoods are most common and can be attached to the suit or worn separately. Most hoods have one-way perforations at the crown to vent excess air from the hood coming from an incorrectly fitting neck seal or mask. Semi-dry hoods are also made of neoprene, attach to the suit and seal around face. Warm neck rings are neoprene collars attached to the drysuit into which the hood skirt is tucked. This option keeps the neck warmer as it reduces water flow on the cold latex seal and keeps the long hood skirt from folding up during the dive. Dryhoods are the warmest, but add difficulty in donning the suit. The latex hood is attached to the suit and seals around the face but requires a separate insulating hood worn underneath the latex hood and will not work well with a beard. Care must be taken to avoid external ear squeeze.

Inflator valves are operated via push-button activation, are connected to a low-pressure inflator hose connected to the first-stage regulator, and are typically located on the center of the chest. Most can swivel to allow flexibility in hose direction. The valve must be accessible while diving (other equipment configuration is important) and be easily disconnected with heavy gloves. Inflator valves are also subject to freeflow failure, because of water entry into the inflation mechanism. Drysuit and buoyancy compensator (BC) inflators must be kept completely dry and hose connectors blown free of water and snow before attachment to the valve. When inflating a drysuit or a BC, frequent short bursts of air are used and inflator buttons must never be depressed for longer than one or two seconds at a time because rapid air expansion, adiabatic cooling (5°C temperature drop), and subsequent condensation and freezing may cause a freeflow. Most exhaust valves are “automatic” and will vent by themselves when positioned at the highest point on the drysuit, but can also be vented manually. Valves are generally located on the upper left arm and are rotated clockwise to close and counterclockwise to open. Generally, drysuit exhaust valves do not vent air as rapidly as a buoyancy compensator.

Buoyancy compensators need to be designed to allow unimpeded access to drysuit inflator and exhaust valves. Water must be removed from the BC bladder after diving and rinsing because freshwater in the bladder may freeze upon submersion of the BC in ambient seawater. Use of a BC with a drysuit is mandatory because it provides secure flotation at the surface in the event of a catastrophic zipper failure or flooding of the suit. Excess air in the drysuit at the surface can put too much pressure on the neck and/or unexpectedly vent through the neck seal, causing a water leak and possible loss of buoyancy. One exception exists in the McMurdo area where BC use is not currently required when the dive is conducted under a fast-ice ceiling because of the lack of need for surface flotation where tenders are present to assist with the diver exit from the dive hole.

Divers must wear sufficient weight to allow for maintenance of neutral buoyancy with an increased amount of air in the drysuit. Extreme cold water diving requires more air in the drysuit as insulating gas than temperate water diving with the same equipment. Weighting considerations include the type of drysuit, the amount and type of undergarments, personal buoyancy characteristics, diver volume and total weight, cylinder type (all cylinders become more buoyant as the compressed air is used) and whether diving in a fresh or salt water environment. Runaway negative buoyancy is as great a safety problem to recover from as an out-of-control ascent. Because of the amount of weight (17-20 kg) and the potential for accidental release, weight belts are not used. Diving Unlimited International (DUI) has developed weight and trim systems that retain the benefits of a harness while still allowing full or partial dumping of weight pockets under water. The weight system improves comfort by shifting the weight load from the diver's hips to the shoulders. The system is also adjustable to allow for the back strap to be positioned over the coccyx, which eliminates hyperextension and soreness in the small of the back from horizontal swimming. Ankle weights are nylon fabric-covered rubber sleeves filled with lead shot secured with special buckles. They are usually 0.5 kg weights attached to each ankle that help to keep the feet down and retain trim under water, especially in new drysuit divers or with the use of floating fins.

Relief zippers can be installed that may be useful for urinary relief if dressed for long periods but this adds another potential source of leaks and expense. Pockets are offered in many styles and multiple attachment points are available but create additional drag under water.

Because of their buoyancy characteristics and durability in cold temperatures, steel, instead of aluminum, scuba cylinders are used.

Drysuit operational considerations

The added mass of wearing a drysuit with undergarments demands that the fin pockets are large enough to fit over drysuit boots and the BC large enough to fit over the drysuit. A drysuit low-pressure inflator hose must be installed onto the regulator first stage and connected to the drysuit inflator valve. Standard buddy checks should be performed and dive plan and emergency procedures discussed.

Drysuits should not leak. Upon entering the water, check for leaks and fix the problem if water is entering the suit. A small trickle at the surface may get worse at depth and will certainly continue throughout the dive. Once the suit is zipped up, the humidity inside rises to 100%. A moderate degree of dampness is acceptable as long as the diver is warm. Even when not perspiring, moisture is constantly coming from the skin's pores. Body heat moves the moisture to the cool inside surface of the suit where it condenses. It is common to find moisture on the inside of the suit after a dive and ice crystals after a polar dive. Flexing the wrists and turning the head allows water to enter around pronounced tendons but can be avoided with knowledge and practice. Leak location is accomplished by closing the zipper and also the neck seal with rubber bands. Attach the inflator to the suit and depress the button just enough to lightly inflate it and brush soapy water on the suit to observe any bubbles**.** Minor leaks can be repaired with Aquaseal and Cotol once completely dry. The suit should be returned to a dealer or the factory to repair major leaks or damage.

The goal of proper buoyancy control is to dive with the minimum amount of weight possible and the minimum volume of air inside the drysuit. A diver with excess weight needs a lot of air in the suit to achieve neutral buoyancy. Unfortunately, dives in extreme environments require more air volume inside the suit to stay warm than in temperate waters. As the air shifts in the suit, it creates buoyancy control issues. Ideally, only enough weight should be worn to allow for a 5-m safety stop at the end of the dive with approximately 35 bar left in the cylinder. Control of the suit's buoyancy is accomplished by inflating on descent to avoid squeeze and slow the descent rate and by venting air on ascent to slow the ascent rate. The largest pressure, and thus buoyancy, changes (50%) occur in the top 10 msw.

Drag is the water's force of resistance to movement and it acts opposite to the direction of travel. Lift is the upward or downward force that results from drag when the diver swims at an angle to the direction of movement. Both drag and lift can be significant, especially in divers who are overweighted or have poor diving skills. The more the diver and equipment are streamlined, the easier it is to move through the water. The greater the surface area presented, the greater the force resisting forward propulsion, hence the importance of proper trim. The normal underwater swimming position is horizontal to minimize drag and increase propulsion.

It is always advisable to maintain a minimum volume of air inside the suit. There should not be a large bubble of air, nor should a massive air shift be noticed when changing position in the water. Particular care must be taken to ensure that excessive volumes of air do not move to and become trapped in the feet of the drysuit which do not have pressure release valves. Trapped air may become difficult to control if it expands, resulting in inversions and rapid ascents. If air does become trapped there it is advisable to hold onto something and bring the legs down below the waist. Buoyancy control at depth should be achieved using only the drysuit, without adding air to the BC, as it becomes difficult to control buoyancy in two separate compartments simultaneously, particularly on ascent. A constant awareness of buoyancy status should be maintained in extreme-environment diving.

c. Cold stress and DCS

Man in the cold environment, thermal constraints and problems in diving, and prolonged and repeated work in cold water have been a repeating physiological theme in extreme environment diving for almost 40 years (Webb, 1974, 1985; Schilling, 1980; Kuehn, 1981). Diver thermal protection status, passive and active thermal protection systems, physiological considerations, and thermal measurement techniques and monitoring systems were subsequently reviewed (Nishi, 1992; Stinton, 2007).

More recently, the effect of cold on DCS risk was reviewed by Mueller (2007). The relative contributions of tissue nitrogen solubility and tissue perfusion to the etiology of DCS are not resolved. However, the prevailing thought is that the diver should be kept warm throughout the dive and during the immediate post-dive period external heat application and heavy lifting should be avoided to not induce DCS. The effect and timing of exercise has been studied with implications for cold water diving as a stress factor (Dujic *et al.*, 2005, 2006; Gerriets *et al.*, 2000; Jankowski *et al.*, 2004; Mekjavic *et al.*, 2003; Tetzlaff *et al.*, 2001). Cold and the physical exertion required to handle heavy dive gear in polar diving may increase the risk of DCS.

The average body temperature is 37°C. Hypothermia can occur when body heat is lost faster than it is produced, lowering the core temperature. Prolonged chilling can progressively incapacitate a diver without ever becoming hypothermic as an end result. Chilling increases fatigue, affects short-term memory and the ability to think clearly, increases air consumption (a diver's metabolism increases as the body burns more calories in an effort to maintain temperature) and may increase the risk of DCS (Mueller, 2007). Operationally, chilling reduces hand dexterity, creating difficulties working buckles, valves, removing fins and even holding onto exit ladders. The goal is to keep the diver warm during the dive, paying particular attention to the hands and feet (Stinton, 2007). Cold ambient temperature is the overriding limiting factor on dive operations, especially for the thermal protection and dexterity of hands. Dives are terminated before a diver's hands become too cold to effectively operate the dive gear or grasp a down line. This loss of dexterity can occur quickly (5-10 min) if hands are inadequately protected. Holding on to a camera, net, or other experimental apparatus will increase the rate at which a hand becomes cold by squeezing air out of the glove. Switching the object from hand to hand or attaching it to the down line allows hands to rewarm. Dryglove systems have greatly improved thermal protection of the hands by eliminating constrictive wrist seals that isolate warm air flow from the body of the drysuit to the hands.

The cold environment causes chilling of the diver, resulting in a reduced cognitive ability with progressive cooling. Monitoring the progression of the following symptoms to avoid life-threatening hypothermia is important: cold or numb hands or feet, shivering, increased air consumption, fatigue, confusion, inability to think clearly or perform simple tasks, loss of memory, reduced strength, cessation of shivering while still cold, and finally hypothermia. In scientific diving, reduced mental acuity, reasoning and cognitive function is of particular interest because the scientific diver who suffers from hypothermia may also cause errors during the course of scientific work (Vaughan, 1975, 1977; Hanson, 1978; Knight, 1981). Heat loss occurs through inadequate insulation, exposed areas (such as the head under an inadequate hood arrangement), and from breathing cold air. Scuba cylinder air is initially at ambient temperature and drops by approximately 5°C from the cooling effect of expansion as it passes through the regulator. Air consumption increases as the diver cools, resulting in additional cooling with increased ventilation. Significant chilling also occurs during safety stops while the diver is not actively moving. Polar diving requires greater amounts of air and insulation, which results in decreased mobility and increased potential for buoyancy problems. This also means that increased drag and swimming effort, along with the donning and doffing of equipment, increase fatigue.

Dive teams are aware that the weather can change quickly in polar environments. While they are in the field, all divers and tenders have in their possession sufficient cold-weather clothing for protection in any circumstance, which includes loss of vehicle power or loss of fish hut caused by fire. Boat motor failure may strand dive teams away from the base station. Supervisors/tenders on dives conducted outside must also be prepared for the cooling effects of inactivity while waiting for the divers to surface. Some food and water are a part of every dive team's basic equipment. In addition to serving as emergency rations, water is important for diver rehydration after the dive. Besides the dehydrating effect of breathing filtered, dry, cold compressed air on a dive, Antarctica and the Arctic are extremely low-humidity environments where dehydration can be rapid and insidious. Continuous effort is advised to stay hydrated and maintain proper fluid balance. Urine should be copious and clear and diuretics (coffee, tea, and alcohol) should be avoided before a dive.

Mueller (2007) described thermoregulation is a well-tuned balance between production and loss of heat in the human body (Rochelle and Horvath, 1978; Tetzlaff *et al.,* 2001) and as fully automatic.

Physiological factors affecting heat loss include distribution of blood flow, gender, body composition and age (Paik *et al.,* 1972; Russell *et al.,* 1972; Hong, 1973; Takano *et al.,* 1983; Curley *et al.,* 1989; Shake *et al.,* 1990; Tetzlaff *et al.,* 2001). Environmental factors such as temperature, wind-chill, acclimatization, adaptation and thermal insulation play an important role in the determination of the amount of heat loss (Skreslet and Aarefjord, 1968; Park *et al.,* 1983; Park and Hong, 1991; Lippitt and Nuckols, 1983; Cattermole, 1999; Beckett *et al.,* 1993). On the other hand, physiological heat production is determined solely by muscle activity, with shivering being the typical example during hypothermia.

The primary effect of the exposure to cold is a vasoconstriction in the human peripheral vasculature leading to a perfusion of the core (heart, lungs, CNS) only. The purpose of this severe peripheral vasoconstriction is to preserve heat in the core, which is particularly vulnerable to hypothermia, to avoid triggering potentially fatal arrhythmias when the core temperature drops below 32°C. Present decompression models are based on the absorption and diffusion of gases only and do not take into account changes in perfusion during the dive or decompression (Hills, 1967a; 1967b) or intra- and inter-individual factors (Rattner *et al.,* 1979). The vasoconstriction-induced perfusion changes should be taken into account to enable a more precise determination of the actual process of inert gas elimination during decompression (Mueller, 2007).

Furthermore, temperature changes and inert gas distribution are linked by a causal relationship between the temperature of different biological fluids and tissues, and the solubility of inert gases (Bove *et al.,* 1978; Leitch and Pearson, 1978; Simmons *et al.,* 1982). Tissue temperature may influence the formation of venous emboli and the rate of inert gas exchange. However, the actual incidence of DCS is more likely related to the temperature-induced changes in the distribution of peripheral blood flow than the temperature of the tissues *per se* (Mekjavic *et al*., 2003).

For deep Helium diving additional factors would appear to be in need of consideration. The density of gases increases with pressure and exhibit different heat transport capacities. The breathing gas is warmed to 37°C within the human respiratory system and its solubility in liquids decreases with the absolute temperature of the liquid. The gas uptake in the blood occurs passively through absorption. Diffusion also occurs passively and is responsible for the movement of gases between different liquid compartments. The movement of liquid compartments within the body (blood flow) is actively accomplished through perfusion. These factors become important because Helium increases the heat loss through the respiratory system significantly (Hall and Galvin, 1969; Brubakk *et al.,* 1982; Jammes *et al.,* 1988; Burnet *et al.,* 1990; Naraki and Mohri, 1988).

Reduced blood flow caused by vasoconstriction and the consequent reduced inert gas washout from tissues can cause symptoms of DCS (Hesser, 1962). The inert gas transport-limiting process (diffusion or perfusion) through tissues is influenced by cold (Belaud and Barthelemy, 1979) and Hempleman *et al.* (1984) demonstrated that local occlusion of blood flow causes skin mottling post decompression. Cold is thus not favorable to tissues during, or following, decompression. When cold post-decompression exposure was followed by a hot shower, symptoms of DCS were recognized by Mekjavic and Kakitsuba (1989).

Exposure to a cold thermal environment following diving, particularly when the air temperature is colder than the water temperature, may be a previously unrecognized risk factor for DCS (Broome, 1993). Hampson and Dunford (1997) attribute diving in cold waters as one potential cause of pulmonary edema in scuba divers, a potentially life-threatening situation.

Toner and Ball (2004) conducted a critical review and found no definitive study that demonstrated a causal relationship between thermal conditions and DCS risk or the magnitude of any effect. However, they did conclude that there was sufficient evidence to believe that the studies in the aggregate weakly supported the hypothesis that DCS risk was increased when a diver was warm on the bottom, cold during decompression, and cold on the surface. One study suggested that the use of hot-water suits at the same temperature on the bottom and during decompression was likely to increase DCS risk. The studies were found insufficient to determine if being cold on the bottom and cold during decompression would increase DCS risk. The magnitude of any thermal effect could not be precisely determined from these studies, but it is probably small. They hypothesized that physiological mechanisms responsible for the effect include changes in inert gas solubility and blood flow in peripheral tissue. Based on the conclusions of their review, it would seem prudent to keep divers relatively cold on the bottom and relatively warm during both in-water and surface decompression.

Ruterbusch *et al.* (2004; 2005) examined diver thermal status as a risk factor for DCS. U.S. Navy divers completed 357 working air decompression dives to 37 msw. The working bottom phase, or the resting decompression, was completed semi-nude in water that was either "warm" (W) at 36ºC or "cold" (C) at 27ºC. (CW represents cold compression and time at bottom followed by warm decompression; WC represents the reverse case.) All decompressions were 37 msw/70 min U.S. Navy Standard Air Tables (91 min decompression) and were followed by a 4-hour resting observation period at 26ºC. 11 DCS cases occurred in 112 WC dives and 2 DCS cases occurred in 245 CW dives. At the extremes of thermal status and BT examined, diver thermal status had a large effect on DCS risk under the conditions tested, with warm decompression favoring lower DCS risk. Appropriate manipulation of diver thermal status during different phases of a dive might therefore significantly decrease diver DCS susceptibility. These experimental findings were followed by operational dives by applying the use of hot-water suits to warm the divers. Divers were immersed in 13 ± 0.5°C water while wearing MK 21 helmets and U.S. Navy standard-issue hot-water suits. During the bottom phase, all divers performed cycle-ergometer exercise and diver thermal status was controlled by circulating cold (27 ± 0.5°C) water through the hot-water suit. Warm water (36 ± 0.5°C) was circulated through the suits while divers were at rest during the ensuing decompression. Depth, time and temperature recorders (DTTR) logged data from 4 skin temperature sensors placed on the chest, back, and left calf and forearm to monitor regional skin temperatures (T_{SK}) induced by the circulating water system. The results of 128 man-dives completed under these more operationally relevant conditions were in full accord with those obtained with semi-nude divers. One DCS case occurred in one hundred 37 msw/70 min man-dives decompressed on the 37 msw/70 min Standard Air schedule. Moreover, it was also shown that decompression from this dive could be shortened under these thermal conditions (C/W). One DCS case occurred in twenty-eight 37 msw/70 min man-dives decompressed on the 37 msw/60 min Standard Air schedule. This work established the efficacy of warm decompression.

Gerth *et al*. (2007) continued this work by comparing the DCS incidence in divers who completed air decompression dives while fully immersed in water at temperature controlled independently [either warm (36°C) or cold (27°C)] during BT and decompression phases. Divers remained under controlled resting conditions at 26 ± 2.8^{o}C during the immediate 4-hour postdive period when they were monitored for central venous gas emboli (VGE) with 2-D cardiac echo imaging. Four hundred man-dives were completed with 21 diagnosed cases of DCS in seven series of dives to 37 msw with different combinations of thermal conditions and BT from 25 to 70 min, but with the same U.S. Navy Standard Air 37 msw/70 min (depth/BT) decompression schedule (stops: 9 msw/9 min, 6 msw/23 min, 3 msw/55 min). The DCS odds ratio for a 10°C increase in $T_{W,B}$ was 23.8 while the odds ratio for a 10 °C increase in $T_{W,D}$ was 0.01. In another series of 84 man-dives to 46 msw and BT = 60 min, divers were cold during compression and bottom phases and warm during subsequent decompression on a U.S. Navy Standard Air 46 msw/60 min schedule (stops: 12 msw/3 min, 9 msw/19 min, 6 msw/26 min, 3 msw/62 min). With only a single case of DCS, the DCS incidence in this series was significantly lower than obtained in a series of 46 msw/60 min dives (5 DCS in 20 man-dives) conducted in the earlier study with divers cold throughout the dives and decompressed on a schedule nearly 2.5 times longer. Postdive VGE scores were only weakly associated with DCS occurrence. Beneficial effects of warm conditions during decompression were more pronounced than deleterious effects of warm conditions during BT, while effects of a 10°C increase in $T_{W,D}$ were comparable to effects of halving BT. It is worth noting that a study of U.S. Navy surface decompression tables as used by North Sea commercial divers concluded that the major factor involved in the occurrence of DCS cases was the severity of the hyperbaric exposure of the dive, with the use of hot-water suits acting as a contributory factor both to the overall incidence of DCS and to the proportion of Type II cases (Shields and Lee, 1986). The results of their analysis, relying on trends in the data because of small numbers, versus statistical analysis, are consistent with the hypothesis that warm on the bottom increases DCS risk.

It seems most likely that the inert gas uptake into the blood is not affected by the ambient temperature to a relevant degree since the distribution of inert gas is mainly determined by perfusion, while diffusion only plays a limited role. This effect of cold on inert gas uptake in diving is obviously complicated by the diver's activity level and the duration of the dive. The findings also indicate that it may actually be beneficial for the diver to be cold during the dive, but not during the decompression, which continues at the surface. For scientific diving it may, however, not be beneficial for the diving scientist to be cold during the dive, as this will impair mental acuity and dexterity which are absolute requirements for the diver.

Mathematical models for the elimination of inert gases in cold environments have not yet considered the redistribution of inert gas between the different compartments during and after decompression, determined largely by local perfusion, which still has to be satisfactorily implemented into physiological models of decompression (Mueller, 2007). The relatively slow tissue compartments with less perfusion (bone, skin) are most likely to develop symptoms of DCS after diving in cold waters, compared with the well-perfused slow tissues such as muscle, where local perfusion matches the inert gas liberation. Nevertheless, physical exercise such as lifting of heavy weights after diving, must be avoided. However, general physical activities such as swimming during decompression or walking after the dive may play an important role for a reduced incidence of DCS, particularly in coldwater diving. This should be further investigated.

The scientific diving community is perhaps fortunately not in a position to contribute significant knowledge to this aspect of extreme-environment diving because of its very low DCS incidence rate for polar diving (cf. Chapter 7.b. DCS incidence rates). The three largest Antarctic diving programs (Antarctica New Zealand, US Antarctic Program, and British Antarctic Survey) reported a combined DCS incidence rate of 0.28 cases per 1,000 person dives (Sayer *et al*., 2007). Over a combined 56 years of diving 618 divers had logged 17,647 dives and only presented with a total of 5 cases of DCS Type 1.

Long-term health effects on divers with a high proportion of coldwater dives should be considered in the future. One ongoing project is the evaluation of electrically heated drysuit undergarments (vest, gloves and socks) powered by 6V external batteries. This active heating adjunct may predictably increase our average BT under ice from 41 min because of the increased thermal comfort level. However, the average BT is now short enough to be well into the no-decompression zone of most of our working dives, but monitoring of decompression status will now become even more important.

d. Life-support breathing equipment

The primary safety concern of diving in extreme environments currently resides with the identification of the next generation of life-support equipment for under-ice scientific diving. The under-ice performance of several commercially available regulators was evaluated to select a successor model to the currently used 1991 Sherwood SRB3600 Maximus regulators in the National Science Foundation USAP Diving Program. The most desirable criterion was a low propensity to freeflow (freeze-up) and thereby expending a diver's gas supply in an overhead environment.

In 1991, double-hose regulators were retired from service and replaced with single-hose modified Sherwood Maximus SRB3600 regulators (Fig. 1). A heat-retention plate was fitted over the second-stage exhaust valve and around the air-delivery lever and the intermediate pressure was detuned from 10 to 8.6 bar to reduce the probability of freeflow in supercooled sea water at -1.86^{o}C. The breathing characteristics of these regulators were less than optimal. USAP used an *ex post facto* data collection method of ice-diving regulator performance (Bozanic and Mastro, 1992; Pollock and Mastro, 1996). Alternate regulator model performance has not been evaluated due to the existing availability of adequately performing regulators that have enjoyed a high level of non-freezing success (to date, over 7,000 dives incurred a freeflow incidence rate of 0.3%). *A priori* evaluation of regulator models that best meet our needs for safety and optimal breathing performance is prudent management to avert possibly fatal consequences to members of our scientific diver population.

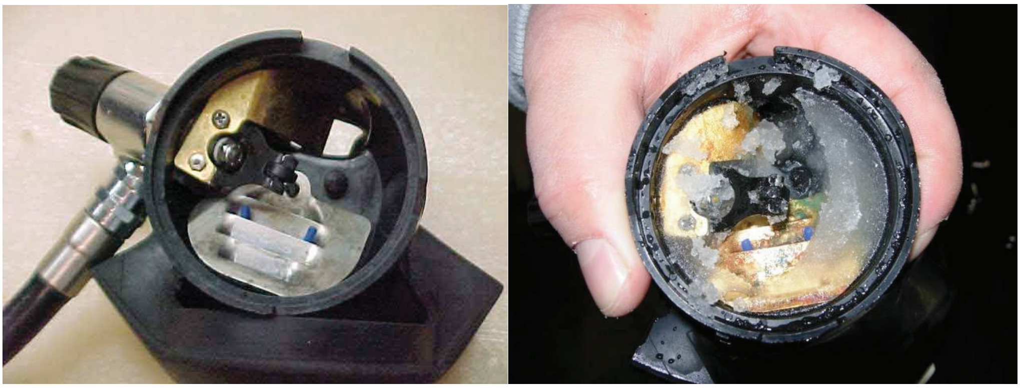

Figure 1. a. Sherwood Maximus SRB3600 second stage with heat retention plate on lever and exhaust valve (left); **b.** Second-stage ice build-up resulting from massive freeflow (right).

Lang and Robbins (2009) noted that divers are required to have two fully independent regulators attached to their air supply via Y valves (“slingshot valves”) whenever they are diving under a ceiling. The U.S. Navy Experimental Diving Unit similarly points out the need for ice diving field validations of regulators, an experience/facility the U.S. Navy currently does not have, to complement objective and subjective findings and laboratory-derived data from breathing machines in hyperbaric chambers (Clarke and Rainone, 1995). This project was guided, in part, by the tendency for regulators to freeflow under polar conditions and the relevant consensus recommendations of the 2007 International Polar Diving Workshop (Lang and Sayer, 2007), calling for continued data collection on the performance of regulators; field experience or independent lab testing validation prior to adoption of new regulator models for polar diving; a minimum of two independent regulator systems for diving in overhead environments and diver proficiency in switch-over procedures; use of a second-stage isolator valve in conjunction with a first-stage overpressure relief valve to manage regulator freeflow; and, proper pre- and post-dive regulator care.

Seventeen scientific divers conducted dives in -1.86 ^{o}C sea water under 6-m thick Antarctic fast ice over two field seasons in 2008 and 2009 in the vicinity of McMurdo Station, Antarctica. Thermal protection consisted of layers of polypropylene undergarments and a 400 g Thinsulate jumpsuit worn underneath a trilaminate shell drysuit.

All regulators experienced the same diving conditions and pre- and post-dive regulator care was standardized. Regulators were kept warm and dry before a dive and divers did not breathe from the regulator prior to immersion. Regulator purge buttons were not used because large volumes of air exhausted rapidly almost certainly result in a freeflow failure. Drysuit inflator hoses were attached to the back-up regulator in case the air supply to the primary regulator had to be turned off to stem a freeflow. Surgical tubing mouthpiece holders secured the backup regulator (Sherwood SRB3600) second stage to the cylinder harness on the right side of the diver's chest, to be swapped with the freeflowing primary regulator after the flow had been shut off. Regulators were not rinsed with fresh water in between dives; however, with second-stage diaphragm covers removed, regulators were blown dry with low-pressure compressed air.

Each test regulator was fitted with an isolator valve (Fig. 2) in line on the intermediate pressure hose adjacent to the second stage and used in conjunction with an overpressure relief valve (Fig. 2) on the regulator's first stage. The isolator valve has 10 mm of horizontal travel towards the regulator mouthpiece to shut off air flow after switching out to the back-up second stage prior to closing the cylinder valve. The isolator valves used for this study were found to only marginally increase breathing resistance (resistive effort, RE) at respiratory minute volumes of 40 and 62.5 L/min down to 60 msw, but in general the RE lay below the performance goals established by the U.S. Navy for scuba regulators.

Figure 2. Zeagle isolator valve (freeflow shut-off device; product no. 333-0233) on the regulator second stage (left) used in conjunction with a first-stage overpressure relief valve (product no. 330-4905; right).

Unmodified test regulators (69 units from 12 manufacturers) were purchased off the shelf from commercial vendors. Regulator models were selected for ice-diving evaluation based on criteria such as design, materials, manufacturer performance claims and diver reviews. Regulators were randomly assigned to divers who were selected based on their ice-diving experience and variations in body size, and RMV (Respiratory Minute Volume). Dives were conducted as no-decompression profiles and recorded with UWATEC One dive computers. Several bounce dives were conducted deeper than 40 m with those regulator models that did not freeflow at shallower depths.

The combined diver population of 17 divers (9 male, 8 female) was purposefully heterogeneous in body habitus. Average diver height was 176 ± 9.0 cm (mean ± SD) with a range from 163 to 191 cm. Mean diver weight was 76.7 ± 20.5 kg with a range from 53.5 to 127.5 kg. The U.S. Navy showed that freeze-up incidence is related to duration of cold water exposure and ventilation rate (Clarke 1996, Clarke 1999). Consequently, the correlation of the current results with dive duration and ventilation rate was examined.

A total of 305 dives were conducted (Fig. 3a) by 17 divers for a total dive time of 8,942 min (Fig. 3b), resulting in 65 freeflows. The freeflows were not evenly distributed across the regulator brands. Regulator failure rates by brand fell into two categories (<11% and >26%). The pooled incidences for the seven best performing regulators (DiveRite Jetstream, Sherwood Maximus SRB3600, Poseidon Xstream, Poseidon Jetstream, Sherwood Maximus SRB7600, Poseidon Cyklon, and Mares USN22 Abyss) were compared to the ten remaining regulators. The regulators classified for the purpose of the test as “better” (< 11% failure rate) suffered only 9 freeflows out of 146 exposures (6% freeflow incidence); and those classified as “worse” (> 26% failure rate) suffered 56 freeflows out of 159 exposures (35% freeflow incidence; Fig. 4). Of the top seven regulators, four models suffered no more than 1 freeflow incident out of 60 dives. Those models were the DiveRite Jetstream, Sherwood Maximus SRB3600, Poseidon Xstream, and Poseidon Jetstream.

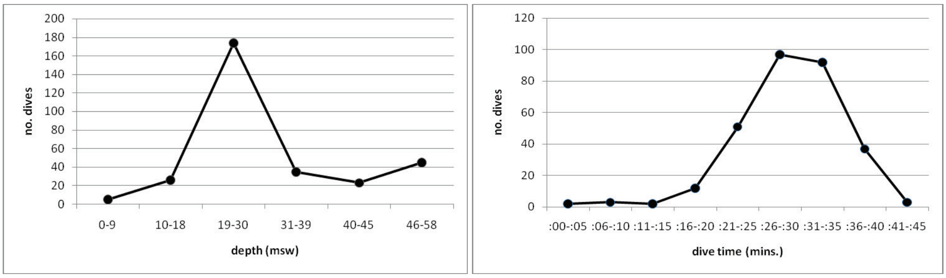

Figure 3. a. Number of dives (n=305) as a function of dive depth (left); **b.** dive times (right).

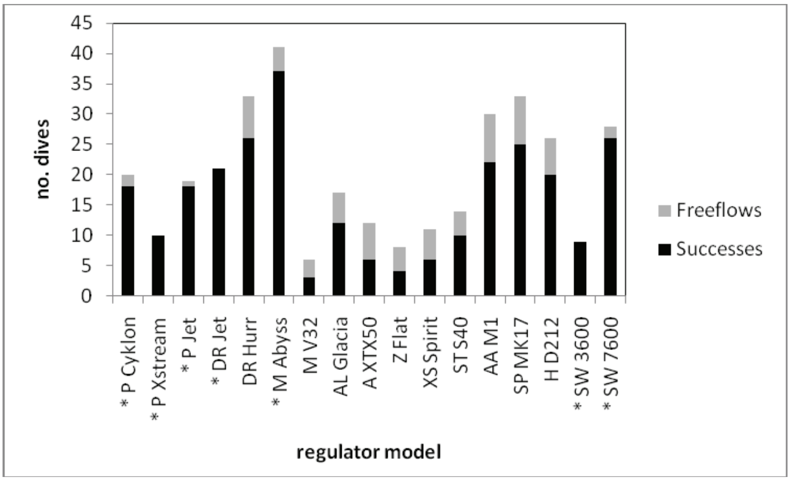

Figure 4. Freeflow incidents by regulator model; * indicates best performing regulators.

Statistics supported the conclusion that the in the bimodal distribution of regulator freeflows, those regulators with the lower incident rate were less likely to freeflow than the others. Of the total freeflows (n=65) the mean onset time was 18 min (± 9 min SD) and the mean onset depth was 16 msw (± 10 SD), as reported by the divers.

Testing on regulators was aborted when the freeflow incidence exceeded stopping criteria. Five regulators (SITECH S40 Forever, XS Scuba Spirit, Mares V32 Proton Ice Extreme, Apeks XTX50, and Zeagle Flathead VI) exceeded the stopping rules and were excluded from further testing. In 2008, phase 1 of this field study narrowed the number of regulator models being considered for the rigorous conditions of the USAP Diving Program from nine models to two: the Poseidon Xstream and the Sherwood Maximus SRB7600. In 2009, phase 2 narrowed the regulator models from seven to two: the DiveRite Jetstream and the Mares Navy 22 Abyss. Ejection of ice spicules from the Jetstream into the mouth was a uniform, albeit subjective, objection by all divers.

The relative freeflow frequency, i.e., the number of freeflows experienced by each diver divided by their total number of dives, ranged from a minimum of 0.03 to a maximum of 0.48. There were virtually no anthropometric differences between the divers at the extremes as estimated from their height, weight and gender data.

e. Operations

The polar environment

Ice crystallization begins at the air-sea interface where the temperature differential is greatest. Because the air may be as much as 50°C colder than the water, heat conduction to the air from the water promotes the formation of ice. Under calm conditions, this *congelation ice* is composed of needles, small disks, and dendritic stars and will form a smooth sheet over the sea. When the freezing sea is subjected to wind and wave action, *frazil ice* crystals clump together into *pancake ice* (0.5 m to 2 m in diameter) that consists of roughly circular, porous slabs with upturned edges. If the water between them freezes, the "pancakes" may solidify and join together. Otherwise, pancake ice continually interacts with wind, waves, and other ice to create complex, many-layered floes of *pack ice*. When the ice sheet, whether congelation or frazil ice in origin, becomes a solid surface joined to the shoreline, it forms *fast ice*. Once the ice sheet is established, it continues to grow from beneath. Low-density seawater emanating from beneath ice shelves and floating glaciers undergoes adiabatic supercooling. *Platelet ice* crystals form in this supercooled water and float upward, accumulating in an initially loose and porous layer at the bottom of the surface ice sheet. This unfrozen platelet layer (1 cm to several m thick) continually solidifies by freezing, increasing the thickness of the ice sheet. The platelet layer forms a substrate for the growth of microbial communities dominated by microalgae fed upon by amphipods, krill and ice fish. Ice may also crystallize on the benthos. This *anchor ice* generally forms at depths of 15 m or less, attaching to rocks and debris, and even to live invertebrates. If enough ice forms on these objects, they will float up and may become incorporated into the ice sheet.

Diving conditions are usually associated with solid fast-ice cover for most of the austral diving season at McMurdo Station (annual average thickness 2 m, multiyear 4 m), limited freezing at Palmer Station (under 30 cm), periodically in the Svalbard fjords (average 1 m), and the perennially ice-covered Dry Valley lakes (greater than 6 m; Andersen, 2007). A solid fast-ice cover provides a calm, surge-free diving environment and offers a stable working platform with no surface wave action. Fast-ice strength and thickness varies with time of year and ambient temperature affecting diving operational support. The under-ice topography varies dramatically at dive site, time of year, microalgal activity, ocean current, age of ice, and other oceanographic and physical factors. When viewed from below, a fast-ice sheet may appear relatively homogenous as a hard, flat surface but in places can be punctuated by cracks and openings that appear as bright lines in an otherwise dark roof. If platelet ice is present, the underside of the ice appears rough and uneven. Areas of multiyear ice and thick snow cover are darker. Where pressure ridges and tidal cracks are present, the under-ice topography has more relief. Large and small chunks of broken ice may jut down into the water column in profusion, creating an environment reminiscent of cave diving. *Brine channels* or *ice stalactites* form as seawater cools and freezes and salt is excluded. This salt forms a supercooled brine solution that sinks because of its increased density and freezes the seawater around it resulting in a thin, hollow tube of ice stretching down from the underside of the ice sheet. These brine channels can reach several m in length and may appear singly or in clusters.

Fast-ice diving differs from pack-ice diving (Quetin and Ross, 2009), where broken ice cover usually eliminates the need to cut access holes for diving because of easy access to the surface. The pack-ice environment tends to be more heterogeneous than that of fast ice. Ice may be present in all stages of development and the floes themselves may vary in size, age, structure, and integrity. Pack-ice divers will find themselves under an ever-shifting and dynamic surface and wave action and currents must be considered. At sites where the pack ice is forced against the shore and is solid but unstable, an access hole will have to be opened near shore in shallow water. Tidal fluctuations may alter the size of dive holes or vary the water depth under the holes.

In August and September in the McMurdo region, horizontal underwater visibility may range up to a record 300 m. As solar radiation increases during the austral summer, an annual plankton bloom develops and quickly diminishes visibility to as little as 1 m by late December. Other water visibility factors influencing the polar regions include glacial melt and wind and temperature conditions. Visibility in the open waters of the Antarctic Peninsula may vary from 300 m to less than 3 m, depending on plankton densities and sea state. As glacial or sea ice melts, the resulting water may form a brackish water lens over the seawater. Visibility within these lenses is markedly reduced, even when the visibility in the water is still good otherwise. It may be possible to lose sight of the entry hole even when divers are near the surface.

Polar diving procedures

Tidal action, currents, and other forces produce open cracks and leads that divers may use to enter the water. Divers working from U.S. Antarctic Program research vessels often use the leads cut by the vessel for their access to the water (Quetin and Ross, 2009). A hydraulically operated mobile drill can be used to cut 1.3-m diameter holes in ice that is over 5-m thick. In addition to the primary dive hole, at times a safety hole is drilled. Hole melters consisting of coiled copper tubing filled with hot circulating glycol or alcohol are used to open a clean, 1-m diameter hole in the thick ice cap that covers the freshwater Dry Valley Lakes (Andersen, 2007), taking from several hours to several days. Chain saws can also be used to cut an access hole through ice that is 15- to 60-cm thick. Access holes are cut into square or triangular shapes and made large enough to accommodate two divers in the water simultaneously. Another method is to use Jiffy drills that bore pilot holes in ice 15- to 30-cm thick and then saws can be used to cut a large dive hole between them; attaching ice anchors to the chunks of ice allows for easy removal once they are sawed free. For ice from 15- to 25-cm thick, ice saws and breaker bars (2-m lengths of steel pipe or solid bar with a sharpened tip) are used to cut and break away the ice to form a hole. Divers enter the water through pack ice from shore, from an inflatable boat launched from shore or a research vessel, or from large ice floes or a fast-ice edge. If dive holes are required in ice thicker than 5 m or in ice out of range of the mobile drill, explosives may be necessary. However, the use of explosives is generally discouraged for environmental reasons and requires several hours of clearing ice from the hole before a dive can be made. Fast-ice diving requires one or more safety holes in addition to the primary dive hole. During times of the year when air temperatures are extremely cold, dive holes freeze over quickly. Positioning a heated hut or other portable shelter over a dive hole will delay the freezing process. Solar powered electric muffin fans are used to blow warm air from near the ceiling of the hut to the ice hole through a plastic tube. Down lines must mark all holes available for use on each dive because safety holes that are allowed to freeze at the surface are hard to distinguish from viable holes while diving under the ice.

A down line is required on all untethered dives conducted from fast ice or any other stable overhead environment with limited surface access. Specific down line characteristics and components are described by Lang and Robbins (2007). A minimum of one supervisor/tender per dive is required. Because they are a critical part of the diving operation and the first responders in case of accident, tenders receive training in diving first aid (Lang *et al*., 2007), radio use and communication procedures, scuba gear assembly, tether management, and vehicle or boat operation. Dives conducted under fast ice where there is a current, reduced visibility or open blue water, or where the water is too shallow to maintain visual contact with the dive hole, require individual diver tethers that are securely attached at the surface. Use of the T- or L-shaped tether system is not ideal, making line-pull communication signals difficult and tether entanglement a possibility. Surface-tender training is necessary to maintain enough positive tension on the tether line to immediately recognize line-pull signals from the safety diver, without impeding the activity or motion of the scientists working under the ice. The safety diver's function is to keep tethers untangled, watch for large predators and communicate via line-pull signals to the surface and other working divers. Other hole-marking techniques to further protect against loss of the dive hole are snow removal (straight lines radiating outward from the dive hole that are very visible from under water) and benthic ropes which consist of 30-m lines laid out by divers when they first reach the bottom, radiating outward like the spokes of a wheel from a spot directly beneath the dive hole and marked so that the direction to the dive hole is clearly discernible.

Drysuits and ice-diving regulator performance, use and maintenance are addressed in Chapters 3.b.and 3.d. Severe cold can damage o-ring seals exposed to the environment requiring frequent cleaning and lubrication. Compressor care and adequate pre-operation warming are necessary to ensure a reliable supply of clean air checked by air-quality tests conducted at six-month intervals. Air filters and crankcase oil must be scheduled for maintenance on a regular basis. The filtering capacity of portable compressors is usually limited, necessitating air-intake hose positioning upwind and well away from compressor engine exhaust. Manual condensate drains are purged frequently to prevent moisture contamination and freezing of the filter.

Each diver conducts a functional check of all equipment before each dive. Particular attention is paid to regulators and inflator valves. If leakage or freeflow is detected at the surface, the dive is postponed and the gear serviced because it will certainly freeflow at depth. All divers must be able to disconnect, with gloved hands, the low-pressure hose from a freeflowing drysuit inflator valve to avoid an uncontrolled ascent. Because a drysuit must be inflated to prevent “suit squeeze” with increasing pressure, it is most efficient to regulate buoyancy at depth by the amount of air in the drysuit (Lang and Egstrom, 1990). Buoyancy compensators (BC) are considered emergency equipment, to be used only in the event of a drysuit failure. This procedure eliminates the need to vent two air sources during ascent, reduces the chance of BC inflator freeflow, and simplifies the maintenance of neutral buoyancy during the dive. The main purpose of air in a drysuit is to provide thermal insulation as a low-conductivity gas. BCs and drysuits must never be used as lift bags. When heavy items must be moved underwater, separate lift bags designed specifically for that purpose are used. Lang and Stewart (1992) concluded that there may be occasions when the drysuit diver is more at risk with a BC than without one. Accordingly, BCs are not required for dives under fast ice where a down line is deployed and the dive is not a bluewater dive.

Robbins (2006) described USAP’s surface-supplied diving activities, history, equipment, training, operations, and costs. By taking advantage of the equipment and expertise brought to the U.S. Antarctic Program by commercial divers, scientific diving has benefited from the use of surface-supplied diving techniques. Safety, comfort, and efficiency are enhanced in some applications by using this mode long associated with industry but rarely used in the scientific arena. Since 1992, USAP has supported surface-supplied diving. In that period, 459 surface-supplied dives (of 8,441 total dives) were logged by 32 divers (of 107 total divers). The vast majority of surface-supplied dives were performed by 8 divers. The USAP’s experience with EXO-26 masks has been 11 freeflows in 106 dives (10.4 percent failure rate). AGA masks have had 2 freeflows in 26 dives (7.7 percent failure rate). These data come from dives in the

Dry Valley Lakes where water temperatures range between 0°C and 2°C. The failure rate would be even higher in -1.8°C water of McMurdo Sound. A minimum of two familiarization dives are made by each new surface-supplied diver over two days in addition to topside and underwater training. A three-person crew is the minimum personnel requirement including a supervisor/tender, a diver, and a suited standby diver using either scuba or surface supply. Currently, the majority of surface-supplied diving is done utilizing 2-m tall high-pressure gas cylinders as an air source. A large 1 m^3/m - 10.3 bar diesel compressor and smaller 0.4 m^3/m - 8.6 bar gas compressor are available but used rarely for scientific diving operations. The USAP uses Kirby-Morgan Heliox-18 band masks and Superlite-17 helmets. While these units have a greater propensity to freeze and freeflow than Sherwood Maximus scuba regulators, their track record is as good as either the EXO-26 or AGA Divator full-face masks.

Polar diving hazards

Lighting is often dim under a solid ice cover, particularly early in the austral spring when the sun is low on the horizon. The amount of snow cover and ice thickness will also attenuate light transmission. Microalgal blooms and increasing zooplankton during the austral summer reduces available light, making it difficult for divers to locate buddies, down lines, and underwater landmarks. High visibility early in the austral summer season may make under-ice or benthic objects seem closer than they are. This illusion may entice divers to travel farther from the access hole than is prudent. The greatest hazard associated with fast-ice diving is the potential loss of the dive hole or lead. Access holes, leads, and cracks in the ice are often highly visible from below because of downwelling daylight streaming through them. However, dive holes may be difficult to see due to conditions of darkness or of covering the holes with portable shelters. Therefore, a well-marked down line is required for fast-ice dives. Divers maintain positive visual contact with the down line during the dive and avoid becoming so distracted by their work that they fail to take frequent note of their position in relation to the access hole or lead. Problems requiring an emergency ascent are serious, since a vertical ascent is impossible except when a diver is directly under the dive hole or lead. Additional safety holes ameliorate the danger of losing the primary dive hole but former dive holes that have frozen over may still look like safety holes from below. To eliminate confusion in a frequently drilled area, all active holes are marked with a down line.

Pack ice is inherently unstable and its conditions can change rapidly, primarily from surface wind conditions. An offshore wind may blow pack ice away from the shoreline and loosen the pack, whereas an onshore wind may move significant quantities of pack ice against shorelines or fast-ice edges, obstructing what may have been clear access areas when divers entered the water. Similarly, increased wind pressure on pack ice may make driving and maneuvering an inflatable Zodiac more difficult or impossible. Under a jumble of pack ice, the topography is reminiscent of cave diving. The condition of the pack must be continually monitored by divers and tenders for changes that may affect dive safety and the entry area must be kept clear. Down lines and tethers can be disturbed by shifting pack ice, forcing dive tenders to be alert in keeping these lines free of moving ice. Surface swells, even if only light to moderate, may cause pack ice to oscillate up and down. In shallow water, it is possible for a diver to be crushed between rising and falling pack ice and the benthos. At Palmer Station, surges from the calving glacier in Arthur Harbor may create a similar hazard. Divers avoid diving under pack ice if the clearance between the ice and the benthos is 3 m or less. In addition, lighting may be dim under a heavy pack-ice cover. Open water develops in McMurdo Sound when the fast ice breaks up in late December or early January. In the Palmer region, any existing fast ice usually breaks up by the end of October. Pack ice may be present for another month or two, and intermittently after that, but open water generally characterizes the diving environment after early December. Kongsfjorden in Svalbard has not formed a substantial ice cover from 2005-2012. Climatic conditions will cause variation in annual ice conditions. Divers operating in open water and from small boats fly a “diver down” or “Alpha” flag to warn other boat traffic in the area. When diving from small boats a rapid exit from the water into the boat may be necessary. Because this can be difficult when fully laden with gear, lines with clips hang over the side of the boat to temporarily secure gear and a ladder facilitates diver exit. When diving in blue water (a deep open water environment devoid of visual cues as to the diver’s vertical position in the water column), blue-water diving guidelines generally apply (Haddock and Heine, 2005). Divers are tethered and wear buoyancy compensators and a down line is deployed if conditions warrant. Divers operating under pack ice in blue water often perceive current increases. Wind action causes the pack to move, which in turn moves the water directly below it. This effect decreases with depth, such that divers in still water at 10 m will have the illusion of movement as the pack ice above them drifts. Ice-edge diving is usually conducted in blue water, and it tends to be shallow (less than 10 msw). The underside of the ice sheet provides a depth reference lacking in ice-free blue water dives. Divers watch continuously for leopard seals known to lunge out of the water to attack people at the ice edge. They may also lurk under the ice waiting for a penguin, or a diver, to enter the water. If penguins in the area demonstrate a reluctance to enter the water, it may be an indication that a leopard seal is nearby.

Few polar animal species are considered dangerous to the diver. Southern elephant seals (*Mirounga leonina*) and Antarctic fur seals (*Arctocephalus gazelli*) may become aggressive during the late spring/early summer breeding season. Crabeater seals (*Lobodon carcinophagus*) have demonstrated curiosity toward divers and aggression to humans on the surface. Leopard seals (*Hydrurga leptonyx*) have been known to attack humans on the surface and have threatened divers in the water. A case report of the single known in-water fatality caused by a leopard seal is described by Muir *et al*. (2006). Should an aggressive seal approach divers in the water, similar techniques to those protecting against sharks are applied. Divers come close together in a group while facing outward to keep the seal in view. Equipment such as cameras can be used to ward off an animal while the dive is aborted and the divers ascend as a group to the surface. Polar bears (*Ursus maritimus*) and walrus (*Odobenus rosmarus*) in the Arctic are considered predatory mammals against which diving personnel must be safeguarded. Encounters with all of the aforementioned mammals are usually restricted to areas of open water, ice edges, or pack ice. Divers in the fast ice around McMurdo may encounter Weddell seals (*Leptonychotes weddelli*) in the water. Occasionally a Weddell seal returning from a dive may surface to breathe in a dive hole to replenish its oxygen stores after a hypoxic diving exposure (Kooyman, 2009). Usually the seal will vacate the hole once it has taken a few breaths particularly if divers are approaching from below and preparing to surface. Divers must approach such a seal with caution, since an oxygen hungry seal may aggressively protect its air supply. Weddell seals protecting their surface access will often invert into a head-down, tail-up posture to watch for rivals. Divers entering or exiting the water are particularly vulnerable to aggressive male Weddells, who tend to bite each other in the flipper and genital regions. There are no recorded incidents of killer whale (*Orcinus orca*) attacks on divers.

Polar diving emergencies

The best method to mitigate scuba diving emergencies is through prevention. Divers must halt operations any time they become unduly stressed because of cold, fatigue, nervousness, or any other physiological reason. Similarly, diving is terminated if equipment difficulties occur, such as freeflowing regulators, tether-system entanglements, leaking drysuits, or buoyancy problems. Emergency situations and accidents stem rarely from a single major cause and they generally result from the accumulation of several minor problems. Maintaining the ability to not panic and to think clearly is the best preparation for the unexpected. Most diving emergencies can be mitigated by assistance from the dive buddy, reinforcing the importance of maintaining contact between two comparably equipped scientific divers while in the water. Loss of contact with the dive hole may require divers to retrace their path. Scanning the water column for the down line is done slowly and deliberately because the strobe light flash rate is reduced in the cold water. If the hole cannot be found, an alternate access to the surface may have to be located. Often there will be open cracks at the point where fast ice touches a shoreline. Lost divers will have to constantly balance a desirable lower air consumption rate in shallow water with the need for the wider field of vision available from deeper water. Maintaining a safe proximity to the surface access point has made losing the dive hole an extremely unlikely occurrence. Loss of the tether on a fast-ice dive that requires its use is one of the most serious polar diving emergencies. Lost diver search procedures are initiated immediately (i.e., assumption of a vertical position under the ice where the tethered buddy will swim a circular search pattern just under the ceiling to catch the untethered diver). The danger associated with the loss of a tether in low visibility is mitigated if the divers have previously deployed a series of benthic lines. If a diver becomes disconnected from the tether down current under fast ice, it may be necessary to crawl along the bottom to the down line. To clearly mark the access hole divers deploy a well-marked down line, establish recognizable "landmarks" (such as specific ice formations) under the hole at the outset of the dive, leave a strobe light, a flag, or other highly visible object on the substrate just below the hole or shovel surface snow off the ice in a radiating spoke pattern that points the way to the dive hole.

The under-ice platelet layer can be several meters thick and can become a safety concern if positively buoyant divers become trapped within this layer, become disoriented, and experience difficulty extricating themselves. The most obvious solution is to exhaust air from the drysuit to achieve negative buoyancy. If this is not possible and the platelet layer is not too thick, the diver may stand upside down on the hard under surface of the ice so that the head is out of the platelet ice to orient to the position of the dive hole and buddy. Another concern is that abundant platelet ice dislodged by divers will float up and plug a dive hole. Fire is one of the greatest hazards to any scientific operation in polar environments. The low humidity ultimately renders any wooden structure susceptible to combustion and once a fire has started, it spreads quickly. Dive teams must always exercise the utmost care when using heat or open flame in a dive hut. If divers recognize during the dive that the dive hut is burning they must terminate the dive and ascend to a safety hole or to the under surface of the ice next to the hole (but not below it) in order to conserve air.

There are several drysuit emergencies that may arise that require diver attention and prompt action. Never lift heavy weights by inflating the drysuit or BC. If the weight drops, dangerous positive buoyancy ensues. Proper procedures, such as the use of lift bags or lift lines must be used to raise heavy objects. Compressed air released from low pressure inflator valves is very cold because of adiabatic cooling. The colder the water, the more readily ice forms from moisture-saturated air in the drysuit that freezes on the valve mechanism. Ice crystals then form, preventing the valve from seating and creating a freeflow, which in turn increases cooling, resulting in more ice formation and an uncontrolled freeflow. Both BC inflator valves and regulator second stages are susceptible to freezing. Prevention includes completely drying the inflator valve between dives and inflating the BC and drysuit using only short bursts of air. Should the inflator valve stick open, immediately attempt to disconnect the inflator hose while remaining aware of depth in the water column. Assume a vertical position and vent excess air through the exhaust valve. If severe enough, pull the wrist seal or dryglove off allowing water to enter the suit. If air cannot be vented, extend arms and legs in a horizontal position to create drag (*i.e.,* flare position.) An inflator valve stuck in the closed position should be caught during pre-dive inspection or immediately stop the descent and terminate the dive. Use the BC as needed to control buoyancy and return to the surface while venting expanding air as normal. For an exhaust valve stuck closed or clogged, failing to exhaust air, immediately stop the ascent, if possible. Rotate or manually operate the automatic exhaust valve to attempt to get it to work. If the valve still does not function properly, pull wrist seal open to vent. Attempt to ascend along a fixed object or down line.

If weights are accidentally dropped at depth and their recovery is unsuccessful, a buoyant, rapid ascent will follow. If an anchor line or fixed object is in close proximity, hold on and try to shimmy up. Do not drag the dive buddy to the surface, rather, attempt to exhaust expanding air as rapidly as possible. If ascending rapidly, exhale and use the flare position to slow the ascent by increasing drag. The flare position slows the ascent dramatically by holding the ankles rigid with fins parallel to the bottom, acting as "water brakes," arching the back, and holding the arms outstretched. Another technique for slowing a rapid ascent is to swim horizontally, so the body presents a greater surface area. It is possible for excess air to move to the feet of the drysuit, making it difficult to return to an upright position and invariably, swim fins will pop off the feet. Attempt to tuck the body into a ball, kick, and roll to an upright position. Once upright, immediately vent the suit through the exhaust valve to regain control.

Drysuit flooding can occur from the complete failure of a zipper, blowout of a neck seal, or the destruction of a valve and may cause immediate negative buoyancy depending on the kind of undergarments worn. Neutral or positive buoyancy must be achieved by inflating the BC or dropping partial weights. Drysuit divers should not only be concerned with an uncontrolled rapid ascent and the concomitant danger of gas embolism or decompression sickness, but also with an uncontrolled rapid descent caused by overweighting or loss of buoyancy. Fins that provide adequate thrust are essential for drysuit diving.

Antarctic environmental protection

There are research diving sites in Antarctica (e.g., Palmer sewage outfall, McMurdo sewage outfall, and Winter Quarters Bay) that must be treated as contaminated water environments because of the high levels of *E. coli* bacteria (that have been measured up to 100,000/100 ml) or the presence of a hydrogen-sulfide layer (e.g., Lake Vanda). Diving with standard scuba or band mask, where a diver may be exposed to the water, is prohibited in these areas. Surface-supplied/contaminated-water diving equipment is used at these sites ranging from Heliox-18 band masks for use with a vulcanized rubber drysuit to Superlite-17 helmets that mate to special Viking suits. All researchers must avoid degrading the integrity of the environment in which they work. In particular, polar divers should avoid over-collecting, to not deplete an organism's abundance and alter the ecology of a research site; unduly disturbing the benthos; mixing of water layers such as haloclines; using explosives for opening dive holes; and, spilling oil, gasoline, or other chemicals used with machinery or in research.

The 50th anniversary of the signing of the Antarctic Treaty was celebrated on December 1, 2009 with an international science policy symposium convened at the Smithsonian Institution (Berkman *et al*., 2011). Increased attention to Antarctic Treaty protocols on environmental protection and implementation of the Antarctic Conservation Act have made human-seal interactions a more sensitive issue. Dive groups should avoid Weddell seal breeding areas during the breeding season and their breathing holes in particular. Interactions with Weddell seals under water are a frequent occurrence because the seals often avail themselves of the dive holes in the vicinity of dive sites.

Analysis of USCG HEALY diving mishap

On 17 August 2006, three Coast Guard divers from USCG Cutter HEALY attempted to conduct two 20-min cold water familiarization dives at 6 msw during an ice liberty stop in the Arctic ice approximately 790 km north of Barrow, Alaska. After one of the divers exited the water due to equipment malfunction, the other two divers continued the dive in -1.8°C waters. The divers quickly descended to depths far exceeding their planned 6-m depth (57 msw and 67 msw). Once it became evident that too much tending line had paid out to support a 6-m dive depth, the divers were brought to the water surface. The divers were recovered with no vital signs and were pronounced dead after extensive resuscitative efforts failed.

Diver experience of the three divers embarked in CGC HEALY on 17 August 2006, showed that only two were up-to-date with the currency requirements set forth in the Coast Guard Diving Manual that requires four dives every six months. Prior to the dive on 17 August 2006, Diver 1 had conducted approximately 24 dives during 19 dive days. Seven of the 24 dives were conducted in the Arctic Ocean during the summer of 2005; however, those dives were conducted with surface-supplied air as opposed to dives with scuba. This was this diver's first cold water scuba dive. The last dive Diver 1 participated in prior to the one on 17 August 2006 was on 10 April 2006. With this dive profile, this diver had limited military dive experience. While initially qualified as a Basic Diving Officer after attending the Navy Diving and Salvage Training Center (NDSTC), this diver's currency qualification had lapsed on 15 May

2006. CGC HEALY's previous Commanding Officer signed a diving requalification letter for Diver 1 on 28 April 2006. However, two of the four dives used to substantiate this requalification were recreational dives and were not conducted in accordance with standards articulated in the Coast Guard Diving Manual. These recreational dives were not authorized to count for periodicity purposes and as such the requalification letter signed on 28 April 2006 was not valid. Therefore, Diver 1 was not qualified for diving duty on 17 August 2006. Diver 2 reported aboard for his first tour afloat on 25 May 2005. He later went to dive school and the NDSTC qualified him as a scuba diver on 1 March 2006. Since receiving his training, Diver 2 had only conducted two dives in one dive day on 10 April 2006. With this dive profile, Diver 2 was a diver with limited military dive experience and had never conducted a cold water dive. The NDSTC qualified Diver 3 as a scuba diver on 8 July 2005. Since receiving training, Diver 3 had only one dive day consisting of four dives on 20 October 2005. Diver 3 reported aboard for Diver 3's first tour afloat on 18 July 2006. With this dive profile, Diver 3 was a diver with limited military dive experience and had never conducted a cold water dive.

In the administrative investigation into the Aug. 17, 2006, accident, Coast Guard Commandant Adm. Thad Allen (2007) found the deaths of Divers 1 and 2 preventable. Among the problems that were discovered during the investigation were a) The Command had performed an inadequate review of the dive plan and lacked familiarization with USCG and USN diving manuals. There was a lack of oversight of the ship's crew during liberty, including the amount of alcohol consumed by crew members and inappropriate use of alcohol by the command cadre during an operation; b) The participants and dive plan constituted an improperly manned operation per USCG standards; at least four trained divers were required. There was limited diving experience among all three scheduled participants and the lead diver was not qualified for military diving duty. An improper briefing took place of dive tenders, who were unqualified. There was a deviation from the dive plan when one diver was forced to exit the water. The dive plan was continued following the loss of manual dexterity, from cold, by one of the divers. Unqualified personnel had conducted the equipment checks and there was inappropriate use of alcohol by dive tenders. Unauthorized “polar bear plunges” and other recreational activities occurred by other crew members near the dive site; c) Dive manual violations included no dive manual present at the dive site and no dive log was maintained. No verification was made that ship equipment and machinery was properly secured and positioned to prevent interference with dive operation. No redundant scuba systems were used and extra weight was loaded into zippered pockets, instead of being added with an easily removable weight belt. The dive tending lines were not properly anchored. There was a lack of medical and emergency evacuation plans, proper treatment equipment or diving medical officer on board HEALY. Dive gear had been improperly stored and there was found to be a lack of a viable preventive maintenance system for dive equipment as well as lack of records dating back to 2002. No safety survey had been conducted of the HEALY dive program since its commissioning in 1999; and, d) Equipment worn showed that neither Diver 1 nor 2 had a low-pressure hose attached to their buoyancy compensator meaning they could not be inflated with air from their cylinders. Their variable-volume drysuits were properly rigged to their air supplies so the suits could be inflated as necessary. Both divers had donned split fins that are designed for high speed, but provide only minimal thrust. Split fins are not considered appropriate for heavy diving and lack the power necessary to overcome the drag of a drysuit. Instead, they are better suited for light diving and snorkeling. None of the divers wore weight belts as required by the USN Diving Manual. A standard diving weight belt is designed to facilitate the ability to jettison weight in emergency conditions. Instead, both divers used the weight pockets integrated into the design of their buoyancy compensators. Additionally, they filled their BC equipment pockets, which are secured by heavy zippers and are not easily opened, and would make an emergency jettison difficult, if not impossible. The divers initially entered the water with over 18 kg, but returned to the side following surface checks to add more weight. Diver 2 specifically commented that he was floating too much. Each diver eventually departed the surface with over 27 kg of weight (including lead shot and steel tank).

The lessons learned from this unfortunate, preventable, dual diving fatality are clear: thorough entry-level training and skills maintenance for extreme-environment diving are an absolute necessity. Properly functioning equipment and trained surface-support personnel are also mandatory. At several points in the evolution of this incident, these diving fatalities could have been prevented.

4. Deep diving

a. Modes

The U.S. Ocean Action Plan calls for an ecosystem-based approach to studying and managing the marine environment. Some marine ecosystem habitats of interest are located in waters of up to 130 msw depth, which roughly corresponds to the continental shelf and the photic zone. A robust capability is therefore needed for scientific divers to once again work at depths of at least 90 msw through a phased approach (Lang and Smith, 2006).

Shallow-water coral reefs are well understood, as are the linkages between adjacent mangroves and seagrass beds and their contributions to the reef ecosystem. Analogous to limiting a tropical rainforest biologist from climbing higher than 10 m (thereby missing the majority of biodiversity that resides in the canopy), a scientific diver cannot effectively study the biodiversity and contributions of the deep reef to the shallow-reef system due to technology and training limitations. Our understanding of the reef ecosystem, *in toto*, is therefore vastly impaired (Lang, 2006).

Scuba diving conducted by scientists is an invaluable research tool; a trained scientific eye under water provides research value and flexibility that unmanned systems often do not. When Scripps Institution of Oceanography organized its scientific diving program in 1951, the maximum depth certification for open-circuit, compressed air scuba was 80 msw (based on the U.S. Navy's maximum PO_2 limit of 2.0 ATA at the time.) Safety concerns have gradually eroded this depth limit to what has become a 60 msw operational compressed air window for scientific diving. The U.S. Department of Labor's Occupational Safety and Health Administration does not regulate the scientific diving community with regard to technology, which allows an operational flexibility to employ mixed gases (through surface supply and rebreathers) and underwater habitats in our research methodology to meet the Nation's marine science needs. Thus, an evaluation of the re-expansion of the scientific diving envelope using deep air, mixed gas and surface-supplied techniques is warranted.

Reliable commercial diving technology exists to reach these depths, but is not routinely employed by the scientific community due to complexity and costs. However, training a competent scientific diver in surface-supplied, mixed gas diving allows the dive, gas mix, depths, bottom times, voice communication, and decompression to be controlled from the surface. The operational limitations of diving on a hose under this scenario appear to allow immediate access to 90 msw.

Attempts at introducing rebreathers into mainstream scientific diving programs have met with inertia and significant safety concerns due to issues of equipment reliability, availability, time investment in training, and proficiency requirements. A renewed effort has been organized for May 18-20, 2012 with Rebreather Forum 3.0 sponsorship by the American Academy of Underwater Sciences, the Divers Alert Network, and the Professional Association of Diving Instructors. The shift in attitude towards rebreathers is due to the recognition by industry and training organizations that in order to expand the market, simpler, more reliable rebreathers need to be designed that require less training, maintenance and acquisition costs, i.e., the emergence of the recreational rebreather unit. There is full recognition that the technical rebreather market shall continue to exist for exposures and operations well beyond the recreational and/or scientific diving limits, but this segment is finite and will not bring the research and development funding needed to allow the industry to advance rebreather technology. The recreational rebreather concept is very much aligned with the goal of developing rebreathers as a mainstream scientific diving research tool, at an acceptable level of risk.

Scientific deep diving history

Historically, each stage of scientific diving development has resulted in the parallel development of improved life-support systems and research tools that have enabled safe underwater work environments. In 1908, Haldane reported on the prevention of compressed-air illness and published staged-decompression table data (Boycott *et al.*, 1908). Behnke *et al*. (1935) studied O_2 toxicity effects at PO_2s of 1 - 4 ATA and determined that bottom time, depth, and highly variable individual responses were critical, i.e., the oxygen window concept. After Jacques Cousteau and Emile Gagnan redesigned a pressure regulator for use under water in 1942, the first official diving course at University of California Los Angeles/Scripps Institution of Oceanography campus was taught by Conrad Limbaugh and Andreas Rechnitzer in 1951, followed by the development of the first wetsuit by Hugh Bradner from the University of California. In 1954, the SIO diving program listed 4 divers (of a total of over 60) certified to 250 fsw (76 msw). The U.S. Navy Experimental Diving Unit published Standard Decompression Tables for air in 1956 and issued 300 fsw (92 msw) certifications after training at the U.S. Naval School, Washington, D.C. In 1963, the U.S. Navy published 300 fsw (92 msw) Extreme Exposure Tables for air and ten years later a PO_2 of 1.6 ATA for normal use for 30 min, and emergency use of 2.0 ATA for 30 min. The first commercially viable electronic dive computer, the ORCA Industries' Electronic Dive Guide (EDGE), was marketed in 1983, changing forever the mechanism of monitoring decompression status. NOAA (1991) published a PO_2 at 1.6 ATA (maximum operating depth is 66 msw on compressed air) for 45 min for normal use, 120 min for emergency use, or 2 ATA for 30 min. The U.S. Navy (1993) published a PO_2 of 1.3 ATA with unlimited exposure, and NOAA (2001) a PO_2 at 1.6 ATA for 45 min and PO_2 at .6 ATA with no limit.

It becomes obvious that maintaining arbitrary depth limits in the presence of a rapidly expanding knowledge and technology database is clearly shortsighted. The ability to develop and use state of the art technology is fundamental to the evolution of scientific diving and is only limited by self-imposed scientific diving community standards. AAUS scientific diving effectiveness may be underdeveloped as the result of arbitrary and unnecessary restrictions.

Lessons learned from deep diving history appear to indicate that the concept of a 190 fsw (58 msw) limit for air diving may be overly conservative, air decompression tables have been widely used to 300 fsw (91 msw) and surface-supplied air dives to this depth are not uncommon. Further, mixed-gas combinations no longer pose an unacceptable risk given the decadal record of successful use of light-weight, mixed-gas apparatus. Scientific diving, in general, has been slow in taking advantage of advancing technology, has not moved to the cutting edge and has suffered from stifling regulatory pressures that favor risk-averse, but not physiologically-based, depth limits.

A substantive literature search, personal observations and diving experience have not revealed any objective evidence, scientific or otherwise, that provides for definitive acceptance or prohibition of dives beyond 60 msw (Egstrom, 2006). The evolutionary development of the current position towards conservative, shallower maximum depth limits appears to have been accepted because it is perceived as sensible but, without adequate supporting physiological or operational data, has unnecessarily restricted our diving behavior.

Surface-supplied bell systems (waystations)

This following exemplar illustrates one example of transfer of commercial diving technology of deep diving to the scientific diving community. The NOAA/USC Interim Science Program (1984-1985) was established at the USC Catalina Marine Science Center in anticipation of the deployment at Catalina Island of the NOAA saturation habitat now known as Aquarius. The waystation and tether training program lasted two days, more than adequate time to acquire the necessary skills for the operational aspects of this surface-supplied diving system (Lang, 2006).

The waystation system (Fig. 5) was a mobile unit consisting of a 500-kg anchor plate, an open bell with skirt, and a surface support barge (Fig. 6). Umbilicals were stored on the outside of the bell, as were oxygen cylinders used for decompression.

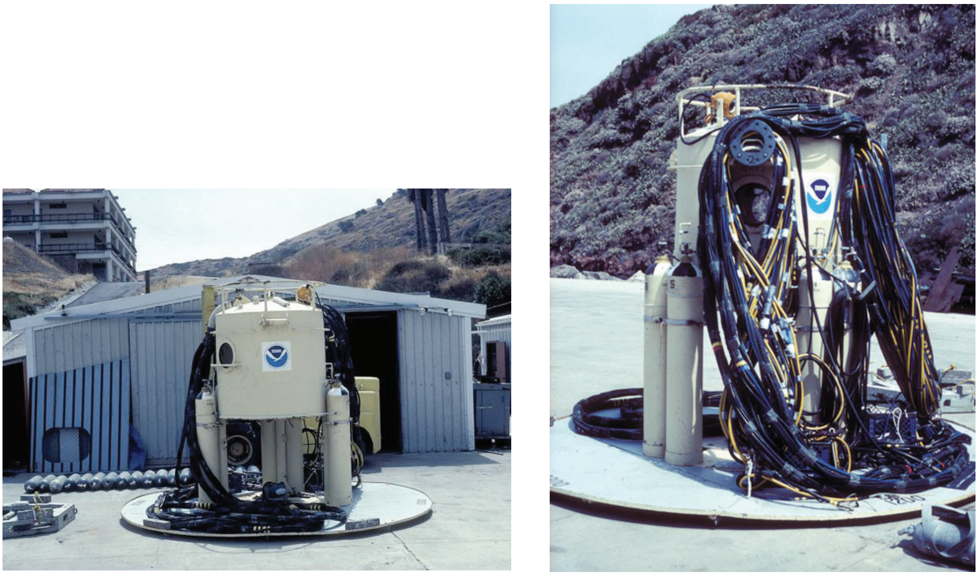

Figure 5. Waystation system (left), and umbilicals (right).

Topside support consisted of hot water and compressed air that were supplied from a surface-support barge positioned directly above the waystation anchored to the bottom at 40 msw. Support boats ferried staff and supplies from shore and stood by in case of diver emergencies. This particular program was supported through the immediate proximity of the Catalina Hyperbaric Chamber.

The success of this program and its participants was attributed to a large degree to the commercial diving experience and qualifications of the all-important crew chief. It remains an example of operational efficiency and scientific productivity through the application of commercial diving technology to the scientific community. The control of the dive was performed by the topside crew chief. The diver-to-surface communications system allowed the scientific diver to focus on the research task and leave all operational aspects to the crew chief such as gas supply, bottom time and depth recordings, decompression stops, oxygen breathing, equipment performance, and hot water supply.

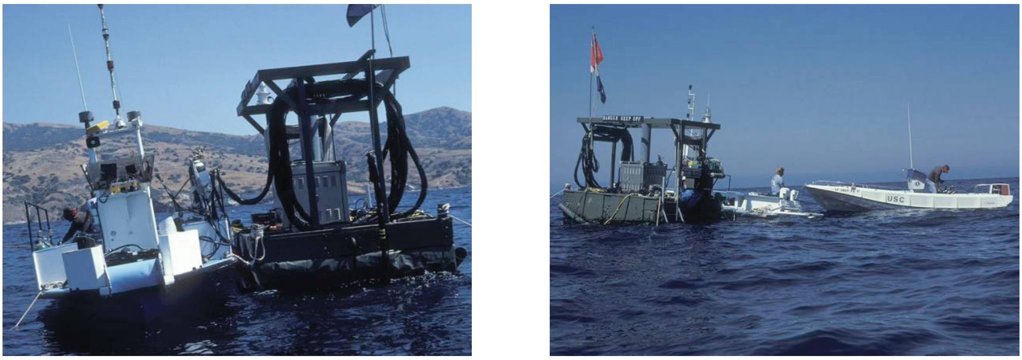

Figure 6. Tender boat and support barge with hot water and compressed air supply.

Perhaps the most revealing aspect of the transition from scuba to surface-supplied diving was the ease by which it was accomplished, under this training program and in this particular environment. An experienced topside crew chief deploying surface-supplied equipment provided several advantages to scientific divers whose experience base was mainly in open-circuit, compressed air scuba in temperate-water California kelp beds. Heretofore having to rely on drysuits or 5-mm wetsuits, there was a significant thermal advantage of wearing a simple 3-mm wetsuit with hot water supplied through a hose inserted through the wetsuit collar ending in a “T” fitting on the chest. Not even gloves were needed due to the hot water flooding through the suit and creating a visible warm-water envelope as it flowed out through the sleeves around the hands.

Further, there was no need for a heavy weight belt, which provided a lightweight sense of freedom of movement. The use of a horse-collar front buoyancy compensator (BC) was mandated, which created a source of distraction for several reasons: the ventral side of the diver was encumbered, and the buoyancy mechanics of a front BC have a tendency to invert the diver while in a horizontal swimming position, the prevalent orientation for the majority of the dives. A back-mount BC or wings that provide buoyancy more similar to that of a hot-air balloon concept with the negative ballast, diver and gear, positioned below the positive buoyancy component is preferable. An independent bail-out system with cylinder was harnessed to the diver’s back.

The management of the umbilical, in this particular environment devoid of overhead obstructions and currents in Big Fisherman’s Cove, was not an issue. It is expected that a similar condition would be experienced descending along a coral reef wall on a multi-level dive for deep science projects. The exploration of the bottom habitat for the two cryptic target species, white abalone (*Haliotis sorenseni*) and

California two-spot octopus (*Octopus bimaculatus*), did not require extensive horizontal excursions. This type of system allows for significant flexibility and can be readily moved to other sites of scientific interest.

Surface-supplied mixed gas

Surfaced-supplied, mixed-gas diving to 90 msw would significantly extend the depth capabilities of the scientific diving community beyond the limitations of air and nitrox diving. Closed-circuit, mixed-gas rebreathers offer some unique advantages including, but not limited to, the ability to perform constant oxygen partial pressure dives with subsequent decompression advantage and minimal deck space requirements for the support vessel. Surface-supplied mixed gas offers some unique capabilities that may be useful for a range of scientific diving operations.

The ability to efficiently train scuba divers to use surface-supplied diving techniques under the supervision of an experienced support team was highlighted through the waystation program described above and has more recently been demonstrated with the NASA NEEMO 8 (NASA Extreme Environment Mission Operations) mission conducted in March of 2005 (Gernhardt, 2006). On this mission, three divers with no previous experience in surface-supplied diving techniques were able to undergo a short training program and safely use surface-supplied diving techniques to make excursion dives from air saturation at 18 msw in the NOAA Aquarius Habitat (Gernhardt, 2006).

Open-circuit mixed gas

Kesling and Styron (2006) reviewed the University of North Carolina, Wilmington, technical diving program development for scientific research applications in support of deep, open-circuit, mixed-gas diving operations to 80 msw. Conventional, open-circuit, compressed-gas scuba diving techniques are advantageous because of their familiarity from entry-level diving training, are relatively inexpensive and commercially available, lightweight and highly mobile, and require minimal support and maintenance. Helium added to the breathing mixture (trimix) reduces the fractions of both oxygen and nitrogen in the mix and thereby their respective partial pressures at depth resulting in less nitrogen narcosis and operating within safe oxygen exposure limits. For example, NOAA Trimix 1 (50% He, 18% O_2 and 32% N_2) was developed for operational flexibility in addition to physiological benefits. A scuba cylinder filled halfway with Helium would be topped off with enriched-air nitrox (EAN_{36}),which easily prepared the dive gas. The key to implementing a technical trimix dive is the ability to perform an efficient and reliable decompression that does not pose a substantial risk of oxygen toxicity (Hamilton, 1999). The use of multi-gas, multi-mode decompression computers has provided far greater flexibility for conducting diving operations than printed schedules.

Rebreathers

Closed-circuit oxygen rebreathers, semi-closed mixed-gas rebreathers and closed-circuit mixed-gas rebreathers reclaim some or all of the diver's exhaled gases for reuse after removing carbon dioxide and replacing consumed oxygen (Bozanic, 2002), a more effective use of the gas supply when compared to conventional open-circuit diving. The depth restriction of 6 msw related to using pure oxygen renders closed-circuit oxygen rebreathers effective only in shallow-water behavioral research or studies of ice-algae and other organisms where disturbance of experimental plots by exhaust bubbles is not desired.

Semi-closed rebreathers inject a steady stream of a single gas mix, enriched air nitrox, trimix, or heliox into the breathing loop. Simultaneously, a valve allows a steady stream of gas to exhaust from the breathing loop. The scrubber removes carbon dioxide and the steady exhaust keeps inert gas from building up disproportionately. Because it is being consumed, the fraction of oxygen in the breathing loop is lower than the supply gas. The preferred means to determine gas composition in the loop is through an oxygen sensor that displays the oxygen percentage (Bozanic, 2002; Thalmann, 1996). These units have been used in the 90 msw depth range, are low cost, mechanically simple, and are approximately three times more gas efficient than open-circuit scuba. However, a given gas mix has a much narrower range and the oxygen content is similar to enriched-air nitrox that cannot be varied to optimize decompression (Bozanic, 2002).

Closed-circuit rebreathers (CCRs) have been used in scientific diving for more than 40 years since the Tektite underwater habitat projects equipped aquanaut scientists with CCRs (Earle and Giddings, 1980). The General Electric Electrolung was marketed as the first commercially available mixed-gas CCR in 1969 but was off the market by 1971 after some use by commercial, military, and scientific divers (Starck, 1993). The 1987 Wakulla Springs, Florida, project and testing of the CisLunar Mark I rebreather entered CCRs into technical diving (Stone, 1989). The CisLunar Mark V CCR was used by Stone's dive team for extensive cave exploration in the 85-100 msw depth range in the Wakulla 2 project (Shreeves and Richardson, 2006). CCRs have been slow to emerge in the recreational diving community but may offer advantages as a deep scientific diving capability once production improves economies of scale, engineering reduces maintenance requirements, and training and skill maintenance time investments are therefore reduced.

Shreeves and Richardson (2006) summarized CCR function as follows: The closed-circuit breathing loop is supplied with diluent (air, enriched-air nitrox, trimix or heliox) with a relatively low fraction of oxygen that provides the breathing loop with volume and inert gas, and with pure oxygen that replaces the consumed oxygen. The CCR is prepared with an oxygen partial pressure set point (usually from .7 to 1.2 ATA) that is typically monitored by three oxygen sensors in contact with gas in the breathing loop. Based on sensor readings, onboard electronics add oxygen via a solenoid-activated valve. To maintain volume during descent and ascent, the diver manually adds/releases gas from the loop. The diver can also manually control the CCR in case of electronics failure or a need to override the settings with oxygen bypass valves (Bozanic, 2002). CCRs are the most gas-efficient rebreather and the best at optimizing decompression by allowing the maximum possible oxygen (within exposure limits) at all stop levels resulting in extended depth capability. CCRs are expensive, involve complex training, and require significant care and effort in setup and maintenance (Bozanic, 2002; Pyle, 1996). Failure potential of electronics and oxygen sensors are safety considerations, which are somewhat mitigated by redundant design and manual override options. Additional advantages, disadvantages, and cost effectiveness of CCRs are discussed in detail by Shreeves and Richardson (2006). Backup approaches for specific diving circumstances and surface-deployed bailout systems require very careful consideration and advance planning to ensure adequate gas for appropriate decompression (Pyle, 1996). For deep scientific diving, Parrish and Pyle (2002) found dramatic differences in both the logistical and consumptive rates comparing deep, mixed-gas, open-circuit scuba to deep, mixed-gas CCR diving, which required seven times less preparation time, consumed 17 times less gas and reduced decompression from 42 to 70 percent.

CCR safety considerations must include accepting that any problems with CCRs are not immediately obvious and can cause a diver to lose consciousness without warning if the diver fails to detect the problem through continuous monitoring of instrumentation. The CCR's capabilities must be able to support the gas requirements for an extended decompression obligation without relying on additional external systems and support. Manual CCR operation requires practice, discipline and strong familiarity with CCR theory and design (Pyle, 1996) and is outside of the operational experience of most scientific divers. For deep decompression diving, all divers using CCRs must have a high degree of discipline, training and experience. The CCR approach for underwater research projects that requires participation by relatively less experienced divers to deep depths under close supervision is not advised. AAUS standards require 25 hours no-stop experience prior to training to make decompression dives, and 50 hours experience prior to training to make mixed-gas dives other than nitrox (Dent, 2006). To further reduce human error in CCR accidents, some engineering solutions and training procedures have proven effective, as have extensive checklists for pre- and postdive specific CCR procedures. Pyle (1996) recommends that CCR training emphasize failure detection, manual control, and bailout.

The final observation on rebreathers used for scientific diving would be that their current requirement of constant monitoring of instrumentation to stay alive under water may be incompatible with the requirements and scientific objectives of the dive to concentrate on making observations and collecting data. The complexity of rebreathers compared to open-circuit scuba is orders of magnitude higher.

Saturation diving

Another mode in the suite of deep diving techniques beyond relatively lower cost rebreathers, open-circuit mixed gas, and lightweight surface-supplied mixed gas, is bell bounce or full saturation diving, which meets the need for additional bottom time requirements for labor-intensive research tasks. Small commercial saturation systems or even the US Navy's fly-away sat system provide a surface platform for bell diving saturation operations and can be placed on research vessels of opportunity. Dynamic vessel positioning allows precise station maintenance and multi-site mobility without the need for multiple anchor mooring.

Bell saturation diving affords the marine researcher the lengthy bottom times required for certain research in a visitor status on the bottom but saturation diving from an underwater habitat offers the researcher residency while minimizing travel and decompression from the work site (Cooper, 2006). Despite providing advantages of bottom times unequalled by non-saturated divers, the present budget climate has significantly reduced funding for large habitat programs and wet diving support in general. NOAA's *Aquarius* was designed as a mobile habitat, but its size and support requirements evolved into long-term deployment in the Florida Keys (first deployed in St. Croix, USVI, 1987-1989, then on Conch Reef, off Key Largo, Florida, 1992-present. The emergence of a new deep habitat program that equals the accomplishments of the following undersea laboratories is not likely: *Sealab I* (1964) at 58 msw off Bermuda; *SeaLab II* (1965) at 62 msw off La Jolla, California; and *SeaLab III* (1969) at 185 msw off San Clemente Island, California; *SeaLabs I-III* conducted U.S. Navy research on diving physiology; *Conshelf I* in the Mediterranean and *Conshelf II* in the Red Sea, (1962-1965; Cousteau, 1965); *Conshelf III* (1965) saturated 6 Aquanauts to 100 msw for 3 weeks; *Tektite I* and *II* in the U.S. Virgin Islands (1969-1970 (Clifton *et al*., 1970); *Hydrolab* in the Bahamas (1970-1976) and subsequently deployed in St. Croix, U.S. Virgin Islands (1977-1985), *La Chalupa* (1972) off Puerto Rico*, Helgoland* (1969-1979) in the Baltic Sea, 1969-1979*;* and *Aegir* (1968) off Hawaii at 180 msw.

Dozens of underwater habitats have been designed and put into regular operation for commercial purposes such as oil exploration to over 500 msw, but relatively few have been constructed and used primarily as scientific research facilities where they have been limited to less than 30 msw depth to increase safety, ease of operation and supply. Physical stamina of the divers and their support team and logistical challenges of air delivery and other support determine the time limits. The ability to work around-the-clock has been important for many behavioral, physiological and ecological studies (Sebens *et al*., 2012). Four undersea laboratories have had the largest scientific research and publication impact: *Helgoland*, *Hydrolab* (Nyden, 1985), and the *Aquarius* underwater laboratory, (Shepard *et al*., 1996; Cooper, 2006; Sebens *et al*., 2012). *Aquarius* has experienced a 20-year span of longevity of deployment and support and afforded an opportunity for long-term research in the Florida Keys that would otherwise have been unlikely (Aronson and Swanson, 1997; Miller *et al*., 2000). With the rapidity of changes in oceans, particularly in shallow coastal systems, these technological assets and their development will continue to be needed to gain a greater understanding of how best to manage these valuable ecological assets (Sebens *et al*., 2012).

Experience with the use of habitats in conjunction with ship-mounted saturation systems exists such as the Navy's *Sealab* project that used a personnel transfer capsule (PTC) to transfer aquanauts under pressure to a topside deck-decompression chamber (DDC) for decompression. Commercial diving operations routinely supported deep hyperbaric pipeline welding by transferring diver-welders between the ambient welding habitat and topside DDC under pressure in bells (Cooper, 2006). These methods should be reexamined for their applicability today. Cooper (2006) describes procedures and advantages of small mobile saturation habitats when offshore weather conditions dictate mode of operation. He uses the example of the turret recovery of the Civil War ironclad *USS Monitor* off Cape Hatteras in 2001-2002, contrasting NOAA/NURC open-circuit, mixed gas divers, Navy surface-supplied HeO_2 divers, and Navy saturation divers, who all worked simultaneously on the wreck. Under rough weather conditions, the NOAA divers with their drift decompression were first to cease diving operations, followed by the stage-riding Navy surface-supplied HeO_2 divers, and finally the sat divers, but only when it was too hazardous to make the bell runs through the air-sea interface as the PTC leaves or returns for DDC mating. Cooper argues that a small ambient habitat next to the wreck, would have allowed diving operations with a four-man team living on bottom to continue, unaffected by the weather topside. The small size would also allow for system mobility to multiple sites of scientific interest.

b. Enriched-Air Nitrox

The use of enriched-air nitrox (oxygen-enriched air) has vested itself as a mainstream diving mode since it was first introduced to sport divers in 1985 by former NOAA Deputy Diving Officer Dick Rutkowski who transferred this technology from the scientific to the recreational diving community. The mainstream recreational diving training associations (PADI, NAUI, and SSI) now support nitrox training programs in addition to their traditional open-circuit, compressed-air scuba programs. The focused technical diving training organizations (IANTD, ANDI, and SDI/TDI) have amassed several additional years of experience in providing nitrox training to the recreational diving community. The scientific diving community has used nitrox since it was first published in the NOAA Diving Manual (NOAA, 1979).

In 2000, the Divers Alert Network (DAN) Nitrox Workshop was prioritized as a diving safety project of interest to the diving industry by means of DAN financial support (Lang, 2001). As with any emerging technology that has found a broader market appeal, controversies invariably arise. Ignorance, myths, and misconceptions often fuel opposite views. A critical interdisciplinary examination of the current issues surrounding nitrox was in order to disseminate credible diving safety information. This forum was provided to objectively evaluate the available nitrox operational and physiological data, risk management, equipment, and training parameters. Physiological issues such as carbon dioxide retention and oxygen toxicity were also in need of critical examination. Nitrox training and equipment issues were discussed to comprehensively address risk management and legal considerations regarding its use. The recreational diver is the ultimate beneficiary of our improved collective knowledge of the state-of-the-art of nitrox diving. The intermediary beneficiaries of this information are the providers and manufacturers of nitrox products (instructors, equipment manufacturers, dive stores, and nitrox dispensers).

An approximation of the magnitude of nitrox consumption was essential. This seemed achievable by our ability to provide a denominator of nitrox divers and nitrox dives, as a sub-set of the overall level of recreational diving activity. Many other discussions of nitrox-related topics flowed from these numbers, *i.e.,* nitrox DCS incidence rates compared to air, and nitrox training and equipment sales growth.

The evolutionary history of nitrox diving appears along the following timeline (Hamilton, 2001):

- **1874:** H. Fleuss probably made the first nitrox dive with a rebreather.
- **1947:** C. Lambertsen published the first nitrox paper.
- **1955:** E. Lanphier described the use of nitrogen-oxygen mixtures in diving and the equivalent air depth method for using a standard air table with an enriched air mix.

- **1960’s:** A. Galerne used on-line blenders for commercial diving.
- **1979:** M. Wells developed NOAA nitrox and Equivalent Air Depth (EAD) tables were published in the NOAA Diving Manual for scientific diving.
- **1985:** D. Rutkowski developed a nitrox training program for recreational diving.
- **1989:** The Harbor Branch Oceanographic Institution Nitrox Workshop (Hamilton *et al*, 1989) addressed the following issues and rationale: oxygen limits, decompression and the EAD, nitrox mixing and terminology; the “nitrox” term borrowed from habitat diving implies that nitrogen is the advantage. The U.S. Navy now prefers “oxygen-nitrogen.” New NOAA designations are NN_{32} and NN_{36}. EANx was agreed upon, with “x” the percentage of oxygen. The correct term proposed was “oxygen-enriched air” or “enriched air nitrox.”
- **1991:** “Not Invented Here” went to work. Bennett (1991), Bove (1992), and SkinDiver Magazine all took stands against nitrox use by recreational divers.
- **1992:** The Scuba Diving Resources Group (a committee of the Outdoor Recreation Coalition of America) organized a nitrox workshop (Hamilton, 1992) in response to nitrox agencies and products being denied access to the Diving Equipment and Marketing Association (DEMA) trade show in Houston resulting in the following endorsements: the EAD principle; the NOAA limits for oxygen exposure (but lower limits were encouraged); using normal DCS treatment procedures for air diving after nitrox dives (the oxygen exposure of recreational nitrox dives should not affect treatment); pending confirmatory testing, mixes up to 40% oxygen could be used in equipment suitable for air provided the equipment was clean and oxygen-compatible lubricants were used; dry nitrox will not corrode cylinders and other gear appreciably faster than air; air for mixing should be “oil free”; cylinders used for nitrox should be compatible with oxygen; mixes should be analyzed properly before use; and, mixing in standard cylinders by adding oxygen and topping with air is considered unsafe.
- **1993:** The aquaCorps TEK93 conference took place in San Francisco. A measurable and attainable air quality standard agreement by nitrox industry leaders was set at 0.1 mg/m^3 oil.
- **1993:** The Canadian Forces (DCIEM, 1993) issued EAD tables, based on the standard air tables, with an upper oxygen limit of 1.5 ATA PO_2 and depth and time limits more stringent that the air tables.
- **1996:** PADI takes the plunge, nitrox has arrived. NAUI, SSI, and even BSAC (1995) have nitrox programs. The diving media has become supportive of nitrox.
- **1999:** A U.S. Navy survey by R.W. Hamilton showed 100,000’s of (not well documented) open-circuit nitrox dives. Commercial diving reported not using nitrox much, but it has become fashionable among recreational divers. The DCS incidence record is good, and nitrox dive computers are readily available.

- **1999:** The Occupational Safety and Health Administration (OSHA) was petitioned by PADI and Oceanic in 1995 on behalf of Dixie Divers, Inc. for a recreational nitrox variance for scuba instructors from commercial diving regulations that was approved for: PO_2 of 1.4 ATA and a maximum 40 percent nitrox mix; 40 msw maximum depth and dives within the no-stop limits; a stand-by diver; and, diving within 1 hour of a chamber.
- **2001:** NOAA Diving Manual includes a chapter as standalone course guide for nitrox diving.

Nitrox physiology

Nitrox improves decompression, which is based on the fraction of N_2 only. Therefore, more O_2 and less N_2 is better, allowing for longer bottom times for no-stop dives. Decompression dives (with required stops) using an enriched-air mix will result in a total decompression time that will be shorter with nitrox compared to air. When nitrox is breathed and air decompression tables are used, the decompression times are not affected, but the dives are considered more conservative. This benefit can apply to repetitive dives, flying after diving, and diving at altitude.

Central nervous system (CNS) toxicity convulsions can occur without warning and likely lead to loss of the mouthpiece and subsequent drowning. Warning signs and symptoms, if they do occur, include: visual disturbances (including tunnel vision); ears ringing; nausea; twitching or muscle spasms (especially in the face); irritability, restlessness, euphoria or anxiety; and, dizziness. Thus, the diver's exposure to high levels of oxygen must be managed by time limits at max PO_2s (Table 1.) Standardized recreational nitrox depth limits are 34 msw (EAN_{36}) and 40 msw (EAN_{32}). Pulmonary or whole body oxygen toxicity (monitored by oxygen toxicity units or unit pulmonary toxicity dose) is unlikely to occur in recreational diving applications because of the required length of exposure to oxygen levels not high enough to invoke CNS effects. Whole-body symptoms include primarily pulmonary effects (coughing, chest pain, and a reduction in vital capacity) and more diffuse symptoms (paresthesias, numbness of fingertips and toes, headache, dizziness, nausea, and a reduction in aerobic capacity).

Nitrogen narcosis in enriched-air nitrox diving is not a real issue. However, oxygen can be as narcotic as nitrogen (Linnarsson *et al.,* 1990) but nitrox diving is not efficient at depths where narcosis becomes prominent.

CO_2 buildup is not an issue for scientific nitrox mixes, but may be a hazard in the deeper range of nitrox diving (Lanphier and Bookspan, 1996). It causes a reduced ventilatory response, such that breathing a dense mix while exercising can lead to unconsciousness. Headaches are a symptom of hypercapnia, caused by dilation of the arterial vessels in the brain. Kerem *et al.* (2001) discussed the Israeli Navy experience with pure oxygen rebreathers, which showed victims of CNS O_2 toxicity to be both retainers and late detectors of buildup of inspired CO_2/malfunctioning absorbers. For higher-risk extreme CO_2 retainers, more conservative limits were adopted (Table 2).

Table 1. NOAA (2001) Oxygen exposure limits.

PO_2	**Max. single dive**	**Max. 24 hr**
(ATA)	**(min)**	**(min)**
1.60	45	150
1.50	120	180
1.40	150	180
1.30	180	210
1.20	210	240
1.10	240	270
1.00	300	300

Table 2. PO_2 limits adopted by the Israeli Navy.

Degree of retention	**End-tidal CO_2 (torr)**	**Mixed-expired CO_2 (torr)**	**Max PO_2 (ATA)**
None	<50	<41	1.6
Moderate	50-55	41-45	1.4
Extreme	>55	>45	1.2

The late Jon Hardy (2001) initiated a human functional aspect study to test nitrox as a product in 1999 asking whether diving with nitrox as breathing gas causes less nitrogen narcosis, less fatigue, lower gas consumption, better thermal balance and less decompression stress. Initial results showed no variation in gas consumption between air and nitrox under similar conditions. Difficulty was acknowledged in experimentally designing a study of how to objectively measure fatigue, decompression stress, and thermal balance. Unfortunately, testing of the reduced nitrogen narcosis of nitrox was not completed.

Nitrox equipment

Oliver (2001) summarized the findings and conclusions of the DEMA Manufacturers Committee on oxygen-enriched air and provided manufacturers' recommendations on nitrox equipment use (Table 3).

Table 3. Manufacturer's nitrox equipment recommendations (modified from Oliver, 2001).

	Maximum fO_2 Authorized (%)				
Company	**23.5**	**<41**	**<51**	**100**	**Comment**
Apeks		1			
Aqua-Lung		1			
Atomic		1			
Beuchat			2		
Cressi-Sub	x				
Dacor		2			Parent company policy
Dive-Rite		2			
Genesis		4			
Int'l Divers Inc.		1			
Kirby-Morgan			1		
Mares America		2			
Oceanic			2		
OMS				1	
Sherwood Scuba		4			
Scubapro		1		2,4	
Thermo valve		2			
Zeagle		3		4	Policy reevaluated

key code - Enriched Air Nitrox (EAN) Sep 00
x Maximum limit. EAN not recommended.
1 All models are factory-prepared for EAN using O_2 compatible materials.
2 Designated models factory-prepared for EAN using O_2 compatible materials.
3 Standard air components declared acceptable. Viton o-rings available.
4 Conversion components available for installation by technician qualified to prepare for O_2 service.

Two major manufacturers (Scubapro and Aqualung) issued technical bulletins in 2001 on the use of their equipment with nitrox:

Scubapro Engineering Bulletin #271 (05 September 2001): All Scubapro regulators sold after October 2000 are approved for use with nitrox up to 40% oxygen and for an operating pressure not to exceed 3300 psi (228 bar). The regulators can be used with gases under the restrictions listed above straight out of the box. Specific models are listed by Scubapro. For use with gases (other than air) falling outside of the range detailed above (*i.e.,* 40+% oxygen, 3300+psi), the only approved regulator is the MK20 (brass version only) after appropriate cleaning and installation of the nitrox kit, when the operational limit becomes 100% O_2 to 3500 psi (241 bar).

Aqualung and Apeks Regulators: New Aqualung and Apeks regulators are now EAN compatible up to 40% oxygen right out of the box. See www.aqualung.com technical library for nitrox compatibility and converting existing regulators to EAN_{40} use. Owner's responsibility is to maintain cleanliness of the regulator and cleaning procedures (note switches from air to nitrox). Second-stage cleaning prevents cross-contamination. Difference in the regulators is in the manufacturing process (*i.e.,* a regulator "safe" room). Hyperfiltered air (condensed hydrocarbons <0.1 mg/m^3) is used for testing, as are some oxygen compatible components.

Nitrox Training and Operational Data.

Table 4 lists the nitrox training requirements for the recreational and scientific diving communities and Table 5 presents updated (through 2005) nitrox instructor and diver certification information since the original data was published (Lang, 2001). For reference, Table 6 shows total numbers of entry-level, open-water scuba certifications as collected by DEMA for the 2000-2005 period. Finally, Table 7 is likewise updated for available nitrox and air exposures and cases of DCS.

Laboratory and open-water experience suggests that nitrox diving may be practiced with low risks of DCS and O_2 toxicity. Vann (2001) showed from DAN data on mixed-gas diving dating from 1990 for diving fatalities, from 1995 for diving injuries, and from 1997 for safe dives demonstrated that a higher proportion of uninjured divers used nitrox than of divers who were injured or died; nitrox divers were older than air divers; over 60% of nitrox divers who dived safely had specialty training; safe nitrox diving was most common aboard charter boats and there were no air or nitrox fatalities from liveaboards; nitrox divers who dived safely dived fewer dives over more days than did air divers; and, in general, nitrox divers dived deeper than air divers, regardless of whether they dived safely, were injured, or died. For either air or nitrox, injured divers and diving fatalities had higher proportions of rapid ascent and running out of gas than did safe divers and maximum PO_2s were above 1.3 ATA for half of the 74 injured nitrox divers. While the incidence of oxygen toxicity during nitrox diving is unknown, convulsions and/or unconsciousness was reported for three divers who had max PO_2s of 1.4, 1.6, and 1.9 ATA. Finally, Vann (2001) emphasized that careful depth control is important to avoid excessively high PO_2s.

Table 4. Recreational and scientific/government training requirements.

	IANTD	ANDI	TDI	PADI	NAUI	SSI	NOAA	NASA	AAUS	UNCW
Max PO_2 limit (ATA)	1.6	1.6	1.6	1.4	1.4	1.6	1.6	1.6	1.6	1.6
O_2 content range (%)	22-40	22-50	22-40	22-40	22-40	22-40	32 & 36	46	22-40	28-40
O_2 cleaning (%)	>40	>21	>40	Mfr.	>40	>40	>40	>23	n.a.	>40
O_2 limits (ATA)	NOAA	NOAA	NOAA	NOAA	NOAA	NOAA	NOAA	NOAA	NOAA	NOAA
OTU/UPTD	300/day	n.a.	n.a.	n.a.	350/day	NOAA	Repex	415/day	Repex	Repex
Mix analysis accuracy	± 1%	± 1%	± 1%	± 1%	± 1%	± 1%	± 1%	± 1%	± 1%	± 1%
EANx table/DC	T/DC	T/DC	T/DC	T/DC	T/DC	T/DC	T/DC	T	T/DC	T/DC
Agency tables	Y	Y	NOAA	Y	Y	Y	NOAA	USN	NOAA	USN
Table model	B-PiN_2	B-PiN_2	USN-EAD	Rogers-RDP	RGBM-USN	USN-EAD	USN99-EAD	USN-EAD	mUSN99-EAD	mUSN99-EAD
Encourage DC	Y	Y	Y	Y	Y	Y	N	n.a.	n.a.	n.a.
Prerequisites	none	none	OW	OW	none	OW	n.a.	n.a.	n.a.	n.a.

Notes: B: Bühlmann; DC: dive computer; EAD: equivalent air depth; m: modified; Mfr: manufacturer's recommendation; OW: open water certification; RGBM: reduced gradient bubble model; Rogers-RDP: recreational dive planner; USN: US Navy; USN99: US Navy 1999 dive tables (unpublished).

The DAN nitrox workshop concluded the following in 2000 for entry-level, recreational open-circuit nitrox diving (Lang, 2001):

- No evidence was presented that showed an increased risk of DCS with the use of oxygen-enriched air (nitrox) versus compressed air;
- A maximum PO_2 of 1.6 ATA was accepted based on its history of use and scientific studies;
- Routine CO_2 retention screening is not necessary;
- Oxygen analyzers should use a controlled-flow sampling device;
- Oxygen analysis of the breathing gas should be performed by the blender and/or dispenser, and verified by the end user;

Table 5. Available nitrox diver certification data up to November 2000 as reported by organization representatives at the 2001 DAN Nitrox workshop and then thereafter.

Period:	**through Nov. 2000**			**Nov. 2000 - Nov. 2005**		
Level:	**Instructors**	**Divers**	**From**	**Instructors**	**Divers**	**Region**
NAUI	878	4,472	1992-	10,221	92,859	worldwide
PADI	7,274	46,788	1996-	24,817	223,932	worldwide
SSI	605	1570	1996-	1,500	12,417	U.S.A.
IANTD	8,140	64,378	1991-	6,140	89,049	worldwide
TDI	12,823	66,206	1994-	8,758	51,592	worldwide
ANDI	3,196	49,118	1989-	5,350	81,200	worldwide
UNCW	n.a.	803	1986-	8	523	U.S.A.
NOAA	n.a.	139	1981-	n.a.	323	U.S.A.
NASA	8	384	1996-	n.a.	n.a.	U.S.A.
AAUS	n.a.	n.a.	1987-	n.a.	n.a.	U.S.A.
Aggressor fleet	n.a.	n.a.	1997-	n.a.	n.a.	worldwide
Sea Hunter fleet	n.a.	n.a.	1997-	n.a.	n.a.	worldwide
TOTAL	**32,924**	**233,798**		**56,794**	**551,895**	

Notes: NAUI instructor number increase (2000-2005) results from their authorization to also teach nitrox in addition to compressed-air scuba; n.a.: data either not tracked organizationally, or not available; nitrox certifications for divers participating in Aggressor and Sea Hunter fleet courses are included in the totals of the training agencies.

- Training agencies recognize the effectiveness of dive computers;
- There is no need to track whole body exposure to oxygen (OTU/UPTD);
- Use of the “CNS Oxygen Clock” concept, based on NOAA oxygen exposure limits should be taught. However, it should be noted that CNS oxygen toxicity could occur suddenly and unexpectedly; and,
- No evidence was presented, based on history of use, to show an unreasonable risk of fire or ignition when using up to 40% nitrox with standard scuba equipment. The level of risk is related to specific equipment configurations and the user should rely on the manufacturer’s recommendations.

Additional data collected for 2000-2005 (Lang, 2006), while insufficient for statistical purposes (due to some data categories not being tracked organizationally and therefore remaining unknown), serve to show several trends. The certification numbers of nitrox instructors and divers has approximately doubled, and there does not appear to be a commensurate doubling of nitrox DCS incidence rates. However, comparisons of DCS probabilities between compressed air and nitrox remain tenuous at best. Yet, over one million more nitrox dives (from fill data) were done in the last five years than in the history of its use until November 2000. Liveaboard diving operations report almost exclusively nitrox and dive-computer use aboard their vessels. Due to their operations at remote locations and given the nature of their captive diver audiences (i.e., adequate time for reporting of DCS symptoms prior to returning to port), one would expect any significant DCS rates from nitrox diving to be readily apparent.

Table 6. Numbers of entry-level, open-water scuba certifications as reported by DEMA (2005) based on records from NAUI, PADI, SDI, and SSI.

Year	No. certifications
2000	185,714
2001	198,241
2002	183,394
2003	173,476
2004	173,225
2005 (Jan-June)	74,758
Total	**988,808**

The Diving Equipment and Marketing Association (DEMA) reported almost one million entry-level open-water scuba certifications and the nitrox training organizations reported over 500,000 nitrox certifications. The relationship or overlap between nitrox and open-water certifications cannot be defined at this point in time due to data collection criteria. The maximum PO_2 limit of 1.6 ATA continues to be used with no documented ill effects. No further issues have arisen from manufacturers with respect to their equipment being used with nitrox without incidental exposure to oxygen content above 40%.

Physiological and operational considerations of mixed-gas diving

In contrast to shallow nitrox diving, the potential for both acute and chronic oxygen toxicity for mixed-gas diving requires careful attention in the selection, mixing, and monitoring of bottom, in-water, and chamber decompression gases. Control of oxygen partial pressure is necessary for the individual dives as well as control of multi-day oxygen Unit Pulmonary Toxicity Doses (UPTDs).

Table 7. Available nitrox and air dive data for occurrence of DCS as reported at the 2001 DAN workshop and then thereafter.

Period:	**through Nov. 2000**				**Nov. 2000 - Nov. 2005**			
	Nitrox Fills	**DCS**	**Air Fills**	**DCS**	**Nitrox Fills**	**DCS**	**Air Fills**	**DCS**
NAUI	17,604	0	n.a.	n.a.	3,242,309	n.a.	n.a.	n.a.
PADI	n.a.	17	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
SSI	n.a.	0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
IANTD	1,411,266	0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
TDI	n.a.	0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
ANDI	967,450	0	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ocean Divers	26,000	n.a.	235,504	n.a.	34,000	0	n.a.	n.a.
UNCW	23,407	5	21,201	n.a.	13,365	0	18,911	1
NOAA	4,894	1	156,697	22	15,618	2	64,757	18
NASA	34,651	0	n.a.	n.a.	45,635	n.a.	0	0
AAUS	18,461	1	442,679	27	52,325	3	518,695	14
Aggressors	33,778	1	n.a.	11	127,759	n.a.	n.a.	n.a.
Sea Hunter	30,400	0	n.a.	n.a.	130,600	0	15,000	0
TOTAL	**2,567,911**	**25**	**856,081**	**60**	**3,661,611**	**5**	**617,363**	**33**

Note: n.a.: data either not tracked organizationally, or not available.

The increased thermal conductivity of Helium can increase respiratory heat loss and, depending on water temperature, can drive the need for dry- or hot-water suits and even respiratory gas heaters under extreme cold-water temperature conditions. Helium is well known to cause speech distortion requiring use of Helium unscrambler radios to maintain clear communications between the dive supervisor and the diver.

Depending on the depth and bottom time, up to four different breathing gases can be used on the same dive. A typical dive profile might utilize a 12% heliox mix on the bottom at 90 msw, followed by switches to air at 50 msw, to 50/50 nitrox at 15 msw, and to 100% oxygen in a deck decompression chamber during the surface decompression portion of the dive (Gernhardt, 2006). Harvey and Lambertsen (1976) described isobaric counter diffusion in localized tissue areas due to the asymmetry between the mass transfer coefficients of the two different inert gases. This can become a problem on very deep and long dives that require long decompressions and would not generally be considered a problem for the bottom times and depth ranges considered for scientific diving.

Proper pulmonary ventilation is required to eliminate CO_2 and provide sufficient tissue oxygenation to meet the metabolic needs of the working diver. The demands of the gas delivery system increase with depth. Most commercial diving helmets or band masks provide both a demand and freeflow gas delivery and have been well proven in the depth ranges and workloads associated with scientific diving to 90 msw (Gernhardt, 2006). Nitrogen narcosis is a consideration for all deep mixed-gas diving and must be carefully considered with respect to gas switches.

Gernhardt (2006) further describes how a 90 msw mixed gas, even with a short bottom times of 15 min incurs a decompression obligation of 67 min of in-water decompression followed by 69 min of chamber decompression. Because of Helium's faster uptake and elimination kinetics than Nitrogen (for most tissue types) a direct ascent to the surface in response to an equipment malfunction is not a viable option. Gernhardt also provides a work efficiency comparison for different diving modes and depth ranges (Table 8).

Table 8. Diving method and depth versus Work Efficiency Index (Gernhardt, 2006).

Dive type	Depth range (msw)	Work efficiency index (WEI) = bottom time/deco time
Sur-D-O_2 (single depth)	21-52	.5-.65
Repet-up	12-58	.8-1.0
Sur-D-O_2 (multi-depth)	9-58	1.75- 2.0
sur-D-O_2 (HeO_2)	61-91	.1- .4
Multi-depth, multi-gas	9-91	1.0 -3.5
HeO_2 saturation	91-305	3-10 (10-30 Days)
Air Saturation (Aquarius)	18	3.8-4.7

There are significant decompression advantages associated with multi-depth diving that have been well utilized by the sport, scientific, and commercial diving industries. It is also well documented that appropriately switching inert gases can result in a decompression advantage. Switching from Helium-Oxygen to nitrox results in a net decompression advantage as the Helium will be eliminated faster than the nitrogen is absorbed (in the majority of body tissues). Combining the decompression advantages of multi-depth diving with inert gas switches can significantly improve the work efficiency index of mixed-gas diving. Some scientific diving operations might involve study of marine life along a vertical wall for which this method of diving would be well suited in optimizing the science return from a given dive (Gernhardt, 2006).

5. Contaminated water diving

a. Contamination risk versus science benefit

Minimization of risk to all dive team members is a priority consideration that must be weighed against the science benefit of engaging in contaminated water diving. Contaminated water is defined as water that contains any chemical, biological, or radioactive substance that poses a chronic or acute health risk to exposed personnel. The contaminants can be of the following nature: chemical (hydrocarbons, solvents, PCBs, heavy metals, tributyl-tin fluorides, pesticides, oxidants); biological (sewage, bacterial pathogens, viruses, protozoans, microorganism toxins); or, radiological.

Contamination assessment is generally performed by local health offices, Environmental Protection Agency, or state agencies that can usually provide information on potential contaminants in local bodies of water or beaches. Bacterial contamination and other common contaminants are routinely tested for in any body of water in which people swim or drink from. Hazard analysis includes determination of whether the contaminant is in the water column, in the sediment, or on the surface, and whether it is water soluble. Exposure-dose determination is whether the contaminant is toxic on contact, on ingestion, on inhalation, or by proximity. Health-risk analysis considers whether the potential effects are acute, chronic or long term. Chapter 6 addresses overarching risk management issues of diving in extreme environments.

b. Water quality categories

The U.S. Navy categorizes four contaminant levels with prescribed diver equipment configurations as preventative measures against incidental contact. These levels provide a working template for scientific diving operations in contaminated water. Category one is the highest contamination, i.e., water grossly contaminated with concentrated chemical or microbiological agents, for example, heavy fuel slicks and sewage operations. Level A protection requires that divers should use full diving helmets with surface-supplied air and communications, vulcanized rubber suits with integrated helmet-mating collar and drygloves with rings. The helmet should be equipped with the double exhaust-valve assembly design for use in contaminated water and must be used in the freeflow mode. Category two is moderate contamination, i.e., water where increased levels of both chemical and microbiological contamination are expected. Level B protection requires that divers may use a positive pressure full-face mask in the positive pressure mode. A block should be used for emergency gas switching to bail out gas in the advent of primary supply failure and a drysuit is required. Category three constitutes baseline contamination, i.e., water where there is no expectation of contamination above the baseline that is normal for human habitation. This category represents what most scientific diving teams will face during the normal course of events. Divers should wear a positive-pressure, full-face mask to avoid water contact with mucous membranes and mouth, unless water analysis shows contact with the mouth is an acceptable risk, and thermal protection appropriate for the diving conditions. Category four (level D protection) includes situations where no contaminated sources are known or expected such as offshore oceanic locations or drinking water reservoirs, recreational swimming areas or areas where water quality is routinely checked and no contaminants are reported.

c. Contaminated water scientific diving procedures

Dive plans for risk management purposes include consideration of the following: contaminant information; diver equipment suitability; monitoring; minimization of direct contact; method of decontamination; emergency plan; tenders' handling and containment of contaminated items; method of decontamination; personal protection equipment; decontamination and quarantine; drysuit permeability, tensile strength and penetration resistance, fit, and ease of donning and doffing; and, thermal balance and heat stress (dehydration, body temperature, heart rate). Decontamination procedures are widely available from various sources, for example, the U.S. Navy, Diving Unlimited International, Inc., National Oceanic and Atmospheric Administration, Environmental Protection Agency, or Federal Emergency Management Administration.

Special circumstances include rainfall runoff (increased pollutants from farming; known point and nonpoint source polluters should be checked); sediments (many lakes and commercial harbors have sediments with significantly higher levels of contamination than the water column, *e.g.*, polychlorinated biphenyls and heavy metals); and, hazardous materials (areas with gross fuel contamination, *e.g.*, leaking ships, storage tanks or aircraft recovery, or in areas with a high concentration of creosote-soaked wood or anti-fouling paint).

d. Contaminated water diving exemplars

Smithsonian Tropical Research Institute Oil Spill Project

Marine environments are subject to man-made disasters. The escape of 100,000 barrels of oil into the mangroves and reefs of Bahia Las Minas (Caribbean coast of Panama) has had unexpectedly prolonged effects (Jackson *et al.*, 1989). Oil seeps into the sediments around mangroves and returns to coat the coral reefs year after year as heavy rain falls (exacerbated by the effects of deforestation) slowly wash it out. Injury, post-impact regeneration and growth of corals have been assessed by scientific divers at this oil spill site (Guzman *et al.*, 1994). The skeletons of corals record the history of acute disasters as well as chronic stresses. X-ray analyses of corals done in response to the oil spill document a worrying decline in coral growth over the past century. Oil pollution, nutrient pollution and sedimentation due to excessive run-off from deforested areas are extreme coral stressors. Multiple stressors have a combinatorial effect on an otherwise resilient system, *e.g.,* Galeta Point, Panama (Jackson, *et al.*, 1989; Keller and Jackson, 1993; Guzman *et al*., 1994).

U.S. Antarctic Program benthic pollution studies

Surface-supplied diving is used when workloads demand higher respiration rates than can be supplied by scuba. Because of the contamination and for thermal protection, the DUI TLS350 or RS1050 drysuits, or Trelleborg Viking Pro or HD vulcanized rubber drysuits work well in extremely cold environments and they do not freeze in the air. Several benthic pollution studies were initiated in 1992 in the contaminated water of Winter Quarters Bay and around the McMurdo Station outfall (Conlan *et al.*, 2004). Initial sampling was done by USAP commercial divers who were working at McMurdo Station. Scientific divers, anxious to see the study site and use this extreme-environment diving mode began diving with the commercial divers to complete the sampling requirements. All diving was done with program-supplied commercial diving equipment (Robbins, 2006). The two-day training program included a minimum of two familiarization dives under direct supervision of the USAP Dive Supervisor. Hands-on briefings with the Scientific Diving Coordinator covered system set-up, introduction and familiarization with Kirby Morgan band mask and Superlite 17 dive helmet, out-of-air emergencies, tether management, line-pull signals, freeflow procedures, equalization, de-fogging, decompression requirements, and surface-supplied diver tending procedures. The minimum personnel requirement for USAP surface-supplied diving is a three-person crew consisting of a supervisor/tender, a diver, and a suited standby diver who can use either scuba or surface supply.

In addition to contaminated water operations, surface-supplied diving has found other applications in the USAP diving program. Surface-supplied diving is now the exclusive mode used by USAP divers operating in the Dry Valley Lakes. Environmental protocols mandate the use of solo divers to minimize disruption of lake haloclines. Safety concerns demand that solo divers using comparatively unreliable band- or full-face masks be provided with a large supply of breathing gas. Robbins (2006) reported the USAP experience with EXO-26 masks as 11 freeflows in 106 dives (10.4% failure rate), and AGA masks have had 2 freeflows in 26 dives (7.7% failure rate). These data come from dives in the Dry Valley Lakes where water temperatures range between 0°C and 2°C. It is assumed that failure rate would be even higher in -1.8°C water of McMurdo Sound. Specific failure rates for either the Heliox-18 or Superlite-17 helmets cannot be extracted from the USAP database, but are presumably similar to the full-face masks (Robbins, 2006).

Another current benthic pollution study requires coring in an area of frozen sediment. At other sampling sites for this study a large number of cores are required at 40 msw. The ability to work fast under inherently high respiration rates results in a reduction of the number of dives required to complete this sampling. Since 2001, 459 surface-supplied dives have been logged by 32 surface-supplied divers (Robbins, 2006).

Smithsonian Environmental Research Center Invasive Species Project

Established in 1997 pursuant to the National Invasive Species Act of 1996, the National Ballast Information Clearinghouse (NBIC) is a joint program of the Smithsonian Institution and the U.S. Coast Guard that collects, analyzes, and interprets data on the ballast water management practices of commercial ships that operate in U.S. waters. The principal goals are to quantify the amounts and origins of ballast water discharged in U.S. coastal systems and to determine the degree to which such water has undergone open-ocean exchange or alternative treatments designed to reduce the likelihood of ballast-mediated invasions by exotic species.

The World Conservation Union (IUCN) established generally accepted distinct bioregions of the world. Organisms have been transferred among bioregion boundaries with economic damage and environmental impacts as a result. Hull fouling and ballast water act as invasive species vectors that require sampling in select harbors and ports at locations such as Oakland-San Francisco Bay, Prince William Sound, Chesapeake Bay, and Tampa Bay by scientific divers, commercial divers and remotely operated vehicles (ROVs). Harbors are often contaminated bodies of water. Smithsonian scientific divers on this sampling project have been trained in drysuit and contaminated water diving techniques because some diving occurs in harbors on ship hulls.

Through personal experience as a commercial diver from 1979-1982 in San Diego Harbor and Mission Bay, observations of fuel spills from boats, sloughing of chemicals from toxic antifouling hull paint and proximity to old creosote soaked wooden dock pilings reinforced the need for adequate diver protection against direct contaminated water contact. In addition, San Diego Bay has been home port to a U.S. Naval fleet of ships and submarine warfare facilities. Hull fouling impedes vessel speed and fuel efficiency. Subjectively, it always appeared that there was much less fouling material on Navy vessels than on surrounding pleasure yachts in the same body of water. There is reason to believe that since then environmental protection laws have also been made applicable to the U.S. Navy, likely resulting in much less effective compounds in current-day antifouling paints. As a marine biologist the conspicuous absence of mollusks (mussels and other fouling organisms that comprise the dock fouling communities) was quite noticeable compared to other West Coast harbors.

6. Risk Assessment

a. Decompression monitoring and dive computers

Egstrom (2006) interprets understanding risk as follows: the identification of hazards should be based upon existing scientific evidence, which can show a cause and effect relationship between dive exposures and serious injury to the diver. The dose-response relationship would require that an objective decision be made as to the degree to which different profiles cause an observed effect. This would normally involve a study of a population of scientific divers and its known response to various exposures. We need to know the likelihood of increased injury in the diving population that is produced by the hazard. The type of profile, length of exposure and depth used are all part of the "dose" that must be evaluated. Risk assessment is relative to a specific set of conditions. The analysis of risk will depend, in part, on the potential damage or benefits of the practice of extreme-environment diving. It may also depend upon the effect of a variety of intervening variables such as physiological fitness, hydration, age, equipment, experience, and many others which may have an effect on susceptibility to decompression sickness. Characterization of the specific nature of the calculated risk that divers must accept if they choose to dive becomes part of the informed consent to undertake an extreme-environment exposure.

The description of the risk is then based upon the objective evaluation of the likelihood of the occurrence of undesirable side effects following a given "dose" of diving exposure. Usually, a risk ratio of 1:1,000,000 is considered acceptable for virtually any risk. Risks at the level of 1:100,000 are minimal but the severity of the injury becomes an issue. Contaminated water diving, ice diving and deep diving risk assessment needs a review of the actual number of exposures or the accurate size of the population as well as the number and severity of the injuries to make a reasonable assignment of risk. Without the denominator the attempts at assigning risk are speculative (Egstrom, 2006). There is a problem of determining outcomes, i.e., DCS in general, and an inability of the models and procedures to determine risk of serious versus non-serious DCS symptoms. DCS can be defined operationally as manifestations consistent with the Perceived Severity Index (PSI) within 48 hours of diving and resolution with recompression (Ozyigit *et al.*, 2010). The PSI is a hierarchical severity scale ranging in perceived order of severity from 1 for serious neurological signs to 6 for constitutional/non-specific symptoms.

Scientific diving programs have been slow to change in the face of new developments and controversy has followed virtually every new development (single versus double-hose regulators, life vests versus buoyancy compensators, alternate air sources, dive tables versus dive computers, air versus mixed gas, order of dive profiles, deep air limits, etc.) Unfortunately, the outcomes of procedural change are often based on emotion and tradition rather than upon credible scientific fact. The important assessment is of the diving risks and, if minimal, the benefit should outweigh the assumption of that risk and be acceptable to our diving population. It is also recognized that there can be no guarantee of ultimate safety and that all risks are relative to the specific conditions of each dive.

"Decompression sickness is caused by inadequate decompression following a dive. An excessive amount of gas in the tissues can result from any condition (in the man or in the surroundings) that causes an unexpectedly large amount of inert gas to be taken up at depth or that results in an abnormally slow elimination of gas during the decompression procedure. In such situations, following the table to the letter would not always assure adequate decompression. However, the decompression tables are designed to cover all but exceptional cases of this sort, so the actual risk of decompression sickness is small if the right table is properly employed." (U.S. Navy, 1959).

The introduction of scuba in the mid-1940s changed diving operations that were carried out by hardhat divers using surface-supplied air for dives at single depths for as long as they needed to complete the mission while decompression status was monitored by surface tenders. Scuba divers without surface contact now had to be responsible for their own decompression status under water. Without an unlimited air supply from the surface the repetitive dive concept became an actuality with the exchange of full scuba cylinders. Three-dimensional freedom of movement during a dive led to multi-level dive profiles. Searle (1956) indicated in a Navy Experimental Diving Unit report the need for some type of decompression device because of the ever-widening fields of both civilian and military free-swimming diving using self-contained underwater breathing apparatus. Particularly when scuba diving was untended from the surface, there arose a very pressing need for a small portable apparatus to be used by the diver to indicate proper decompression and ascent. Various mechanical and electrical analog and microprocessor-based digital dive computers to determine a diver's decompression status in real time have been produced since the advent of scuba in the 1950s (Huggins, 1989; Lang and Angelini, 2009). Current computers only use depth and time as variables to compute decompression status. Future computers should incorporate individual and environmental variations and additional variables that play a role in decompression sickness susceptibility, and perhaps ultimately monitor actual inert gas levels in the diver.

Historically, the diving community has depended predominantly on the United States Navy Air Decompression tables, a direct descendant of Haldane's work, which has served divers well for over five decades. Dive computers, utilizing mathematical models of human tissue compartments and gas exchange, allow the constant computation of the diver's decompression status during the dive. They vary in the assumptions incorporated in their models and in their capabilities. As predicted by Lang and Hamilton (1989) these real-time tools now enjoy widespread use in the recreational, scientific and military diving sectors. Logically, dive computer evolution was a natural progression from decompression tables and as such they experienced several generations of development. Computers replaced the diver's watch and depth gauge, provided greater accuracy and computerized, real-time, at-depth, continuous dive profile data, eliminating the need for the diver to remember tables and make decompression decisions while under water and while multi-level diving, and allowed for longer bottom times than permitted by tables. Many divers are highly motivated in their activities and interested in maximizing underwater time and efficiency. They view decompression requirements as a hindrance and distraction from their dive objectives, yet are generally concerned about safety.

Huggins (1989) outlined the evolution of a series of digital dive computers once the microprocessor revolution was underway in the mid 1970s. Thalmann (*et al.,* 1980; 1983; 1984) and Presswood *et al.* (1986) worked on developing an E-L (exponential linear) decompression model and algorithm to program into an Underwater Decompression Computer to be used with the USN constant partial pressure of oxygen, closed-circuit mixed-gas system. This model assumed that nitrogen absorbed by tissues at an exponential rate (as in Haldanean models), discharged at a slower linear rate. In 1996, Thalmann's VVAL 18 model was tested in the USN's Cochran Navy dive computer.

The first commercially mass-produced electronic dive computer, the 1983 ORCA Industries' EDGE incorporated a 12-compartment model (half times from 5 to 480 min) was based on no-decompression limits (to 40 msw) determined, in part, by Doppler ultrasonic bubble detection (Spencer, 1976). The EDGE display was perhaps one of the most innovative to date, divided into graphical and digital information split into two sections by a curve (limit-line) representing the maximum pressure (Mo values) allowed in the twelve compartments. One glance by the diver established whether all compartment bars were above the limit-line, indicating a no-decompression dive. The Aladin (Uwatec) had a 12-compartment version (ZHL-12) based on Bühlmann's Swiss 16-compartment model developed with compartment half-times ranging from 4 to 635 min and designed for altitude diving up to 4500 meters above sea level. Time to fly information was first introduced into a computer. The Uwatec computer could be interrogated and the log entries for the last five dives recalled by activating two wet switches. The Aladin Pro Plus in 1987 was likely the first commercially successful mass-produced dive computer.

The operational experience with dive computers is now enormous, yet some key considerations remain such as: decompression model effectiveness and accessibility, acceptable validation and human testing, assumption of acceptable risk, imposition of depth, time and specific profile-type limitations, dive computer failure and contingency procedures, and operational reliability data. The incidence of decompression sickness would appear to be an appropriate metric to evaluate the efficiency of dive computers. Assuming that the diver wore the computer, actually looked at it during the dive, and the computer can be interrogated by the hyperbaric chamber operator, useful dive profile information can be retrieved and used in treatment decision-making protocols.

Huggins (1989) aptly concluded *"It is interesting to speculate about the present state of scuba diving if the Foxboro Decomputer Mark I had performed properly and had been adopted for U.S. Navy use in 1956. If so, the present U.S. Navy air decompression tables might not have been computed and the standard tool used to determine decompression status might have been a dive computer. Dive computer technology would be far more advanced, and more information and studies about the effects of multi-level diving would be available today."*

In 1908 John Scott Haldane published a paper (Boycott *et al.,* 1908) that to date represents the most significant milestone in decompression physiology. A multitude of researchers (Hills, 1966; Workman, 1963, 1965; Bühlmann, 1990) and many others over the years have published numerous versions of decompression models which, by and large, are all intrinsically linked to this century-old publication.

As a diver descends in the water column and is exposed to increased ambient pressure, the partial pressure of the inhaled inert gas is higher than that of the dissolved inert gas in the various bodily tissues. This imbalance leads to inert gas travelling from the lungs via the blood stream throughout the body, where it is absorbed in the various tissues at a rate that is a function of the tissue itself (*e.g.,* muscle tissue will "load" up with inert gas faster than fat tissue). The characteristic by which a tissue loads with inert gas is defined by the term "half-time," an artificial parameter that defines the time required for a tissue to equilibrate to within 50% of the imposed external pressure.

Similarly, as the diver ascends at the end of the dive and is exposed to a diminishing ambient pressure, the partial pressure of inert gas in a tissue will become higher than the partial pressure of the inhaled inert gas (supersaturation), and hence the inert gas transfer process is inverted. Excess inert gas is returned from the tissues via the blood stream to the lungs, from where it is eliminated by exhalation. The key concept in every form of Haldanean implementation is that decompression sickness is preceded by inert gas bubbles forming due to excessive supersaturation. Therefore, a successful decompression strategy involves controlling the supersaturation in each tissue within defined values. The various versions of Haldanean models differ primarily in the number of tissues considered, their half-times and their tolerance to supersaturation (up to the tipping point of bubble formation) and mathematical tricks that are applied to cover a variety of influencing factors (*e.g.,* cold, workload, repetitive diving). The primary reason for the success of Haldanean models is that, in spite of their simplistic approach, a vast amount of data exists to which the models have been fitted. Enough empirical observations and data fitting can make any model yield excellent results within its tested range.

Most decompression models in use today are, aside from a few mathematical manipulations, almost entirely based on the ideas of John Scott Haldane presented in that historic 1908 paper (Doolette, 2009). Haldanean theory, which does not consider inert gas in free form, and consequently its effects on the human body, has been refined over a century with the input of Workman (1963), Bühlmann (1990), Thalmann *et al.* (1980) and Thalmann (1983; 1984) to name a few, and provides us today with an extremely valuable and powerful tool. During the 1980s the prevailing opinion was that bubbles formed during almost all dives, even those not producing any sign or symptom of decompression sickness. This prompted a new wave in decompression modeling that implicitly included bubble formation and growth, and its consequences to the diver. As a main departure from the Haldanean model, inert gas was not only present in dissolved form, but also in free form as a bubble. David Yount proposed a free-phase decompression model, the Variable Permeability Model (Yount and Hoffman, 1986), Michael Gernhardt the Tissue Bubble Dynamics Model (Gernhardt, 1991), and Wayne Gerth and Richard Vann (Gerth and Vann, 1997) the Probabilistic Gas and Bubble Dynamics Model. The most widely implemented model in a simplified version in a variety of dive computers is the Reduced Gradient Bubble Model (Wienke, 1990). Gutvik and Brubakk (2009) are the proponents of Copernicus, and Lewis and Crow (2008) presented an introduction to their Gas Formation Model (GFM). Whereas Yount and Hoffman, and Wienke consider supersaturation as a mechanism to begin bubble formation, Gernhardt, Gerth and Vann, and Gutvik and Brubakk track bubbles from their initial form as microscopic nuclei and follow their evolution and growth as the dive progresses. These latter models are of considerable higher mathematical complexity but can be solved within the realm of a modern microprocessor (Gutvik, 2011). The overarching goal of future dive computer models should be to more closely reflect the individual physiology of the diver, evolving as a true electronic instrument designed to solve a physiological problem. Moon *et al.* (1995) reinforced that the probabilistic models on which tables and computers are based should reflect the individual reality of the divers, to enable them to conduct their dives in accordance with their individual characteristics.

Divers must adhere to the manufacturer's recommended ascent rate, whether variable or uniform, which is an integral component of the algorithm's tissue-tension calculations. Training in, and understanding of, proper ascent techniques is fundamental to safe diving practice, including mastering proper buoyancy control, weighting and a controlled ascent with a "hovering" safety stop in the 3-9 msw zone for 3-5 min (Lang and Egstrom, 1990). It is in the ascent phase of the dive that computers reveal one of their strengths. Existing computers have maximum ascent rates that do not exceed 18 msw/min from depth and many are limited to 9 msw/min in shallower water. Future dive computer models may favor slower rates but operationally, the 9 msw/min is achievable and effective, while slower rates most likely are not. Multiday, multi-level repetitive computer diving within the tested envelope characterizes the mainstream practice today, and it appears to be less stressful than square multiday square-wave profile diving. Deep repetitive dives with short surface intervals should nevertheless be given special consideration. Because of limited analysis of the existing profile databases, no firm conclusions have been reached regarding repetitive diving limits to date (Lang and Vann, 1992). The maximum depth sequence of repetitive dive profiles is not restricted by dive computers. Lang and Lehner (2000) found that there was no physiological reason for prohibiting reverse dive profiles for no-decompression dives less than 40 msw and depth differentials less than 12 msw because this was never a rule in either U.S. Navy or commercial diving, but more of an operational constraint due to the organization of depth/time profiles in a square-wave table format.

There exists no dependable distinction between "safe to fly" and "not safe to fly" in dive computers. There is a gradual reduction of risk for which the diver needs to choose an acceptable degree, i.e., wait at least 24 hours, the longer the wait, the further the reduction in probability of decompression sickness (Sheffield and Vann, 2002). Lang and Hamilton (1989) provided examples of dive computer computations for "time to fly" that include offgasing to 0.3-0.6 msw over ambient pressure, waiting until 12 hours have elapsed after the last dive, or not exceeding 0.58 bars as maximum ceiling setting (approximately 2,438 m of altitude).

Adjusting oxygen fractions in dive computer software from 0.21 to standard enriched-air nitrox of 0.32 or 0.36 is simple and an available function in most computers. Huggins (2006) examined dive computer options to support scientific surface-supplied diving on heliox or trimix, limiting simulated dives to depths of 90 msw for 20 min because of the rapidly increasing total decompression time (TDT) debt incurred at that depth. Four dive computers were determined to be able to operate under these conditions: the Cochran Undersea Technology EMC-20H, the Delta P Technology VR3, the Dive Rite

NiTek He, and the HydroSpace Engineering HS Explorer. Computer simulations allowed for many possible decompression schedules for a single 90 msw/20 min dive depending upon the algorithm, any conservatism added to it, the composition of the bottom mix, and the decompression gases (composition and switch depth). The actual decompression schedule would vary greatly even though the same TDT was achieved and many of the stops would occur deeper and have shorter times with a final decompression gas. Huggins (2006) found that the total decompression time (TDT) obligation from the most liberal dive computer for a heliox dive without decompression gas switches was unacceptably long (5 hours). It was determined that multi-gas decompression protocols were required for more efficient operations. Switching to a single nitrox decompression reduced the TDT dramatically. Adding an additional nitrox mix did not make a significant difference. Moving to a trimix bottom mix with two nitrox mixes for decompression did have a major impact on reducing the TDT. For the trimix scenario the required decompressions for the four simulations of the computers, in their most liberal mode, were within eight minutes of each other (89-97 min). Specific comparisons to U.S. Navy heliox decompression tables and DCIEM heliox tables were presented and discussed under various conservatism settings of these four dive computers (Huggins, 2006).

It was Huggins' opinion that in surface-supplied operations diver-carried dive computers are best used as a backup and that the major control of decompression should be assigned to the surface-support personnel using a preplanned set of tables that the dive computer emulates. Finding a computer that can be set to mirror established heliox table (e.g., U.S. Navy or DCIEM) decompression requirements (both in total decompression time and decompression gas times) will prove difficult. In trimix operations software packages can be used to generate decompression tables that can closely reflect the dive computer's response. However, the paucity of data supporting the safety of models brings up risk management issues. In lieu of having a level of confidence from validation studies, scientific divers must have enough comfort and experience with the decompression algorithms and protocols they use to be able to justify their use to their Diving Control Board. Emergency protocols need to be established to be able to handle the possibility of diver blow-ups from depths that can potentially produce fatal decompression sickness.

The dive computer of the future will benefit from advances in science and technology to increase functionality, features and configurations. According to Lang and Angelini (2009), these can be grouped into three distinct categories: 1) benefits from advances in consumer electronics technology (high resolution color display, rechargeable battery, GPS receiver, underwater communication and navigation, and emergency position indicating radio beacon – EPIRB); 2) monitoring technology integrated in the algorithm (heart rate monitoring, skin temperature measurements, oxygen saturation measurements, and inert gas bubble detection); and, 3) advances in decompression physiology research.

b. DCS incidence rates

Evaluations of the available databases on pressure-related injuries to examine the effectiveness of dive computers showed that these devices had demonstrable advantages over dive tables. It remains clear that neither tables nor dive computers can eliminate all decompression problems, which have a probabilistic component to their occurrence. However, the current generation of dive computer technology represents an important tool for further improving diver safety. Divers Alert Network has managed to collect 125,000 dive profiles by 11,000 divers in 17,600 dive series from 1995 to 2008 through its Project Dive Exploration (PDE), a worldwide study of recreational diving to record more than one million dive profiles to produce statistically accurate analyses of dive profiles, diver characteristics, and diver behavior. This collection of real-time depth/time profiles for statistical analysis and modeling assists in characterizing the effect of diving environment on DCS (Dunford *et al*., 2011). Each case was categorized by its most serious manifestation. Type II DCS is equivalent to Perceived Severity Index (PSI) of 1-3, and Type I DCS is equivalent to PSI of 4-6. Cases with PSIs of 3 (mild neurological) and 4 (pain) were most common. Dunford *et al*. (2011) concluded that conditions associated with "cold-water wreck" dives had a 17-fold higher DCS incident rate compared to "warm-water liveaboard" dives when controlled for maximum depth, and that nitrox was associated with lower DCS incidence despite deeper depths and longer times compared to air. They further speculated that current recreational diving procedures are not of uniform DCS risk for gas, repetitive diving, and maximum depth.

The American Academy of Underwater Sciences' organizational membership comprised an annual mean of 75 (± 15) institutions whose diving records for a 10-year period between January 1998 and December 2007 were reviewed (Dardeau *et al*., 2012). Case (diagnosis) classification or reclassification was done using DAN criteria (Vann *et al*., 2005). A total of 1,019,159 scientific dives (annual mean of 101,916 ± 23,701) were logged by 3,572 (± 575) divers annually. There were 33 cases (annual mean 3.3 ± 0.9) determined to involve decompression illness (DCI), yielding an incidence rate of 0.245/10,000 person-dives. All but four incidents occurred at depths between 9 and 30 msw. One AGE case and one ambiguous case occurred in less than 10 msw and two DCS cases occurred in dives in excess of 40 msw. Of the total 1,019,159 dives 98 percent were shallower than 30 msw (Dardeau *et al*., 2012). Recompression therapy was successful in at least 85 percent of cases with 58 percent (19/33) reporting success with a single treatment and 27 percent (9/33) with multiple treatments.

This DCI rate was substantially lower than the 0.9-35.3/10,000 rates published for recreational, instructional/guided, commercial and/or military diving. Scientific diving safety may result from a combination of relatively high levels of training and oversight, the predominance of shallow, multi-level no-decompression diving, experience-based depth certifications and, possibly, low pressure to complete dives under less than optimal circumstances. Dardeau and McDonald (2007) concluded from a retrospective evaluation that the total pressure-related injury rates from 1998 to 2005 in the scientific diving community were similar to those calculated by the U.S. Occupational Safety and Health Administration (OSHA) for scientific divers during the late 1970s. DCI is the collective term that includes both DCS and AGE, which makes it difficult to determine the frequency of DCS events alone. However, these rates are low when compared to the 1.4-95.5/10,000 person-dive estimates for commercial and military diving communities (Sayer *et al*., 2007). There is evidence that DCI can be over-reported. Vann *et al*. (2004) found that of 435 cases of DCI reported in the recreational diving community treated with recompression, 85 (20 percent) were appropriately reclassified as not DCI, making it clear that accurate incidence rates are dependent on careful evaluation of individual cases.

A review of published DCS/DCI rates ranging from 0.00 to 9.55 per 1,000 dives is summarized in Table 9 (Sayer *et al*. 2007). Any comparative review of this type is always complicated through the inconsistent use of terminology relating to DCS or DCI. In addition, it is not always clear whether the reports are based on person-dives or on dives alone irrespective of the number of divers performing those dives. These DCS/DCI incident rates provide a comparison among different types of diving. Previously-published rates for scientific diving ranged from 0.00 to 0.06 DCS/DCI cases per 1,000 person dives; in the Antarctic, the rate for scientific diving was greater (0.28).

Since 1985, information about Antarctic diving activities has been routinely collected by national Antarctic scientific diving programs of Antarctica New Zealand (ANZ), the U.S. Antarctic Program (USAP), and the British Antarctic Survey (BAS) (Sayer *et al*., 2007). The datasets are not all complete but, when combined, give a total of nearly 18,000 person dives by over 600 divers. The three diving programs collated different kinds of data; for example, the USAP collated dive times and depths (over 6,111 hours logged under water at an average depth of 22 msw and average duration of 34 min), the BAS profiled their diving by depth ranges (33.7% of dives shallower than 9 msw, 31.5% between 10 and 19 msw, 16.9% in the 20-29 msw depth range, and 17.8% of the dives in 30 msw or deeper).

Table 9. A summary review of published DCI /DCS* rates per 1,000 dives. Rates in parentheses have been calculated based on a single incidence of DCI/DCS. From Sayer *et al*. (2007).

Type of diving	DCI/DCS incidence per 1000 “dives” **	Reference
US Navy: deep air diving (50 msw)	9.55	Hunter *et al.* (1978)
US Navy: 4th quartile of no-stop time (USN57)	1.28	Flynn *et al.* (1998)
Multi-day decompression diving	1.12	Sayer *et al.* (2007)
Commercial (oil platform) scuba 30-50 msw	1.03	Luby (1999)
Commercial (oil platform) all diving 50 msw+	(0.76)	Luby (1999)
UK multi-dive multi-day wreck diving	0.25-0.49	Trevett *et al.* (2001)
Tropical multi-dive multi-day	0.29-0.33	Davis and Walker (2003)
US Navy shallow no-stop air diving	0.29	Flynn *et al.* (1998)
US Navy: 1st quartile of no-stop time (USN57)	0.22	Flynn *et al.* (1998)
Overseas US military community	0.14	Arness (1997)
Commercial (oil platform) all diving 9-30 msw	0.14	Luby (1999)
West Canada amateur scuba	0.10	Ladd *et al.* (2002)
Caribbean recreational scuba	0.09	Gilliam (1992)
UK recreational / amateur divers	0.07	Wilmshurst *et al.* (1994)
UK scientific diving	(0.06)	Sayer and Barrington (2005)
Japan recreational scuba	0.05	Nakayama *et al.* (2003)
US scientific diving	0.05	Lang (2005)
International scientific diving	0.04	Sayer (2005)
Australian scientific diving	0.00	Carter *et al.* (2005)
Antarctic scientific diving	0.28	Sayer, Lang, Mercer (2007)

* Some studies are specifically DCS; some are specifically DCI; some do not make the distinction; ** Dive is assumed to be a “person dive” but not all studies make this clear.

The only consistent data collected were person-dives, numbers of divers and incident rates. Only data relating to DCS and barotraumas were collated consistently between the three programs. There were 5 cases of mild barotraumas and 5 cases of mild DCS and no serious diving incidents (DCS Type II or AGE). This produced DCS incident rates of 0.00, 0.18 and 0.55 cases per 1,000 person dives in the ANZ, USAP and BAS diving programs, respectively. Collectively, the incidence of DCS was 0.28 cases per 1,000 person dives.

Although scientific diving in the Antarctic has a comparatively low rate of DCS/DCI cases compared with other types of diving, the rates are higher than those previously reported for scientific diving *per se*. An obvious explanation for this might be the general acceptance that cold-water diving carries a proportionately higher risk of DCS/DCI (*e.g.,* Mekjavic *et al*., 2003; Mueller, 2007). In particular, peripheral vasoconstriction following prolonged immersion in cold water is known to contribute to the likelihood of causing cutaneous decompression sickness (Mekjavic *et al.,* 2003). In fact, all three of the DCS Type I cases reported by BAS were cases of cutaneous DCS. However, it is also likely that because of the remoteness of the diving operations in Antarctica that there is probably an increased inclination to perform precautionary treatments in association with over eager diagnoses. A note of caution for Antarctic diving: because of the polar atmospheric effect, the mean annual pressure altitude at McMurdo Station is 200 m. Under certain conditions, pressure altitude may be as low as 335 m at sea level. Surfacing from a long, deep dive (on dive computer sea level settings) to an equivalent altitude of 335 m may increase the probability of DCS. Safety stops of three to five minutes between 3.3 - 10 msw depths are required for all dives (Lang and Egstrom, 1990) and there has been a developing tendency in the Antarctic scientific diving programs to adopt more conservative dive profiles.

Kesling and Styron (2006) reviewed the NOAA National Undersea Research Center/University of North Carolina, Wilmington supported technical dives from August 1994 to November 2005. During this period a total of 2,376 dives were logged to an average depth of 53 msw (max. 86 msw) of average bottom time of 23 min (max. 40 min) and average decompression duration of 51 min (max. 162 min). There were three reported cases of DCI, i.e., one case incurring lymphatic bends and the other two cases involving DCS Type II with vestibular involvement. One DCS II case developed as a result of using published decompression schedules while the other occurred from a diver-worn dive computer. All three cases were treated and responded to recompression therapy.

Finally, some remarks are provided about diving fatalities in addition to the dual diving fatality from the USCG HEALY described in polar diving operations (Chapter 3.e.) The risk of dying during diving is small, but no activity is completely risk-free, and deaths occasionally occur. The Divers Alert Network held a workshop to consider whether the risks could be reduced further (Vann and Lang, 2011). Topics included investigation, surveillance, operational safety, and cardiovascular disease. Investigation is essential to determine causes and involves on-scene inquiry, forensic examination of the deceased, and testing of life support equipment, but while local coroners or medical examiners may be responsible for establishing the cause of death (COD), they are frequently unfamiliar with the special requirements of diving autopsies that differentiate among causes such as drowning, AGE and DCS. Life-support equipment for compressed-gas diving is generally robust and reliable, but poor maintenance, improper use, or design flaws can compromise its operation and contribute to events leading to death. Both United

States and European courts are requiring strict adherence to preservation of evidence such as data contained in a dive computer.

Annual per capita diving fatality rates among DAN America (16.4 deaths per 100,000 persons per year) and British Sub-Aqua Club (BSAC) members (14.4 deaths per 100,000 persons per year) were similar and did not change during 2000-2006, the period examined (Vann and Lang, 2011). Per capita fatality rates are poor measures of exposure risk, however, and may not be as informative of true risk as are fatality rates per dive. Richardson (2011) reported a mean annual fatality rate of 0.48 deaths per 100,000 student training dives per year from PADI data of 17 million student diver certifications during 63 million student dives over a 20- year period (1989-2008). To understand the extent of the recreational diving fatality problem, moreover, estimates of the total population size need updating from John McAniff's 1995 estimate of 2.8 to 3.5 million U.S. recreational scuba divers (Hornsby, 2011).

The most frequently cited root cause among the independent population samples was insufficient gas or running out of gas. Other common factors included entrapment or entanglement, buoyancy control, equipment misuse or problems, rough waters and emergency ascent. The principal injuries or causes of death included drowning or asphyxia due to inhalation of water, air embolism and cardiac events. Older divers were at greater risk of cardiac events, with men at higher risk than women although the risks were equal at age 65 (Vann and Lang, 2011). Suggested operational diving contributing factors included inexperience, infrequent diving, inadequate supervision, insufficient pre-dive briefings, buddy separation, entanglement, and dive conditions beyond the diver's training, experience or physical capacity. The most common causes of sudden death in the general population are arrhythmia and acute myocardial infarction, usually due to occult cardiovascular disease with little indication of abnormality (Thompson, 2011; Douglas, 2011). Divers face additional stresses from immersion and cold, which cause a central shift of blood and can lead to acute volume overload and decompensated heart failure (Bove, 2011). Ischemia and arrhythmia may be aggravated during exercise due to increased blood pressure and sympathetic activation.

7. Discussion and Conclusions

My colleague and friend Glen Egstrom is known to have remarked that all too often we have been placed in the intellectually awkward position identified by Poul Anderson who stated “I have never encountered a problem, however complicated, which, when viewed in the proper perspective, did not become more complicated.” However, Egstrom also provides an encouraging position by Ben Franklin who in 1887 observed “Having lived long I have experienced many instances of being obliged by better information and for consideration to change opinions even on important subjects which I once thought right but found to be otherwise.” If we are to evaluate the risks of increasing scientific diving capability in extreme environments, then it appears that we must delve into the complications that go with the understanding of the problem in order to properly assess the risk involved.

The scope of extreme-environment diving defined within this work encompasses diving modes outside of the generally accepted no-decompression, open-circuit, compressed-air diving limits on self-contained underwater breathing apparatus in temperate or warmer waters. Lessons learned from the outer edge of diving often further refine and improve our operational knowledge and facilitate advances in equipment technology and training. This trickle-down effect benefits millions of scuba divers diving worldwide in the recreational diving environment and facilitates the underwater work of thousands of scientific divers internationally. There has also been a transfer of knowledge from the commercial diving industry to the scientific diving community in recent years, in particular as it relates to deep and surface-supplied diving. The diving universe primarily examined here is the scientific diving community. Since 1978, this is the model from which my experience base is derived. A synthetic review of the scientific diving medical and safety procedures characterizes the capabilities of the diver examined, i.e., the diving scientist, and the framework within which scientific missions are successfully conducted with a remarkably high margin of safety and productivity. The main findings between extreme-environment diving and recreational or ubiquitous scientific diving validate the increased level of operational diving skill, knowledge and training required to conduct these activities within acceptable degrees of safety.

The scientific diving community has effectively used scuba as a research tool for over 50 years, since the first program was established at Scripps Institution of Oceanography. Lang and Vann (1992) published DCS incidence rates that were by a factor of 10 lower than recreational diving and commercial diving. In part, this is due to thorough medical, training and operational standards and programmatic supervision of diving activities, but also to usually non-aggressive, multi-level, multi-day no-decompression dive profiles. Safety considerations are of primary concern for the diving programs whose regulations are promulgated by the underwater scientists who live by them.

Scientific research objectives, whether through mensurative or manipulative experiments, in many instances could not have been accomplished without scientific diving techniques, as evidenced in materials and methods sections of peer-reviewed published literature (Lang *et al*., 2012). The complimentary use of diving and remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), and remote sensing equipment has greatly advanced our underwater research capabilities in recent years. One-Man Atmospheric Diving Systems (OMADS) have also become more sophisticated and affordable in recent years and are more widely used by the marine research community (e.g., DeepWorker, Exosuit – currently undergoing testing). At some point in the future, decompression, dive training, and medical issues may no longer be of major concern to scientists, as emerging technologies develop. In the mean time, many topics of current scientific interest, including marine biodiversity, coral reef health, sea-level change and global warming are to a large degree dependent on placing the trained scientific eye under water to record, interpret and sample the underwater environment.

The conduct of underwater research in polar environments requires special consideration of diving physiology, equipment design, diver training, and operational procedures, all of which enable this under-ice approach. The scientific community has progressed tremendously since those first ice dives in 1963 in wetsuits and double-hose regulators without buoyancy compensators or submersible pressure gauges. Novel ice diving techniques have expanded the working envelope based on scientific need to include the use of dive computers, enriched-air nitrox, rebreather units, bluewater diving, and drysuit systems. The International Polar Diving Workshop in Svalbard (Lang and Sayer, 2007) promulgated consensus polar diving recommendations through the combined international, interdisciplinary expertise of participating polar diving scientists, equipment manufacturers, physiologists and decompression experts, and diving safety officers. The National Science Foundation U.S. Antarctic Program scientific diving exposures in support of underwater research enjoy a remarkable safety record and high scientific productivity due to a significant allocation of logistical support and resources to ensure personnel safety.

Additional research could be conducted to strengthen our confidence in a causal link between thermal factors and DCS risk, to better estimate the magnitude of the effect for different phases of the dive, and to recommend modifications to decompression and thermal procedures (Toner and Ball, 2004). A specific goal of such research would be to determine what temperature ranges need to be maintained on each phase of the dive to maximize decompression efficiency. Studies focused on the mechanism of action of such an effect would be useful by providing insight into the fundamental question of DCS pathophysiology and the factors that influence its occurrence. At least two types of experimental studies could be conducted: studies that examine the effect of thermal factors on DCS risk; and studies that examine mechanisms of thermal effects on DCS risk. Whereas currently our average scientific dive depths and times (38 msw/34 min) under ice are exposures that are met with passive insulation strategies, the advent of electrically heated drysuit undergarments, gloves and socks, is imminent, which will increase our length of underwater comfort and likely require additional consideration of approaching no-decompression limits. The commercial industry would be better positioned to undertake a study to definitively answer whether or not hot-water suits increase the risk of DCS. Toner and Ball (2004) suggest that a possible study matrix would have one group of divers warmed during the entire dive; a second group would be cold on the bottom and warm during decompression; the third group would be kept cold throughout the dive; and a fourth group would be warm on the bottom and cold during decompression, with decompression times held constant. To date there is weak support for an effect between thermal factors and DCS risk. Because the magnitude of the effect is unknown and may be small, several hundred dives (a major human trial) would be required to determine if there is any significant difference in risk. Examination of hypothesized mechanisms of cold and DCS risk in extreme environments might provide insight into the broader question of DCS pathophysiology.

Life-support breathing apparatus performance in extreme environments (under ice, at depth, and in contaminated water) is a significant concern that can acutely and chronically affect diver safety. The under-ice performance study of several commercially available regulators was meant to select a successor model to the currently used 1991 Sherwood SRB3600 Maximus regulators in the U.S. Antarctic Diving Program. Single-hose scuba regulators dived in very cold water have a probability of experiencing first- or second-stage malfunction yielding complete occlusion of air flow or massive freeflow that rapidly expends a diver's air supply, both conditions referred to as regulator “freeze-up”. Ice crystal build up in the regulator second stage can inhibit the valve from completely seating itself and is the main cause of freeflow. Principal factors contributing to ice crystallization in the regulator second stage include manufacturer's design, materials, and quality control, moisture in the diver’s exhaled breath, adiabatic gas expansion, mass flow, time, temperature, and water leakage into the second stage. We were fully expecting to find a continuous variation in freezing susceptibility among the regulator brands but what we encountered, a clearly bimodal susceptibility, was surprising. This bimodal population lent itself to the classifications of “better” and “worse” regulators for Antarctic service. In 305 dives, there were 65 freeflows, which were not evenly distributed across the regulator brands. Regulator failure rates fell into two categories (<11% and >26%). The regulators classified for the purpose of the test as “better” (< 11%

failure rate) suffered only 9 freeflows out of 146 exposures for a 6% overall freeflow incidence; and those classified as "worse" (> 26% failure rate) suffered 56 freeflows out of 159 exposures (35% freeflow incidence.) Testing on regulator models was aborted when freeflow incidence reached 40% (n=1), and 50% (n=3), which exceeded our *a priori* stopping rules. Dive duration and gas consumption varied only slightly among the test divers. It appears that better insulated divers tolerated longer dives, on average. However, statistically those divers did not have more freeflow incidents than the other divers, and the freeze-ups occurred relatively early in the dives rather than late. There was, in other words, no association between diver body habitus and freeze-up incidence. The pooled incidences for the seven best performing regulators (DiveRite Jetstream, Sherwood Maximus SRB3600, Poseidon Xstream Deep, Poseidon Jetstream, Sherwood Maximus SRB7600, Poseidon Cyklon, Mares USN22 Abyss) were compared to the ten remaining regulators. Regulator freeze-up is a probabilistic event; even the best regulators can fail under polar conditions. Nevertheless, some regulators seem better suited for the under-ice environment than others.

We were unwilling to allow a regulator to be used for service in Antarctica if there was a 33% incidence of freeflow in our testing, or a 60% or greater chance of it failing in a larger sample. While we would have liked more stringent requirements, this was not possible due to the small available sample size. The U.S. Navy discovered through unpublished testing of prototype heat exchangers that if sufficiently sized they are able to bring super-cooled air up to seawater temperature (-2° C) prior to reaching the second stage. When that happens, freeflows are prevented. This principle was applied in one of the test regulators (Aqua Lung Glacia), but arguably that regulator's heat exchanger was too small for its intended purpose. The intermediate pressure hose connecting the first- and second-stage regulators is itself a heat exchanger, although one with low efficiency. A low-efficiency heat exchanger requires more time to bring internal temperature into equilibrium with external temperature than do high-efficiency heat exchangers. Thus, the additional time for heat transfer provided by slow breathing rates may serve favorably in reducing the risk of second-stage freeflow. However, without further study, the above comments are merely speculative. The isolator valve data shows that resistive effort increases, but not by a significant amount unless the diver is breathing very hard really deep, which is operationally not attractive. From diving safety considerations, the addition of the isolator valve to the regulator dramatically increases the margin of safety for ice-diving operations.

The final consideration of USAP regulator replacement acquisition also considered several subjective factors such as regulator performance observations by test divers, ease of regulator maintenance and servicing, and manufacturer's support. The most important consideration remains a low probability of freeze-up. The combination of laboratory (NEDU) and field testing (McMurdo) should be the preferred method for evaluating ice-diving regulator performance. If it also does not freeflow under severe NEDU test conditions, then it is very unlikely to cause air delivery problems for scientists under ice if the units are properly cared for. In conclusion, the 1991 Sherwood SRB3600 regulators must follow the path of the Royal Aquamaster double-hose ice-diving regulators that were retired from the USAP in 1990. Of the seventeen regulator models tested for ice diving performance and reliability, seven appear worthy of consideration for meeting the scientific diving community and military needs.

Nitrox has been used in the scientific diving community since the 1970s. For entry-level, open-circuit nitrox diving, there is no evidence that shows an increased risk of DCS from the use of nitrox versus compressed air (Lang, 2001). A maximum PO_2 of 1.6 ATA is generally accepted based on the history of nitrox use and scientific studies. Routine CO_2 retention screening is not necessary for open-circuit recreational or scientific nitrox divers. Oxygen analyzers should use a controlled flow-sampling device for accurate mix analysis, which should be performed by the blender and/or dispenser, and verified by the end user. Recreational training agencies and scientific diving programs recognize the effectiveness of nitrox dive computers. For recreational and scientific nitrox diving there is no need to track pulmonary or whole body oxygen toxicity (OTU-oxygen toxicity units or UPTD-units pulmonary toxicity dose), the "CNS Oxygen Clock" concept is taught based on NOAA oxygen exposure limits. However, it should be noted that CNS oxygen toxicity could occur suddenly and unexpectedly. Regarding nitrox compatible scuba equipment, the objective is to avoid incidental exposure to oxygen above 40%. Most nitrox mixes available through scuba shops is premixed at 32% (EAN_{32} with a maximum operating depth of 40 msw) or 36% (EAN_{36} with a maximum operating depth of 33 msw). Based on history of use, no evidence is available to show an unreasonable risk of fire or ignition when using up to 40% nitrox with standard scuba equipment. However, the level of risk is related to specific equipment configurations and the user should rely on manufacturer's recommendations.

The age of electronic diving has arrived with the development of the modern electronic dive computer as the most significant advancement in self-contained diving since the invention of the Aqualung by Jacques Cousteau and Emile Gagnan. Twenty-five years after modern day dive computer introduction several key questions remain surrounding the decompression models used, validation and human testing, acceptable risk, limitations, failures, and operational reliability. Educated predictions are offered on the functionality, features and configurations of future dive computer evolution based on benefits from advances in consumer electronics technology, and monitoring technology integrated into the dive computer algorithm that allows for a closer approximation of physiological parameters.

Additional advances in diving physiology research complementary to Haldane's original work in 1908 will shape the dive computer landscape of the future. However, dive computers are the most accurate means of monitoring decompression status in real-time and their accommodation of multilevel diving and indication of ascent rates their most important contributions. Because of small amounts of residual nitrogen, multilevel diving can be affected on multiple days of diving, but there is no data showing that adequate controls for multi-day diving are incorporated into dive computer algorithms. Even so, electronic dive computers have for all practical purposes replaced dive tables in recreational and scientific diving and are increasingly implemented in particular segments of the military diving community. For the commercial diving industry and its standard operating methods of surface-supplied/controlled diving or saturation diving, a dive computer's advantages in monitoring decompression status appear to be minimal. It would not be unreasonable to state that regardless of the number of algorithm variations incorporated in modern dive computers, they all appear to fall within an acceptable window of effectiveness based on available databases of pressure-related injuries. It is also clear that neither tables nor dive computers can eliminate all decompression problems, but if utilized conservatively, computers have emerged as an important tool for the improvement of diver safety.

All things considered, the dive computer's functions of ascent rate monitoring, real-time computation of nitrogen balances, air consumption monitoring and profile downloading capability form a solid, reliable basis for advancements that will emerge in the future. We can only imagine the progress that John Scott Haldane's brilliant decompression insight would have made had the dive computer tools available to us now and in the future been available to him 100 years ago.

Scientific divers wishing to utilize surface-supplied heliox or trimix for diving to depths of 90 msw need to be make decisions on whether to use dive computers with heliox and trimix capabilities to control decompression. If the dive computer or decompression software options are chosen (versus established tables, then in lieu of studies which have validated the decompression algorithm, the divers must have significant comfort and experience with the decompression algorithms and protocols they intend to use.

DCI is a relatively rare event, requiring monitoring of exposure over a broad geographic area and a long periods of time to yield meaningful rates. A number of incidence measures have been published. DAN's Project Dive Exploration estimates of the incidence of DCI in the recreational community to range between 2.0-4.0/10,000 person-dives. This is higher than previous estimates of DCI incidence of 0.96/10,000 person-dives (Ladd *et al.*, 2002) and DCS incidence of 0.90/10,000 person-dives (Gilliam, 1992). DCS rates among divemasters and instructors have been estimated at 12.7-15.2/10,000 person-dives (Hagberg and Ornhagen, 2003). DCI rates among military sport divers have been estimated at 2.65/10,000 person-dives Shallow no-decompression dives among Navy divers produced DCS rates of 2.9/10,000 person-dives (Flynn *et al*., 1998). The National Oceanic and Atmospheric Administration (NOAA), which conducts both working dives as well as scientific dives, reported a DCS rate of 1.8/10,000 person-dives (Dinsmore and Vitch, 2005). The DCS incidence of commercial decompression diving has been reported to be as high as 35.3/10,000 person-dives (Imbert *et al*., 1992). A more recent study reported commercial diving DCS rates ranging from 1.4 to 10.3/10,000 dives, depending on the depth of dive operations (Luby, 1999).

Antarctic scientific diving programs are maintained by several nations (Lang and Robbins, 2009). The rate of DCS for Antarctic scientific diving is reported as 2.8/10,000 dives and estimates of DCI incidence in the scientific diving community in general are lower than in other diving populations. (Sayer *et al*., 2007). Estimates of DCI in the scientific diving community range from 0.1/10,000 dives (Lang, 2005) to 0.6/10,000 dives (Sayer and Barrington, 2005). The requirements for routine medical surveillance, equipment maintenance, and additional training and oversight, combined with the predominance of shallow, no-decompression diving, may result in lower incidence rates in the scientific community than in other diving populations.

There are several limitations of risk estimate efforts. A frequent challenge of epidemiological studies is the accurate quantification of all relevant activity, effectively the denominator needed to compute incidence rates. With DCI, an additional complication is that it is not always clear whether the denominator is the number of dives or the number of person-dives (Klingmann *et al*., 2008). A challenge with all cases is the sometimes idiosyncratic and often difficult to define nature of DCI. Given the difficulty of diagnosis, combined with a tendency to treat conservatively, it is no surprise that nearly one third of cases can be classified as either not DCI or as ambiguous on review.

Notwithstanding evidence that DCS may be over-reported and often treated conservatively, there are also an unknown number of unreported cases. Prior to the 1980s, when minor symptoms of pain were more accepted as a routine part of diving, divers may have been reluctant to report symptoms. Even with the current emphasis on early reporting and the greater availability of treatment, some divers may still be hesitant to report minor symptoms. There may also be some variability in events deemed reportable by individual dive programs. Documenting the degree of risk associated with a given dive or dives is also problematic. The maximum depth of the dive preceding insult has been presented, but this can be of little value without knowing the exact trigger that causes symptoms (Dardeau *et al*., 2012). Decompression stress can be influenced by both repetitive diving and the specific profile of a given dive.

The 10-year determined DCI incidence rate of 0.245/10,000 person-dives (for a total of 1,019,159 scientific dives by 3,572 divers) is substantially lower than the previously published rates for recreational diving, instructional/guide diving, commercial and military diving (Dardeau *et al*., 2012). Despite the limitations of this study and many of the others evaluating diving risk, it does appear that scientific diving represents one of the safer types of diving (Dardeau *et al*., 2012). This safety may be caused by a combination of relatively high levels of training and oversight, the predominance of relatively shallow, no-decompression diving and, possibly, low demand to complete dives under less than optimal circumstances. Additional research to compare the decompression stress of actual exposures, the pressure to conduct dives, or other variables that exist between the diving sub-fields could provide useful insights to understand the real risks. As mentioned above, DCS risk may increase through the advent of better technology, commensurately increasing thermal comfort and thus extending bottom times.

The scientific diving operational safety and medical framework is the cornerstone from which diving takes place in extreme environments. From this effective baseline, as evidenced by decades of extremely low DCS incidence rates, the question of whether compressed air is the best breathing medium under pressure was addressed with findings indicating that in certain depth ranges a higher fraction of oxygen (while not exceeding a PO_2 of 1.6 ATA) and a lower fraction of nitrogen result in extended bottom times and a more efficient decompression. Extreme-environment diving under ice presents a set of physiological, equipment, training and operational challenges beyond regular diving that have been met through almost 50 years of experience as an underwater research tool. The monitoring of decompression status in extreme environments is now done exclusively through the use of dive computers and evaluations of the performance of regulators under ice have determined the characteristics of the next generation of life-support equipment for extreme-environment diving for science.

8. Summary of Papers

The scope of extreme-environment diving defined within this work encompasses diving modes outside of the generally accepted no-decompression, open-circuit, compressed-air diving limits on self-contained underwater breathing apparatus (scuba) in temperate or warmer waters. Lessons learned from the outer edge of diving often further refine and improve our operational knowledge and facilitate advances in equipment technology and training. This trickle-down effect benefits millions of scuba divers diving worldwide in the recreational diving environment and facilitates the underwater work of thousands of scientific divers internationally. The diving universe primarily examined here is the scientific diving community. Since 1978, this is the model from which my experience base is derived. A synthetic review of the scientific diving medical and safety procedures characterizes the capabilities of the diver examined, i.e., the diving scientist, and the framework within which scientific missions are successfully conducted with a remarkably high margin of safety. The main findings between extreme-environment diving and recreational or ubiquitous scientific diving validate the increased level of operational diving skill, knowledge and training required to conduct these activities within acceptable degrees of safety.

a. Scientific diving operational safety and medical framework.

Lang, M.A. 2005. U.S. scientific diving medical and safety experience. *SPUMS J.,* **35(3):** 154-160.

The first paper established the baseline for understanding the operational safety and medical framework for scientific diving that allows scientists to work in extreme environments (Lang, 2005). The scientific diving community has effectively used scuba as a research tool since the first program was established at Scripps Institution of Oceanography in 1951. The scientific diving community has a traditional proactive record of furthering diving safety. Decompression sickness (DCS) incidence rates for the scientific diving community have been documented as being lower by a factor of 10 than recreational diving and commercial diving (Lang and Vann, 1992). This is, in part, due to thorough medical, training and operational standards and programmatic supervision of relatively conservative diving activities. Safety considerations are of primary concern for the diving programs and regulations are promulgated by the underwater scientists who live by them. This community has also been proactive over the last 20 years in addressing diving physiological and operational questions that directly impact the safety and health of the scientific diver. The results of the scientific diving safety projects have benefited the recreational diving community in many ways as evidenced by the incorporation of consensus guidelines and operational practices into recreational diver training curricula and operations. Scientific research objectives, whether through mensurative or manipulative experiments, in many instances could not have been accomplished without scientific diving techniques, as evidenced in materials and methods sections of peer-reviewed published literature. At some point in the future, decompression, dive training, and medical issues may no longer be of major concern to scientists, as emerging technologies develop. In the mean time, many topics of current scientific interest, including marine biodiversity, coral reef health, sea-level change and global warming are to a large degree dependent on placing the trained scientific eye underwater to record, interpret and sample the underwater environment. The extreme environments of the polar regions are no exception and scientific and political interest in them for biological, geological, physical, commercial and sociological reasons continues to increase.

Diving safety programs can be generalized as fulfilling a two-fold purpose. The first being a research-support function, which assists the diving scientist with specialized underwater equipment, advice, and diver support to assist in fulfilling the scientific objectives of the diving project. The second is a risk management function that protects the safety and health of the individual scientist, and the employing organization from excessive liability exposure, by providing state-of-the-art diving equipment, breathing air, training and medical surveillance programs.

Ongoing scientific diving safety research has been conducted to consider a more effective means of decompression status monitoring using dive computers (Lang and Hamilton, 1989). Diving Control Boards approve specific makes and models of dive computers that may be used as a means of determining decompression status. Each diver relying on a dive computer to plan dives and indicate or determine decompression status must have his/her own unit and pass a practical and written training session. On any given dive, both divers in the buddy pair follow the most conservative dive computer. If the dive computer fails at any time during the dive, the dive is terminated and appropriate surfacing procedures are immediately initiated. A scientific diver is not allowed to dive for 18 hours before activating a dive computer to control his/her diving, and once in use, it is not switched off until complete outgasing has occurred. Multiple deep dives and/or decompression dives with dive computers require careful consideration.

An investigation of the slowing of ascent rates and performance of safety stops has provided scientific divers with a greater margin of decompression safety (Lang and Egstrom, 1990). Scientific divers are trained to slow and control their ascents, of which buoyancy compensation can be a significant problem yet is fundamental to safe diving practice. Before certification, the diver demonstrates proper buoyancy, weighting and a controlled ascent, including a "hovering" stop. Ascent rates are controlled at a maximum of 10 m/min from 20 m and are not to exceed 20 m/min from depth, at the rate specified for the make and model of dive computer being used. Scientific diving programs require a stop in the 3-10 msw zone for 3-5 minutes on every dive. Scientific divers using drysuits receive additional practical training in their use. Drysuits must have a hands-free exhaust valve and buoyancy compensators a reliable rapid exhaust valve that can be operated in a horizontal swimming position. A buoyancy compensator is required with dry suit use for ascent control and emergency flotation. In the case of a runaway ascent, breathing 100% oxygen above water is preferred to in-water air procedures for omitted decompression.

The next phase of this long-term scientific diving safety project was to consider multi-day, repetitive diving physiological aspects (Lang and Vann, 1992). Although diving is a relatively safe activity, all persons who dive must be aware that there is an inherent risk to this activity. In 1992, the risk of decompression sickness in the United States was estimated at 1-2 incidents per 1,000-2,000 dives for the commercial diving sector, 2 incidents per 10,000 dives for recreational diving activities and 1 incident in 100,000 dives for the scientific diving community. Scientific diving programs provide continuous training, recertification and dive site supervision, which helps maintain established safe diving protocols. Recreational divers, who may lack such direct supervision, need to be aware of staying within established protocols, especially when making repetitive dives over multiple days, in which the risk of DCS may be higher. Increasing knowledge regarding the incidence of DCS indicates that our ability to predict the onset of DCS on multi-level, multi-day diving is even less sensitive than our ability to predict DCS on single square-wave dives. There appears to be good evidence that there are many variables that can affect the probability of the occurrence of DCS symptoms. The ability to mitigate these variables through education, good supervision and training appears to be possible for hydration, fitness, rate of ascent, fatigue, etc., and are continuously promoted. Scientific divers are subject to a host of specific conditions, particularly in extreme environments, that may increase risk if precautions are not taken. There is adequate technical support for the use of enriched-air nitrox and surface-oxygen breathing in scientific diving where higher gas loadings are anticipated in multi-level, multi-day dives. We must continue to remember that DCS is generally recognized as a probabilistic event, which tends to predispose the scientific diving community towards a more conservative diving position.

The order of repetitive dive profiles was investigated, in part, because of the difficulty for scientific divers to adhere to the “dive progressively shallower” rule while on projects investigating coral reefs or polar benthos at varying transect depths (Lang and Lehner, 2000). More importantly, the genesis and physiological validity of the “dive deep first” rule was in need of examination. Historically, neither the U.S. Navy nor the commercial sector has prohibited reverse dive profiles. Reverse dive profiles are acknowledged as being performed in recreational, scientific, commercial, and military diving. The prohibition of reverse dive profiles by recreational training organizations cannot be traced to any definite diving experience that indicates an increased risk of DCS. There is no convincing evidence that reverse dive profiles within the no-decompression limits lead to a measurable increase in the risk of DCS. No reason was determined for the diving communities to prohibit reverse dive profiles for no-decompression dives less than 40 msw and depth differentials less than 12 msw.

b. Scientific diving under ice.

Lang, M.A., and R. Robbins. 2009. Scientific Diving Under Ice: A 40-Year Bipolar Research Tool. In: *Smithsonian at the Poles: Contributions to International Polar Year Science,* eds. Krupnik, I., M.A. Lang, and S.E. Miller, pp. 241-252. Washington, DC: Smithsonian Institution Scholarly Press.

This second paper described four decades of underwater research conducted in extreme environments under ice and the considerations for the physiological, equipment, training and operational procedures to effectively do so. This extreme environment diving is a specialized activity but ties in to the scientific diving safety and medical framework and in some projects takes advantage of the enriched air nitrox benefits described in the second paper.

Approximately four decades ago, scientists were first able to enter the undersea polar environment to make biological observations for a nominal period of time. Since my first Antarctic scientific dives logged in 1986, extreme environment diving under ice has captured my academic interests for a long time (Lang, 1987; Lang and Mitchell, 1988; Lang and Stewart, 1992; Lang and Sayer 2007). The conduct of underwater research in extreme environments requires special consideration of diving physiology, equipment design, diver training, and operational procedures, all of which enable this under-ice approach. The first Antarctic scientific dives in the 1961 were performed in wetsuits and double-hose regulators, without buoyancy compensators or submersible pressure gauges. Novel ice diving techniques developed since then have expanded the working envelope based on the scientific need to include the use of dive computers, enriched air nitrox, rebreather units, blue-water diving, and drysuit systems. The International Polar Diving Workshop in Svalbard promulgated consensus recommendations through the combined international, interdisciplinary expertise of participating polar diving scientists, equipment manufacturers, physiologists and decompression experts, and diving safety officers (Lang and Sayer, 2007). The National Science Foundation U.S. Antarctic Program scientific diving exposures in support of underwater research enjoy a remarkable safety record and high scientific productivity due to a significant allocation of logistical support and resources to ensure personnel safety. Over 15,000 ice dives have been logged since 1989, with only one minor case of suspected DCS reported.

This operational experience formed the foundation for further investigations into the current and future status of decompression monitoring through the use of dive computers, and the field evaluation project for ice-diving regulator performance and electrically-heated undergarments for drysuits.

c. Regulator performance in extreme environments.

Lang, M.A., and J.R. Clarke. Submitted. Performance of life support breathing apparatus for under-ice diving operations. *Diving Hyperb. Med.*

This third paper presented the results of a two-year under-ice performance evaluation study of engineering considerations and operational procedures that contributed to the probability of life-support equipment freeflow in extreme temperature environments.

Single-hose scuba regulators dived in very cold water have a probability of experiencing first- or second-stage malfunction yielding complete occlusion of air flow or massive freeflow that rapidly expends a diver's air supply, both conditions referred to as regulator “freeze-up”. Ice crystal build up in the regulator second stage can inhibit the valve from completely seating itself and is the main cause of freeflow. Principal factors contributing to ice crystallization in the regulator second stage include manufacturer's design, materials, and quality control, exhalant breath of diver, adiabatic gas expansion, mass flow, time, temperature, and water leakage into the second stage.

Seventeen divers logged a total of 305 dives in -1.86°C sea water under 6-m thick Antarctic fast ice over two field seasons in 2008 and 2009. Dive profiles had average depths of 38 msw and dive times of 29 min, including a mandatory 3-minute safety stop at 6 msw. Sixty-nine commercially available, unmodified regulator units (17 models) from 12 different manufacturers underwent standardized pre-dive regulator care and were randomly assigned to divers. Depths and times of onset of second-stage regulator flow were recorded. In 305 dives, there were 65 freeflows. The freeflows were not evenly distributed across the regulator brands. Regulator failure rates fell into two categories (<11% and >26%). The regulators classified for the purpose of the test as “better” (< 11% failure rate) suffered only 9 freeflows out of 146 exposures for a 6% overall freeflow incidence; and those classified as “worse” (> 26% failure rate) suffered 56 freeflows out of 159 exposures (35% freeflow incidence.) Testing on regulator models was aborted when freeflow incidence reached 40% (n=1), and 50% (n=3), which exceeded *a priori* stopping rules. Differences between categories of regulator freeflow incidence (better versus worse) were tested by the Chi-square test. The pooled incidences for the seven best performing regulators (DiveRite

Jetstream, Sherwood Maximus SRB3600, Poseidon Xstream Deep, Poseidon Jetstream, Sherwood Maximus SRB7600, Poseidon Cyklon, Mares USN22 Abyss) were compared to the ten remaining regulators. The differences between the groupings was significant at P<0.001. Regulator freeze-up is a probabilistic event; even the best regulators can fail under polar conditions. Nevertheless, some regulators seem better suited for that environment than others. Combined laboratory and field-testing, proper pre-dive regulator care, depth-dependent gas density control, breathing rate, and diver experience can influence freeze-up incidence.

The European testing standard EN250:2000 (Respiratory Equipment: Open-circuit self-contained compressed air diving apparatus. Requirements, Testing, Marking), for which the CE mark is given for cold water (<10°C) regulators, does not adequately replicate the harsh conditions (-2°C) of polar diving.

In the final consideration of USAP Diving Program regulator replacement acquisition, several subjective factors were also considered: regulator performance observations by test divers, ease of regulator maintenance and servicing, and manufacturer's support. The ejection of ice spicules from the second stage was a uniform, albeit subjective, objection from all project divers. The combination of laboratory (NEDU) and field testing (McMurdo) of ice-diving regulators points out that if a regulator does not freeflow at all under ice, it should be favorably received. If it also does not freeflow under severe NEDU test conditions, then it is very unlikely to cause air delivery problems for scientists under ice if the units are properly cared for. In conclusion, the 1991 Sherwood SRB3600 regulators must follow the path of the Royal Aquamaster double-hose ice-diving regulators that were retired from the USAP in 1990.

d. Enriched-Air Nitrox.

Lang, M.A. 2006. The state of oxygen-enriched air. *Diving Hyperb. Med.*, **36(2):** 87-93.

This fourth paper considered whether breathing compressed air under pressure was the ideal mixture of nitrogen and oxygen, and whether increased risk of decompression sickness was incurred with enriched-air nitrox (nitrox) use. It further asked if a maximum partial pressure of oxygen at 1.6 ATA was operationally acceptable, and whether carbon dioxide retention or oxygen toxicity posed a problem within the recreational and scientific diving operational envelope.

In 2000, the DAN Nitrox Workshop provided an industry-wide forum to objectively evaluate the available nitrox operational and physiological data, risk management, equipment, and training parameters. As with any emerging technology that has found a broader market appeal, controversies invariably arise and ignorance, myths, and misconceptions often fuel opposite views. This critical interdisciplinary examination of the current issues surrounding nitrox was in order to disseminate credible diving safety information.

Nitrox has been used in the scientific diving community since the 1970s. For entry-level, open-circuit nitrox diving, there is no evidence that shows an increased risk of DCS from the use of nitrox versus compressed air (Lang, 2001). A maximum PO_2 of 1.6 ATA is generally accepted based on the history of nitrox use and scientific studies. Routine CO_2 retention screening is not necessary for open-circuit recreational or scientific nitrox divers. Oxygen analyzers should use a controlled flow-sampling device for accurate mix analysis, which should be performed by the blender and/or dispenser and verified by the end user. Recreational training agencies and scientific diving programs recognize the effectiveness of nitrox dive computers. For recreational and scientific nitrox diving there is no need to track pulmonary or whole body oxygen toxicity (OTU-oxygen toxicity units or UPTD-units pulmonary toxicity dose), the "CNS Oxygen Clock" concept is taught based on NOAA oxygen exposure limits. However, it should be noted that CNS oxygen toxicity could occur suddenly and unexpectedly. Regarding nitrox compatible scuba equipment, the objective is to avoid incidental exposure to oxygen above 40%. Most nitrox mixes available through scuba shops is premixed at 32% (EAN_{32} with a maximum operating depth of 40 msw) or 36% (EAN_{36} with a maximum operating depth of 33 msw). Based on history of use, no evidence is available to show an unreasonable risk of fire or ignition when using up to 40% nitrox with standard scuba equipment. However, the level of risk is related to specific equipment configurations and the user should rely on manufacturer's recommendations.

Nitrox has vested itself as a mainstream recreational diving mode since it was first introduced to sport divers in 1985 by former NOAA Deputy Diving Officer Dick Rutkowski and it has been operational in the scientific diving community since first published in the NOAA Diving Manual by J. Morgan Wells in 1979 (Lang, 2006). Technical diving training organizations have offered nitrox programs and the mainstream recreational diving training associations now support nitrox programs in addition to their traditional open-circuit compressed air scuba programs. How safe nitrox was required an approximation of the magnitude of nitrox consumption. This seemed achievable by our ability to provide a denominator of nitrox divers and nitrox dives, as a sub-set of the overall level of recreational diving activity. Many other discussions of nitrox-related topics flowed from these numbers, *i.e.,* nitrox DCS incidence rates compared to air, and nitrox training and equipment sales growth. Physiological issues such as carbon dioxide retention and oxygen toxicity were also in need of critical examination and were determined to not pose a safety issue within the recreational and scientific diving contexts. Nitrox training and equipment issues were discussed to comprehensively address risk management and legal considerations regarding their use. The recreational diver is the ultimate beneficiary of our improved collective knowledge of the state of the art of nitrox diving (Lang, 2006). The intermediary beneficiaries of this information are the providers and manufacturers of nitrox products (instructors, equipment manufacturers, dive stores, and nitrox dispensers).

e. Dive computers.

Lang, M.A., and S.A. Angelini. 2009. The Future of Dive Computers. In: *The Future of Diving: 100 Years of Haldane and Beyond,* eds. Lang, M.A., and A.O. Brubakk, pp. 91-100. Washington, DC: Smithsonian Institution Scholarly Press.

This final paper acknowledged the effectiveness of dive computers in monitoring decompression status and provided a forward-looking perspective towards anticipated advances in dive computer technology.

Concern over the effects of cold on DCS have prevailed since the publication of the 1957 U.S. Navy dive tables that prescribed the next longer depth and time if a dive was particularly cold and arduous., a rather imprecise adjustment. Advances in equipment technology for diving in extreme environments relating to thermal protection and decompression monitoring obviate the need to dive cold or use table correction factors. The age of electronic diving has arrived with the development of the modern electronic dive computer as the most significant advancement in self-contained diving since the invention of the Aqualung by Jacques Cousteau. Twenty-five years after the modern-day dive computer was introduced, several key questions remain: effectiveness of the decompression models used, validation and human testing, acceptable risk, limitations, failures, and operational reliability. Existing decompression models incorporated into dive computers have employed a variety of approaches since Haldane’s original findings (Lang and Brubakk, 2009). Some models incorporate water temperature and/or work load as a variable. Educated predictions are offered on the functionality, features and configurations of future dive computer evolution based on benefits from advances in consumer electronics technology, and monitoring technology integrated into the dive computer algorithm that allows for a closer approximation of physiological parameters. Final remarks conclude with how advances in diving physiology research based mainly on Haldane’s original work in 1908 will shape the dive computer landscape of the future.

Electronic dive computers have for all practical purposes replaced dive tables in recreational and scientific diving and are increasingly implemented in particular segments of the military diving community. For the commercial diving industry and its standard operating methods of surface-supplied/controlled diving or saturation diving, a diver-worn dive computer's advantages in monitoring decompression status appear to be minimal. It would not be unreasonable to state that regardless of the number of algorithm variations incorporated in modern dive computers, they all appear to fall within an acceptable window of effectiveness based on available databases of pressure-related injuries for the recreational and scientific diving communities. It is also clear that neither tables nor dive computers can eliminate all decompression problems, but if utilized conservatively, computers have emerged as an important tool for the improvement of diver safety.

All things considered, the dive computer's functions of ascent rate monitoring, real-time computation of nitrogen balances, air consumption monitoring and profile downloading capability form a solid, reliable basis for advancements that will emerge in the future. Benefits from advances in consumer electronics technology will undoubtedly incorporate features such as high resolution color display, rechargeable battery, GPS receiver, underwater communication and navigation, and Emergency Position Indicating Radio Beacon (EPIRB.) Further, benefits from monitoring technology integrated in the dive computer algorithm will surely include heart rate monitoring, skin temperature measurements, oxygen saturation monitoring, and perhaps even inert gas bubble detection. We can only imagine the progress that John Scott Haldane's brilliant decompression insight would have made had the dive computer tools available to us now and in the future been available to him 100 years ago.

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10. List of Papers

PAPER 1.

The USA scientific diving medical and safety experience

Michael A Lang

Key words
Scientific diving, research, operations – diving, medicals – diving, standards, safety

Abstract

(Lang MA. The USA scientific diving medical and safety experience. *SPUMS J.* 2005; 35: 154-61.)
The scientific diving community has very effectively used scuba as a research tool for over 50 years, since the first programme was established at the Scripps Institution of Oceanography. Lang and Vann published decompression sickness incidence rates that were by a factor of 10 lower than those for recreational diving and commercial diving. This is, in part, due to thorough medical, training and operational standards and programmatic supervision of relatively conservative diving activities. Safety considerations are of primary concern for the diving programmes and regulations are promulgated by the underwater scientists who live by them. This community has also been proactive over the last 15 years in addressing physiological and operational questions related to diving that directly impact the safety and health of the scientific diver. The results of the scientific diving safety projects have benefited the recreational diving community in many ways as evidenced by the incorporation of consensus guidelines and operational practices into recreational diver training curricula and operations. Scientific research objectives, whether through mensurative or manipulative experiments, in many instances could not have been accomplished without scientific diving techniques, as evidenced in materials and methods sections of peer-reviewed published literature. At some point in the future, decompression, dive training, and medical issues may no longer be of major concern to scientists, as emerging technologies develop. In the meantime, the investigation of many topics of current scientific interest, including marine biodiversity, coral-reef health, sea-level change and global warming, largely depends on placing the trained scientific eye under water to sample, record and interpret the underwater environment.

Introduction

The purpose of a research diving project is the advancement of science. Scientific divers, by the very nature of their activities, use scientific expertise in studying the underwater environment and, therefore, are scientists or scientists-in-training. The tasks of a scientific diver are those of an observer and data gatherer who uses scuba diving as a research tool. Information and data resulting from a scientific project usually are disseminated in a technical document or peer-reviewed research publication. 'Scientific diving' is defined by the Department of Labor's Occupational Safety and Health Administration (OSHA) as "*diving performed solely as a necessary part of a scientific, research, or educational activity by employees whose sole purpose for diving is to perform scientific research tasks*."[1] Scientific diving does not include performing any tasks usually associated with commercial diving such as: placing or removing heavy objects under water; inspection of pipelines and similar objects; construction; demolition; cutting or welding; or the use of explosives.

The scientific diving programmes in the United States can be broadly categorised into three groups: those of research institutions (predominantly research); public and private universities, museums and aquaria (predominantly education and teaching, and research); and consulting companies (predominantly contractual environmental, geological and archaeological investigations). The current scientific diver population in the United States is estimated at 4,000 individuals. A minority of these are long-term, career scientific divers (e.g., federal employees, university professors) who may be considered in the average age category of 40+ years. At the university level, the turnover of scientific divers can be rather high as evidenced by undergraduate students enrolled in diving courses, research technicians on grant funds, or students in master's or doctoral programmes. This population tends to be in the age category of 18–34 years. An upper age limit for scientific diver certification does not exist; the lower limit is generally 18 years of age. Of the total scientific diver population, approximately one quarter is estimated to be female.

The American Academy of Underwater Sciences (AAUS) publishes *Standards for scientific diving certification and operation of scientific diving programs*.[2] The purposes of this document are to ensure that all scientific diving is conducted in a manner that will maximise protection of scientific divers from accidental injury and/or illness and to set forth standards for training and certification that will allow a working reciprocity between organisational member institutions that adhere to them. This document sets minimum standards for AAUS-recognised scientific diving programmes, the organisation and conduct of these programmes, and the basic regulations and procedures for safety in scientific diving operations. The AAUS standards are generally considered the standard of practice for scientific diving in the US.

Diving medical surveillance

The employer determines that scientific divers who are exposed to hyperbaric conditions have passed a current diving medical evaluation and have been declared by the examining physician to be medically fit to engage in diving activities as may be limited or restricted in the scientific diver medical certification. All medical evaluations are performed by, or under the direction of, a licensed physician of the applicant-diver's choice, preferably one trained in diving/undersea medicine. The diver must be free of any acute or chronic disabling disease or condition contained in the list of conditions by Bove for which restriction from diving may be recommended.[3] There currently are no fitness standards *per se* for scientific divers other than those imposed during the initial scientific diver training course, which include in-water time/distance parameters for swimming, or a stress tolerance test prescribed by a physician based on coronary artery disease risk-factor screening.

Medical evaluations are completed before a diver may begin diving; thereafter, at five-year intervals up to the age of 40, every three years after age 40, and every two years after age 60 (Table 1). Any major injury or illness, or any condition requiring hospital care requires diving medical clearance. If the injury or illness is pressure related, the clearance to return to diving must be performed by a physician trained in diving medicine. Diving medical evaluations conducted initially and at the interval frequency specified above consist of the following: a diving medical history, a diving medical examination, and completion of a scientific diver medical certification by the examining physician.

Diver training

SCIENTIFIC DIVING AUTHORISATIONS

There are three types of scientific diving authorisations.

Diver-in-Training

This authorisation signifies that the diver has completed entry-level training requirements through a nationally or internationally recognised scuba certification agency (e.g., PADI, NAUI, SSI, BSAC) or scientific diving programme.

Scientific Diver

This certification is a permit to dive with compressed air within no-decompression limits of current US Navy dive tables or, if using an approved dive computer, within no-decompression limits specified by the dive-computer manufacturer. This permit is valid only while it is current and for the depth and specialty intended (see below).

Temporary Diver

This authorisation is issued only following a demonstration of the required proficiency in diving and if the person in question can contribute measurably to a planned dive. Temporary diver authorisation is restricted to the planned diving operation under the host institution's auspices and complies with all other scientific diving policies, regulations and standards, including medical requirements.

DEPTH CERTIFICATIONS

The scientific diving community has long adhered to a proven experience-accumulation schedule. Depth certifications provide a mechanism by which diving experience may be gathered incrementally. The Scientific Diver certification authorises the holder to dive to a specific depth as indicated on the approved dive plan. A diver shall not exceed his/her depth certification, unless accompanied by a diver certified to a greater depth. Under these

Table 1
Laboratory requirements for diving medical evaluations and intervals (ECG – electrocardiogram)

	Initial examination Age in years		**Re-examination intervals Age in years (interval)**		
	< 40	**> 40**	**< 40 (5 yrs)**	**> 40 (3 yrs)**	**> 60 (2 yrs)**
Medical history	X	X	X	X	X
Physical exam (emphasis on CNS and otological components)	X	X	X	X	X
Chest X-ray	X	X			
Resting EKG	n/a	X			
Spirometry	X	X			
Haematocrit or haemoglobin	X	X	X	X	X
Urinalysis	X	X	X	X	X
Any further tests deemed necessary	X	X	X	X	X
Coronary artery disease risk-factor assessment including lipid profile and diabetic screening	n/a	X	n/a	X	X
Exercise stress testing (if indicated by risk-factor analysis)	n/a	X	n/a	X	X
Resting ECG	n/a	n/a	n/a	X	X

circumstances the diver may not exceed his/her depth limit by more than one step. Diving with compressed air is not permitted beyond a depth of 58 metres' sea water (msw).

- Certification to depth of 9 msw – This is the initial certification, approved upon the successful completion of the Scientific Diver training.
- Certification to depth of 18 msw – A diver holding a 9 msw certification card may be certified to a depth of 18 msw after successfully completing, under the supervision of a scientific diver certified to that depth or greater, 12 logged training dives to depths between 10 and 18 msw, for a minimum total time of four hours.
- Certification to depths of 30 msw and 40 msw – A diver holding a 18 msw certification may be certified to depths of 30 and 40 msw respectively, by logging four dives near the maximum depth, and successfully completing an approved check-out dive.
- Certification to depths over 40 msw – A diver may be certified to depths of 45 and 58 msw by logging four dives near each depth, and successfully completing an approved check-out dive.

Dives are planned and executed under the close supervision of a scientific diver certified to these depths. The diver also needs to demonstrate knowledge of the special problems of deep diving, and of special safety requirements.

DIVING SPECIALTIES

Diving specialties require additional training and approval. Scientific Diver certification is a prerequisite for engaging in the following specialties: decompression diving, surface-supplied diving, mixed-gas or oxygen-enriched air (nitrox) diving, semi- or closed-circuit rebreather diving, lock-out and saturation diving, blue-water diving, drysuit diving, overhead environment (ice, cave or wreck) diving, altitude diving, and diving with dive computers as the sole source for monitoring decompression status.

SWIMMING EVALUATION

The applicant for training performs the following tests, or their equivalent, without swim aids:

- underwater swim for a distance of 25 m without surfacing
- 400-metre swim in less than 12 minutes
- 10-minute water tread (or two minutes without the use of hands
- transport of another person of equal size for a distance of 25 m in the water.

SCIENTIFIC DIVER TRAINING

The 100-hour Scientific Diver training course consists of theoretical training, practical skills training in confined water, and completion of 12 supervised open-water dives in a variety of dive sites for a minimum cumulative bottom time of six hours.

CONTINUATION OF CERTIFICATION

During any 12-month period, each certified scientific diver must log a minimum of 12 dives, including two dives within the certified depth range. Divers certified to 48 msw or deeper may satisfy these requirements with dives over 40 msw. If no dive is made for a six-month period, a check-out dive must be made. Once the initial Scientific Diver certification requirements are met, divers whose depth certification has lapsed due to lack of activity may be requalified. If a scientific diver's certification expires, is suspended or revoked, he/she may be recertified after complying with such conditions as the scientific diving programme may impose.

Operational procedures

DIVING SUPERVISION

Diving Officer (DO)

The DO has full responsibility and accountability to the Diving Control Board (DCB) in all operational, diving and safety matters. The DO is appointed by the appropriate administrator on the recommendation of the DCB; is a certified scientific diver; is certified by a nationally recognised scuba certification agency to teach basic and advanced scuba diving courses; and, is responsible for the conduct of the diving programme. The DO also oversees scientific diving activities, and ensures compliance with all diving policies, requirements and procedures established in the diving safety manual. The DO is responsible for maintaining diver and medical certification records and dive logs, and has the unilateral authority to suspend diving operations or scientific divers whose diving activities he/she considers unsafe and refer such actions to the DCB.

Lead Diver

For each dive, one scientist is designated as the Lead Diver, who is present at the dive location during the entire diving operation. The Lead Diver is responsible for coordination, briefing, dive planning, and emergency equipment and procedures.

Individual scientific diver's responsibilities

The scientist initially submits a Scientific Diver application to the DO and obtains a Scientific Diver medical certification. The scientist must maintain him/herself in good physical condition and at a high level of diving proficiency commensurate with the frequency, scope, and type of diving activity being undertaken. The individual has the right to refuse to dive if in his/her judgment the conditions are unsafe or unfavourable for the type of diving operations planned; for any reason he/she believes his/her diving participation might jeopardise human life; he/she is not in proper physical or mental condition; and/or, he/she believes the scuba equipment to be used is faulty.

Each scientific diver receives current emergency-care training, has maintenance performed on their scuba equipment annually and conducts a pre-dive functional check of diving equipment. The diver is responsible for terminating the dive while there is sufficient cylinder pressure to permit a safe ascent to the surface, including a safety stop. The diver submits a dive plan for DO approval prior to engaging in any diving activity. Dive log sheets or dive files from down-loading dive computers are periodically submitted to the DO to monitor diving activities. The ultimate responsibility for personal safety and compliance with the diving safety manual regarding a planned diving operation is borne by the diver.

DIVING EQUIPMENT

Each scientific diver wears the following equipment: mask and fins (snorkel is optional), regulator and alternate breathing source, scuba cylinder, underwater timing device, depth indicator and pressure gauge. An approved dive computer is authorised after the diver receives training in its use and is preferable to monitoring decompression status with dive tables. A buoyancy compensator that provides the diver with the capability of attaining and maintaining positive buoyancy is equipped with a low-pressure power inflator. A dive knife, sharp enough to cut through monofilament line, and appropriate thermal insulation must also be worn.

DIVING PROCEDURES

All scientific diving is planned and executed in such a manner as to ensure that every diver maintains constant, effective communication with at least one other comparably equipped, certified scientific diver in the water. This buddy system is based upon mutual assistance, especially in the case of an emergency. If loss of effective communication occurs within a buddy team, all divers surface and re-establish contact. A dive flag is displayed prominently whenever diving is conducted.

Scientific diving is not conducted unless procedures have been established for emergency evacuation of the diver(s) to a hyperbaric chamber or appropriate medical facility, and these procedures have been approved by the DO. Emergency-care training (CPR, oxygen administration, first aid, field neurological evaluation and dive rescue) is requisite for Scientific Diver certification. First-aid and emergency oxygen kits are present at the dive location. Hyperbaric chambers, as a rule, are not required to be in close proximity to the diving operation. Where an enclosed or confined space is not large enough for two divers, a diver is stationed at the underwater point of entry and an orientation line is used.

In the case of an asymptomatic diver diving within the US Navy tables or dive computer no-decompression limits during the previous 48 hours, there should be a minimum 12-hour delay prior to flying. The longer the diver delays an ascent to altitude, the lower the probability of onset of symptoms of decompression sickness (DCS).

Scientific dives are planned around the competency of the least experienced diver. Before conducting diving operations, the Lead Diver for a proposed project submits to the DO a dive plan for approval that lists all divers' qualifications, emergency contact information, an emergency plan, the nearest hyperbaric chamber location and method of transport to be used, the Divers Alert Network (DAN) emergency phone number, the location and approximate number of proposed dives (including estimated depths and bottom times), the proposed work, equipment and boats to be employed, and any hazardous conditions anticipated.

Scientists log dives made under the auspices of their employer and the logs are periodically submitted to the DO for review. If pressure-related injuries are suspected, or if symptoms are evident, the following additional information is recorded and retained by the DO with the record of the dive for a period of five years: complete accident report, description of symptoms (including depth and time of onset) and description and results of treatment. The DO maintains permanent records for each scientific diver certified and retains the following: scientific diver medical certifications (five years), records of dives (one year, except five years where there has been an incident of pressure-related injury), pressure-related injury assessment (five years) and equipment maintenance records (current entry).

All diving accidents requiring recompression or resulting in moderate or serious injury are reported to the DO. The DCB records and reports occupational injuries and illnesses as established by OSHA: the occurrence of any diving-related injury or illness that requires any dive team member to be hospitalised for 24 hours or more, or after an episode of unconsciousness related to diving activity, or after treatment in a recompression chamber following a diving accident.

COMPRESSOR SYSTEMS AND BREATHING-AIR QUALITY

Gas analyses and air tests are performed on each breathing-air compressor at regular intervals of no more than six months. The results of these tests are entered into a log by the DO who also records hours of operation, repair, overhaul, filter maintenance and temperature adjustment for each compressor. Breathing air for scuba meets the Grade E specifications as set forth by the Compressed Gas Association (CGA Pamphlet G-7.1) and referenced in OSHA 29 CFR 1910.134 (Table 2).

Low-pressure compressors used to supply air to the diver are equipped with a volume tank with a check valve on the inlet side, a pressure gauge, a relief valve and a drain valve.

Table 2
Compressed Gas Association Grade E specifications for scuba breathing-air quality (THC – total hydrocarbon content; ppm – parts per 10^6)

Component	Specification
Maximum O_2	20–22%
Maximum CO_2	500 ppm
Maximum CO	10 ppm
THC	25 ppm
Water vapour	67 ppm
Dew point	-50 °Fahrenheit
Condensed hydrocarbons	5 $mg.m^{-3}$
Odours	None

Compressed-air systems over 500 psig (34 bar gauge) have slow-opening shut-off valves and all air-compressor intakes must be located away from areas containing exhaust fumes or other contaminants. These compressors are operated and maintained according to the manufacturer's specifications.

Equipment used with oxygen or mixtures containing over forty per cent (40%) by volume oxygen are designed, dedicated and maintained for oxygen service. Components exposed to oxygen or mixtures containing over forty per cent (40%) by volume oxygen are cleaned of flammable materials before being placed into service. Oxygen systems over 125 psig (8.5 bar gauge) must be equipped with slow-opening shut-off valves.

Scientific diving safety

The scientific diving community has a traditionally proactive record of furthering diving safety. The first scientific diving safety programme was established at the Scripps Institution of Oceanography in 1954 in preparation for the Capricorn Expedition to the South Pacific. This programme pre-dated the national recreational scuba training agencies by five years. Most scientific diving programmes today trace their ancestry to common elements of the original Scripps diving programme.

Diving safety programmes can be generalised as fulfilling two purposes. The first being a research-support function, which assists the diving scientist with specialised underwater equipment, advice, and diver support to assist in fulfilling the scientific objectives of the diving project. The second is a risk-management function that protects the safety and health of the individual scientist, and the employing organisation from excessive liability exposure, by providing state-of-the-art diving equipment, breathing air, training and medical surveillance programmes.

More recently, ongoing scientific diving safety research has been conducted to consider a more effective means of monitoring decompression status using dive computers.[4] DCBs approve specific makes and models of dive computers that may be used as a means of determining decompression status. Each diver relying on a dive computer to plan dives and indicate or determine decompression status must have his/her own unit and pass a practical and written training session. On any given dive, both divers in the buddy pair follow the most conservative dive computer. If the dive computer fails at any time during the dive, the dive is terminated and appropriate surfacing procedures are immediately initiated. After such a failure, a scientific diver is not allowed to dive for 18 hours before activating a dive computer to control his/her diving and, once in use, it is not switched off until complete out-gassing has occurred. Multiple deep dives and/or decompression dives with dive computers require careful consideration.

Lang and Egstrom investigated the slowing of ascent rates and the performance of safety stops to provide scientific divers with a greater margin of decompression safety.[5] It has long been the position of the American Academy of Underwater Sciences that the ultimate responsibility for safety rests with the individual diver. Scientific divers are trained to slow and control their ascents, of which buoyancy compensation can be a significant problem. This is fundamental to safe diving practice. Before certification, the diver demonstrates proper buoyancy, weighting and a controlled ascent, including a 'hovering' stop. Ascent rates are controlled at a maximum of 9 $msw.min^{-1}$ from 18 msw and are not to exceed 18 $msw.min^{-1}$ from depth, at the rate specified for the make and model of dive computer or table being used. Scientific diving programmes require a stop in the 3–9 msw zone for three to five minutes on every dive.

Scientific divers using drysuits receive additional practical training in their use. Drysuits must have a hands-free exhaust valve and buoyancy compensators a reliable rapid exhaust valve that can be operated in a horizontal swimming position. A buoyancy compensator is required with drysuit use for ascent control and emergency flotation. In the case of a runaway ascent, breathing 100% oxygen above water is preferred to in-water air procedures for omitted decompression.

The next phase of this scientific diving safety project was the consideration of the physiological aspects of multi-day, repetitive diving.[6] Although diving is a relatively safe activity, all persons who dive must be aware that there is an inherent risk to this activity. In 1992, the risk of decompression illness in the United States was estimated at one to two incidents per 1,000–2,000 dives for the commercial diving sector, two incidents per 10,000 dives for recreational diving activities and 1 incident in 100,000 dives for the scientific diving community. Scientific diving programmes provide continuous training, recertification and dive-site supervision, which help to maintain established safe diving protocols (Table 3). Recreational divers, who may lack such direct supervision, need to be aware of their need to stay within established protocols, especially when making repetitive dives over multiple days, during which the risk of DCS may be higher.

Table 3
2003 summary of scientific diving of the American Academy of Underwater Medicine

	Total scientific dives			
Organisations	**Dives**	**Minutes**	**Divers**	**Incidents**
76	104,921	4,133,207	4,478	2

	Dives by depth range		
Depth (msw)	**Dives**	**Divers**	**Incidents**
0–9	65,355	2,508	1
9–18	28,650	1,881	0
18–30	8,650	985	1
30–39	1,524	451	0
39–45	459	103	0
45–57	147	54	0
57+	136	28	0

	Dives	**Minutes**	**Divers**	**Incidents**
Dives by classification				
Scientific	90,014	3,695,919	3,032	2
Training/ proficiency	14,907	437,288	1,809	0
Dives by mode				
Open circuit	95,492	3,737,229	3,742	2
Hookah	5,949	313,190	415	0
SSBA	3,035	70,192	194	0
Rebreather	445	12,596	31	0
Dives by breathing gas				
Air	95,295	3,701,615	3,708	1
Nitrox	9,470	420,276	770	1
Mixed gas	156	11,316	27	0
Dives by planning method				
Dive tables	47,993	1,803,510	1,852	1
Dive computer	48,345	2,131,931	2,160	1
PC-based software	107	7,357	20	0
Dives by specialty				
Decompression	435	40,520	75	0
Overhead	600	28,790	78	1
Blue water	366	12,027	80	0
Ice/polar	708	22,730	80	0
Dives during saturation	179	28,318	11	0
Aquarium	44,389	1,043,435	868	0

Table 4
Data set submitted to OSHA covering years 1965–1981, leading to exemption of scientific diving from commercial diving regulations

Scientific diving		
Certified scientific divers		5,441
Dives to depth	10 m	172,546
	20 m	154,751
	30 m	40,199
	40 m	7,002
	50 m	3,202
	60 m	917
	60 m+	40
Total no. dives		380,295
No. decompression dives		1,638
No. pressure accidents		18
No. deaths		4
Scuba diving training		
No. classes		835
No. trainees		18,421
No. training hours		242,979
No. training dives		57,886
Max. training depth (m)		60
No. certified scuba divers		13,786
Programmes with decompression chamber		4

Increasing knowledge regarding the incidence of DCS indicates that our ability to predict the onset of DCS on multi-level, multi-day diving is even less sensitive than our ability to predict DCS on single square-wave dives. There appears to be good evidence that there are many variables that can affect the probability of the occurrence of DCS symptoms. The ability to mitigate these variables through education, good supervision and training appears to be possible for variables such as dehydration, lack of fitness, rapid ascents, undue fatigue, etc., and preventive measures to minimise these factors are continuously promoted. Scientific divers are subject to a host of specific conditions that may increase risk if precautions are not taken. There is adequate technical support for the use of oxygen-enriched air (nitrox) and surface-oxygen breathing in scientific diving where higher gas loadings are anticipated in multi-level, multi-day dives. We must continue to remember that DCS is generally recognised as a probabilistic event, which tends to lean the scientific diving community towards a more conservative diving position.

The scientific diving safety record is remarkably clean. The national scientific diving statistics snapshot of 2003 (Table 3) is representative of the period from 1981–2003. The data set submitted to OSHA that resulted in the scientific diving exemption from commercial diving regulations covered the years 1965–1981 (Table 4). Eighty-eight diving programmes submitted information to the national scuba safety survey conducted at that time through UCLA.

A comparative analysis of pre-and post-1980s diving incidents becomes increasingly difficult due to the lack of descriptive data and the changing 'incident' collection parameters. 'Pressure accidents' from before the 1980s do not solely represent the number of DCS presentations, but also include incidents of other reported barotrauma. That period possibly also represents a significant amount of under-reporting of mild DCS, a period when mild aches and pains associated with diving were accepted as minor miseries of life. Since the early 1980s, scuba divers have been oversensitized to recognition of DCS signs and symptoms, resulting in a significant emphasis on diving safety training in CPR, field neurological examinations, first aid, and oxygen administration. The early reporting of potential DCS and activation of emergency plans coupled with oxygen administration unquestionably results in high percentages of resolution. However, once a diver enters the decision-making tree, it is difficult to extract the number of cases of non-DCS, because invariably they end up at the chamber where precautionary treatment is more often than not provided. This results in over-reporting of DCS cases. Scientific diving DCS data collection criteria need to be refined for a better approximation of rates. No detailed information is available on the four deaths from 1965–1981. Since 1981, there have been at least three scientific diving deaths under the following circumstances: blue-water diving, under-ice diving, and missed decompression.

After 50 years, the DCS rate of 1:100,000 continues to appear acceptable within the scientific diving community. Compared with other sectors of the diving community, the recreational diving profiles most closely resemble those of scientific diving. However, the scientific diving incident rates are an order of magnitude lower, and we attribute this to thorough entry-level and continued training and supervision, and controlled medical and operational procedures. Incident rates in military and commercial diving communities are much higher, but, taking into account the commensurately riskier profiles, are efficiently handled with on-site chambers and diving medical personnel.

The order of dive profiles was investigated by Lang and Lehner, in part because of the difficulty for scientific divers to adhere to the 'dive progressively shallower' rule while on projects investigating coral reefs at varying transect depths.[7] More importantly, the genesis and physiological validity of the 'dive deep first' rule was in need of examination. Historically, neither the US Navy nor the commercial sector has prohibited reverse dive profiles. Reverse dive profiles are acknowledged as being performed in recreational, scientific, commercial and military diving. The prohibition of reverse dive profiles by recreational training organisations cannot be traced to any definite diving experience that indicates an increased risk of DCS. There is no convincing evidence that reverse dive profiles within the no-decompression limits lead to a measurable increase in the risk of DCS. Lang and Lehner found no reason for the diving communities to prohibit reverse dive profiles for no-decompression dives less than 40 msw and depth differentials less than 12 msw.

Oxygen-enriched air (nitrox) has been used in the scientific diving community since the early 1970s. Lang reports for entry-level, open-circuit nitrox diving, that there is no evidence that shows an increased risk of DCS with the use of oxygen-enriched air (nitrox) versus compressed air.[8] A maximum PO_2 of 162 kPa (1.6 ATA) is generally accepted based on the history of nitrox use and scientific studies. Routine carbon dioxide retention screening is not necessary for open-circuit, recreational nitrox divers. Oxygen analysers should use a controlled flow-sampling device for accurate mix analysis, which should be performed by the blender and/or dispenser and verified by the end user. Training agencies recognise the effectiveness of nitrox dive computers. For recreational diving with oxygen-enriched air, there is no need to track whole-body exposure to oxygen (e.g., oxygen toxicity units or unit pulmonary toxic dose); the 'CNS oxygen clock' concept is taught instead, based on NOAA oxygen exposure limits.[9] However, it should be noted that CNS oxygen toxicity could occur suddenly and unexpectedly. Based on history of use, no evidence is available to show an unreasonable risk of fire or ignition when using up to 40% nitrox with standard scuba equipment. The level of risk is related to specific equipment configurations and the user should rely on manufacturer's recommendations.

Operational guidelines for remote scientific diving operations were promulgated on a consensual basis by the senior practising scientific divers for blue-water diving by Heine, and polar diving operations by Lang and Stewart.[10,11]

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PAPER 2.

A Selection from

Smithsonian at the Poles

Contributions to International Polar Year Science

Igor Krupnik, Michael A. Lang,
and Scott E. Miller
Editors

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Scientific Diving Under Ice: A 40-Year Bipolar Research Tool

Michael A. Lang and Rob Robbins

ABSTRACT. Approximately four decades ago, scientists were first able to enter the undersea polar environment to make biological observations for a nominal period of time. The conduct of underwater research in extreme environments requires special consideration of diving physiology, equipment design, diver training, and operational procedures, all of which enable this under-ice approach. Since those first ice dives in wetsuits and double-hose regulators without buoyancy compensators or submersible pressure gauges, novel ice diving techniques have expanded the working envelope based on scientific need to include the use of dive computers, oxygen-enriched air, rebreather units, bluewater diving, and drysuit systems. The 2007 International Polar Diving Workshop in Svalbard promulgated consensus polar diving recommendations through the combined international, interdisciplinary expertise of participating polar diving scientists, equipment manufacturers, physiologists and decompression experts, and diving safety officers. The National Science Foundation U.S. Antarctic Program scientific diving exposures, in support of underwater research, enjoy a remarkable safety record and high scientific productivity due to a significant allocation of logistical support and resources to ensure personnel safety.

INTRODUCTION

Milestones of U.S. Antarctic diving activities (Table 1) start with the first dive by Americans in Antarctic waters made just after New Year's Day in 1947 as part of Operation Highjump, the United States' first major postwar Antarctic venture. Lieutenant Commander Tommy Thompson and a Chief Dixon used "Jack Brown" masks and Desco® oxygen rebreathers. Early scuba divers braved McMurdo Sound's −1.8°C water with wetsuits and double-hose regulators. Equipment advances since then have led to the use of variable volume drysuits, buoyancy compensators (BCs), and dive computers. Because of their resistance to freezing, however, double-hose regulators were used almost exclusively in the McMurdo area from 1963 until 1990. Since then, single-hose regulators that also resist freeze-up failure have been used. From 1947 to 1967, research diving operations fell under the control of the U.S. Naval Support Force Antarctica and divers adhered to established U.S. Navy diving regulations. In 1967, James R. Stewart, Scripps Institution of Oceanography diving officer, established guidelines for the conduct of research diving in the polar

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TABLE 1. Milestones of USAP Dive Program (adapted from Brueggeman, 2003).

Date(s)	Milestone
1947	First dive by Americans in Antarctic waters, LCDR Thompson and Chief Dixon, as part of Operation Highjump, using Jack Brown masks and Desco oxygen rebreathers
1951	First Antarctic open-circuit scuba dive
1947–1967	Research diving operations under USN Support Force, Antarctica
1961–1962	Verne E. Peckham (Donald E. Wohlschlag project, Stanford University) logged 35 science dives tended topside on occasion by Arthur Devries and Gerry Kooyman
1962–1963	John S. Bunt (Donald E. Wohlschlag project, Stanford University) logged 7 science dives
1963–1964	G. Carleton Ray (New York Zoological Society), Elmer T. Feltz and David O. Lavallee logged 10 scuba dives
1963–1964	Gerald Kooyman started diving under ice with Weddell Seals with Paul K. Dayton tending topside
1963–1964	Willard I. Simmonds (Jacques S. Zaneveld project, Old Dominion University) logged 45 tethered science dives
1964–1965	Gerry Kooyman, Jack K. Fletcher and James M. Curtis logged 71 science dives
1965–1966	David M. Bresnahan (NSF OPP) and Leonard L. Nero dived on Zaneveld's project
1965–1966	G. Carleton Ray, Michael A. deCamp, and David O. Lavallee diving with Weddell seals
1967	NSF-SIO agreement for polar research diving (James R. Stewart)
1968	Paul K. Dayton benthic ecology project divers Charles Gault, Gerry Kooyman, Gordon Robilliard. Dayton has logged over 500 hundred dives under McMurdo ice
1978–1979	Dry Valley Lake diving: George F. Simmons, Bruce C. Parker and Dale T. Andersen
1987	USAP Guidelines for Conduct of Research Diving
1990	Double-hose regulators phased out in favor of single-hose regulators.
1992	AAUS Polar Diving Workshop (Lang, M.A and J.R. Stewart, eds.)
1995	RPSC on-site Scientific Diving Coordinator (Rob Robbins)
2001	NSF-Smithsonian Interagency Agreement for polar research diving (Michael A. Lang)
2003–2007	Svalbard ice diving courses (Michael A. Lang)
2007	International Polar Diving Workshop, Svalbard (M.A. Lang and M.D.J. Sayer, eds.)
2008	Smithsonian/NSF ice-diving regulator evaluation project, McMurdo (Michael A. Lang, P. I.)

regions for the National Science Foundation (NSF) Office of Polar Programs (OPP). Since 1995, Rob Robbins, Raytheon Polar Services Company, has served as onsite scientific diving coordinator. In 2001, Michael A. Lang, director of the Smithsonian Scientific Diving Program, enacted an Interagency Agreement between the Smithsonian Institution and the NSF for the management of the U.S. Antarctic Program (USAP) scientific diving program. As NSF OPP Diving Safety Officer (DSO), these responsibilities include, with the USAP Diving Control Board, promulgation of diving safety standards and procedures, evaluation and training of prospective divers, and authorization of dive plans. The USAP *Standards for the Conduct of Scientific Diving* (USAP, 1991) references the scientific diving standards published by the American Academy of Underwater Sciences (AAUS). Approximately half of the Principal Investigators (Table 2) are employees of AAUS organizational member institutions. The USAP researchers understand that polar diving demands the acceptance of responsibility for an increased level of risk and diver preparation. Polar conditions are more rigorous and demanding of scientific divers and their equipment than most other diving environments.

Approximately 36 scientists dive each year through USAP and have logged more than 11,400 scientific ice dives since 1989 (Figure 1). Average dive times are 45 minutes; generally, no more than two dives are made per day within the no-decompression limits. The USAP scientific diving authorization process requires submission of information on diver training and history, depth certification, diving first aid training (Lang et al., 2007) and drysuit experience. Minimum qualification criteria for NSF diving authorization include: (a) a one-year diving certification; (b) 50 logged open-water dives; (c) 15 logged drysuit dives; and, (d) 10 logged drysuit dives in the past six months. Somers (1988) described ice diver training curricula considerations. A pre-dive orientation and checkout dive(s) are done on site to ensure that the diver exhibits a satisfactory level of comfort under the ice with their equipment. Divers new to the Antarctic program are usually accompanying experienced Antarctic research teams and are thus mentored in an "apprentice" mode. However, divers must

TABLE 2. Principal Investigators and Co-PIs of USAP diving projects (1989–2006).

Investigator	Project
Amsler, C.	University of Alabama, Birmingham*
Baker, W.	Florida Institute of Technology/University of South Florida*
Barry, J.	Monterey Bay Aquarium Research Institute*
Bosch, I.	SUNY-Geneseo
Bowser, S.	NY Dept. of Health-Wadsworth Center
Conlan, K.	Canadian Museum of Natural History
Davis, R.	Texas A&M University*
Dayton, P.	Scripps Institution of Oceanography*
DeVries, A.	University of Illinois-Urbana
Doran, P.	University of Illinois-Chicago
Dunton, K.	University of Texas-Austin*
Harbison, R.	Woods Hole Oceanographic Institution*
Kaiser, H.	N/A
Kennicutt, M.	University of Texas-Austin*
Kim, S.	Moss Landing Marine Laboratories*
Kooyman, G.	Scripps Institution of Oceanography*
Kvitek, R.	California State University, Monterey Bay
Lang, M.	Smithsonian Institution*
Lenihan, H.	University of North Carolina*
Madin, L.	Woods Hole Oceanographic Institution*
Manahan, D.	University of Southern California*
Marsh, A.	University of Delaware
McClintock, J.	University of Alabama, Birmingham*
McFeters, G.	Montana State University
Miller, M.	Exploratorium, San Francisco
Moran, A.	Clemson University
Oliver, J.	Moss Landing Marine Laboratories*
Pearse, J.	University of California, Santa Cruz*
Ponganis, P.	Scripps Institution of Oceanography*
Quetin, L.	University of California, Santa Barbara*
Torres, J.	University of South Florida*
Wharton, R.	University of Nevada-Desert Research Institute
Wu, N.	Mo Yung Productions

*AAUS organizational member institution.

become proficient with the gear and techniques they will be using prior to deployment.

THE POLAR DIVING ENVIRONMENT

ICE FORMATION

Ice crystallization begins at the air-sea interface where the temperature differential is greatest. Because the air may be as much as 50°C colder than the water, heat conduction to the air from the water promotes the formation of ice. Under calm conditions, this *congelation* ice is composed of needles, small disks, and dendritic stars and will form a smooth sheet over the sea. When the freezing sea is subjected to wind and wave action, frazil ice crystals clump together into *pancake ice* (0.5 m to 2 m in diameter) that consists of roughly circular, porous slabs with upturned edges. If the water between them freezes, the "pancakes" may solidify and join together. Otherwise, pancake ice continually interacts with wind, waves, and other ice to create complex, many-layered floes of pack ice. When the ice sheet, whether congelation or frazil ice in origin, becomes a solid surface joined to the shoreline, it forms *fast ice*. Once the ice sheet is established, it continues to grow from beneath. Low-density seawater emanating from beneath ice shelves and floating glaciers undergoes adiabatic supercooling. *Platelet* ice crystals form in this supercooled water and float upward, accumulating in an initially loose and porous layer at the bottom of the surface ice sheet. This unfrozen platelet layer (1 cm to several m thick) continually solidifies by freezing, increasing the thickness of the ice sheet. The platelet layer forms a substrate for the

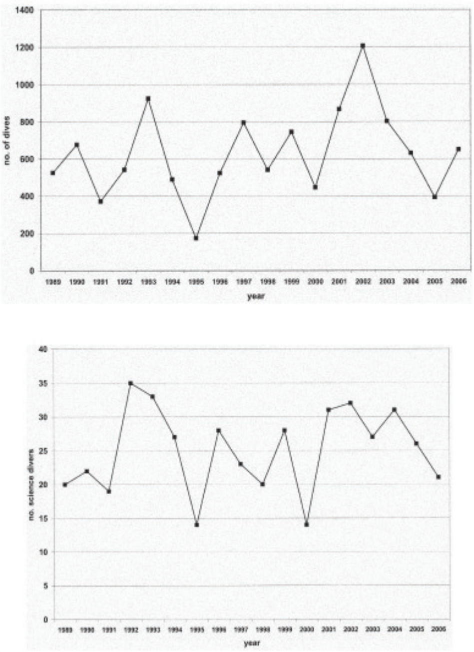

FIGURE 1. (top) USAP dive summary, 1989–2006. (bottom) USAP authorized diver summary, 1989–2006.

growth of microbial communities dominated by microalgae fed upon by amphipods and ice fish. Ice may also crystallize on the benthos. This *anchor ice* generally forms at depths of 15 m or less, attaching to rocks and debris—and even to live invertebrates. If enough ice forms on these objects, they will float up and may become incorporated into the ice sheet.

FAST ICE

Diving conditions are usually associated with solid fast-ice cover for most of the austral diving season at McMurdo Station (annual average thickness 2 m, multiyear 4 m), limited freezing at Palmer Station (under 30 cm), periodically in the Svalbard fjords (average 1 m), and the perennially ice-covered Dry Valley lakes (greater than 6 m; Andersen, 2007). A solid fast-ice cover provides a calm, surge-free diving environment and offers a stable working platform with no surface wave action. Fast-ice strength and thickness varies with time of year and ambient temperature affecting diving operational support. The under-ice topography varies dramatically at dive site, time of year, microalgal activity, ocean current, age of ice, and other oceanographic and physical factors. When viewed from below, a fast-ice sheet may appear relatively homogenous as a hard, flat surface but in places can be punctuated by cracks and openings that appear as bright lines in an otherwise dark roof. If platelet ice is present, the underside of the ice appears rough and uneven. Areas of multiyear ice and thick snow cover are darker. Where pressure ridges and tidal cracks are present, the under-ice topography has more relief. Large and small chunks of broken ice may jut down into the water column in profusion, creating an environment reminiscent of cave diving. *Brine channels* or *ice stalactites* form as seawater cools and freezes and salt is excluded. This salt forms a supercooled brine solution that sinks because of its increased density and freezes the seawater around it resulting in a thin, hollow tube of ice stretching down from the underside of the ice sheet. These brine channels can reach several m in length and may appear singly or in clusters.

PACK ICE

Fast-ice diving differs from pack-ice diving (Quetin and Ross, 2009, this volume), where broken ice cover usually eliminates the need to cut access holes for diving because of easy access to the surface. The pack-ice environment tends to be more heterogeneous than that of fast ice. Ice may be present in all stages of development and the floes themselves may vary in size, age, structure, and integrity. Pack-ice divers will find themselves under an ever-shifting and dynamic surface and wave action and currents must be considered. At sites where the pack ice is forced against the shore and is solid but unstable, an access hole will have to be opened near shore in shallow water. Tidal fluctuations may alter the size of dive holes or vary the water depth under the holes.

UNDERWATER VISIBILITY

In August and September in the McMurdo region, underwater visibility may range up to a record 300 m. As solar radiation increases during the austral summer, an annual plankton bloom develops and quickly diminishes visibility to as little as 1 m by late December. Other water visibility factors influencing the polar regions include glacial melt and wind and temperature conditions. Visibility in the open waters of the Antarctic Peninsula may vary from 300 m to less than 3 m, depending on plankton densities and sea state. As glacial or sea ice melts, the resulting water may form a brackish water lens over the seawater. Visibility within these lenses is markedly reduced, even when the visibility in the water is still good otherwise. It may be possible to lose sight of the entry hole even when divers are near the surface.

POLAR DIVING OPERATIONS

DIVE ACCESS THROUGH ICE

Tidal action, currents, and other forces produce open cracks and leads that divers may use to enter the water. Divers working from USAP research vessels often use the leads cut by the vessel for their access to the water (Quetin and Ross, 2009, this volume). A hydraulically operated mobile drill can be used to cut 1.3 m diameter holes in ice that is over 5 m in thickness. In addition to the primary dive hole, at least one safety hole is required. Hole melters consisting of coiled copper tubing filled with hot circulating glycol or alcohol are used to open a clean, 1 m diameter hole in the thick ice cap that covers the freshwater Dry Valley Lakes (Andersen, 2007), taking from several hours to several days. Chain saws can also be used to cut an access hole through ice that is 15 to 60 cm thick. Access holes are cut into square or triangular shapes and made large enough to accommodate two divers in the water simultaneously. Another method is to use Jiffy drills that bore pilot holes in ice 15 to 30 cm thick and then saws can be used to cut a large dive hole between them;

attaching ice anchors to the chunks of ice allows for easy removal once they are sawed free. For ice from 15 to 25 cm thick, ice saws and breaker bars (2 m lengths of steel pipe or solid bar with a sharpened tip) are used to cut and break away the ice to form a hole. Divers enter the water through pack ice from shore, from an inflatable boat launched from shore or a research vessel, or from large ice floes or a fast-ice edge.

If dive holes are required in ice thicker than 5 m or in ice out of range of the mobile drill, explosives may be necessary. However, the use of explosives is generally discouraged for environmental reasons and requires several hours of clearing ice from the hole before a dive can be made.

Fast-ice diving requires one or more safety holes in addition to the primary dive hole. During times of the year when air temperatures are extremely cold, dive holes freeze over quickly. Positioning a heated hut or other portable shelter over a dive hole will delay the freezing process. Solar powered electric muffin fans are used to blow warm air from near the ceiling of the hut to the ice hole through a plastic tube. Down lines must mark all holes available for use on each dive because safety holes that are allowed to freeze at the surface are hard to distinguish from viable holes while diving under the ice.

Down Lines and Tethers

A down line is required on all untethered dives conducted from fast ice or any other stable overhead environment with limited surface access. Specific down line characteristics and components are described by Lang and Robbins (2007).

A minimum of one supervisor/tender per dive is required. Because they are a critical part of the diving operation and the first responders in case of accident, tenders receive training in diving first aid (Lang et al., 2007), radio use and communication procedures, scuba gear assembly, tether management, and vehicle or boat operation.

Dives conducted under fast ice where there is a current, reduced visibility or open blue water, or where the water is too shallow to maintain visual contact with the dive hole, require individual diver tethers that are securely attached at the surface. Use of the T- or L-shaped tether system is not ideal, making line-pull communication signals difficult and tether entanglement a possibility. Surface tender training is necessary to maintain enough positive tension on the tether line to immediately recognize line-pull signals from the safety diver, without impeding the activity or motion of the scientists working under the ice. The safety diver's function is to keep tethers untangled, watch for large predators and communicate via line-pull signals to the surface and other working divers.

Other hole-marking techniques to further protect against loss of the dive hole are snow removal (straight lines radiating outward from the dive hole that are very visible from under water) and benthic ropes which consist of 30 m lines laid out by divers when they first reach the benthos, radiating outward like the spokes of a wheel from a spot directly beneath the dive hole and marked so that the direction to the dive hole is clearly discernible.

Polar Diving Equipment

Members of the dive team take particular care in the selection and maintenance of polar diving equipment (Lang and Stewart, 1992; Lang and Sayer, 2007). Antarctic waters are among the coldest a research diver can expect to experience (−1.8°C in McMurdo Sound). In these temperatures, not all diving equipment can be expected to operate properly and freeze-ups may be more frequent. Diving under total ice cover also imposes safety considerations that are reflected in the choice of gear. We have developed specific care and maintenance procedures to ensure the reliability of life support equipment.

Divers are required to have two fully independent regulators attached to their air supply whenever they are diving under a ceiling. Modified Sherwood Maximus regulators (SRB3600 models, Figure 2) have been used successfully through the installation of a heat retention plate and adjustment of the intermediate pressure to 125

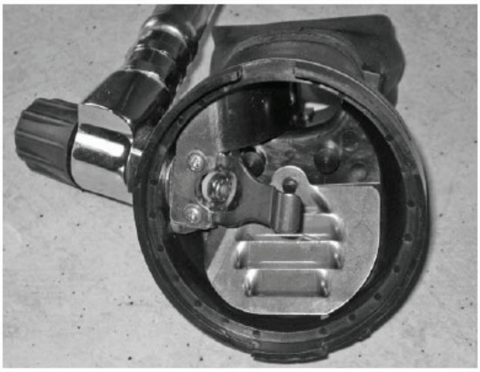

FIGURE 2. Sherwood Maximus SRB3600 second stage with heat retention plate.

psi. These units are rebuilt at the beginning of each season and with more than 7,000 dives have a freeze-up incident rate of 0.3 percent. Proper use and pre- and post-dive care substantially improves the reliability of ice diving regulators, which must be kept warm and dry before a dive. Divers should not breathe through the regulator before submersion except to briefly ensure that the regulator is functioning because of ice crystallization on the air delivery mechanism from breath moisture. This is particularly important if the dive is being conducted outside in very cold air temperatures. During a dive, a regulator is never used to fill a lift bag (small "pony bottles" are available for this purpose) because large volumes of air exhausted rapidly through a regulator will almost certainly result in a free-flow failure. Inflator hoses are attached to the backup regulator in case the air supply to the primary regulator must be turned off to stem a free flow. The backup regulator second stage is attached to the cylinder harness or buoyancy compensator (BC) such that it is readily accessible and easily detached. If the second stage is allowed to hang loosely from the cylinder and drag on the bottom, it will become contaminated with mud and sediment and may not function properly when required. After the dive, the regulators are rinsed and allowed to dry. During rinsing, care is taken to exclude water from the interior regulator mechanism. The diver ensures that the regulator cap is seated tightly, that the hoses and plugs on the first stage are secure, and that the purge on the second stage is not accidentally depressed during the rinse. The primary cause of regulator free-flow failure is from water entry within the mechanism that freezes once the regulator is used (Clarke and Rainone, 1995). Freshwater in the regulator may freeze simply with submersion of the regulator in seawater or upon exposure to extremely cold surface air temperatures. If multiple dives are planned, it is recommended to postpone a freshwater rinse of the regulator until all dives are completed for the day.

Inflator valves are also subject to free-flow failure, because of water entry into the inflation mechanism. Drysuit and BC inflators must be kept completely dry and hose connectors blown free of water and snow before attachment to the valve. When inflating a drysuit or a BC, frequent short bursts of air are used. Inflator buttons must never be depressed for longer than one second at a time because rapid air expansion, adiabatic cooling (5°C drop), and subsequent condensation and freezing may cause a free flow.

Buoyancy compensators need to allow unimpeded access to drysuit inflator and exhaust valves. Water must be removed from the BC bladder after diving and rinsing because freshwater in the bladder may freeze upon submersion of the BC in ambient seawater. In the McMurdo area, BC use is not currently required when the dive is conducted under a fast-ice ceiling because of the lack of need for surface flotation. A BC must never be used to compensate for excess hand-carried weight. Because of their buoyancy characteristics and durability in cold temperatures, steel, instead of aluminum, scuba cylinders are used.

Divers must wear sufficient weight, without overweighting, to allow for maintenance of neutral buoyancy with a certain amount of air in the drysuit. Runaway negative buoyancy is as great a safety problem to recover from as out-of-control ascent. Because of the amount of weight (30 to 40 lbs) and potential for accidental release, weight belts are not used. Diving Unlimited International (DUI) has developed weight and trim systems (Fig. 3) that retain the benefits of a harness while still allowing full or partial

FIGURE 3. DUI weight and trim system with bilaterally removable weight pockets (by pulling surgical tubing loops) and shoulder harness.

dumping of weight under water. The weight system prevents accidental release and improves comfort by shifting the weight load from the diver's hips to the shoulders.

Drysuit choice depends on the diver's preference, the requirement for range and ease of motion, and the options available with each suit. Vulcanized rubber suits must be used when diving in contaminated water because of post-dive suit decontamination requirements. Drysuits must be equipped with hands-free, automatic exhaust valves. Overinflation of the drysuit should never be used as a means to compensate for excess hand-carried weight. The choice of drysuit underwear is perhaps more important than the choice of drysuit construction material, because it is the underwear that provides most of the thermal protection. Many divers wear an underlayer of expedition-weight polypropylene with an outer layer of 400 g Thinsulate®. Dry gloves or mitts with an inner liner instead of wet gloves are now used with the drysuit. The DUI zipseal dry gloves enjoy widespread use and are effective at warm air equalization from the drysuit into the glove at depth. A disadvantage of these dry-glove systems is the complete lack of thermal protection if the gloves flood or are punctured, and the related inevitability of flooding the entire drysuit.

Severe cold can damage o-ring seals exposed to the environment requiring frequent cleaning and lubrication. Compressor care and adequate pre-operation warming are necessary to ensure a reliable supply of clean air checked by air-quality tests conducted at six-month intervals. Air filters and crankcase oil are scheduled to be changed on a regular basis. The filtering capacity of portable compressors is usually limited, necessitating air intake hose positioning upwind and well away from compressor engine exhaust. Manual condensate drains are purged frequently to prevent moisture contamination and freezing of the filter.

Each diver conducts a functional check of all equipment before each dive. Particular attention is paid to regulators and inflator valves. If leakage or free flow is detected at the surface, the dive is postponed and the gear serviced because it will certainly free flow at depth. All divers must be able to disconnect, with gloved hands, the low-pressure hose from a free-flowing drysuit inflator valve to avoid an uncontrolled ascent.

Because a drysuit must be inflated to prevent "suit squeeze" with increasing pressure, it is most efficient to regulate buoyancy at depth by the amount of air in the drysuit. Drysuits must be equipped with a hands-free exhaust valve (Lang and Egstrom, 1990). The BCs are considered emergency equipment, to be used only in the event of a drysuit failure. This procedure eliminates the need to vent two air sources during ascent, reduces the chance of BC inflator free-flow, and simplifies the maintenance of neutral buoyancy during the dive. The main purpose of air in a drysuit is to provide thermal insulation as a low-conductivity gas. Buoyancy compensators and drysuits must never be used as lift bags. When heavy items must be moved underwater, separate lift bags designed specifically for that purpose are used. Lang and Stewart (1992) concluded that there may be occasions when the drysuit diver is more at risk with a BC than without one. Accordingly, BCs are not required for dives under fast ice where a down line is deployed and the dive is not a blue-water dive.

SURFACE-SUPPLIED DIVING UNDER ICE

Robbins (2006) described USAP's surface-supplied diving activities, history, equipment, training, operations, and costs. By taking advantage of the equipment and expertise brought to the USAP program by commercial divers, scientific diving has benefited from the use of surface-supplied diving techniques. Safety, comfort, and efficiency are enhanced in some applications by using this mode long associated with industry but rarely used in the scientific arena. Since 1992, USAP has supported surface-supplied diving. In that period, 459 surface-supplied dives (of 8,441 total dives) were logged by 32 divers (of 107 total divers). The vast majority of surface-supplied dives were performed by 8 divers.

The USAP's experience with EXO-26 masks has been 11 free-flows in 106 dives (10.4 percent failure rate). AGA masks have had 2 free-flows in 26 dives (7.7 percent failure rate). These data come from dives in the Dry Valley Lakes where water temperatures range between 0°C and 2°C. The failure rate would be even higher in −1.8°C water of McMurdo Sound.

A minimum of two familiarization dives are made by each new surface-supplied diver over two days in addition to topside and underwater training. A three-person crew is the minimum personnel requirement including a supervisor/tender, a diver, and a suited standby diver using either scuba or surface supply.

Currently, the majority of surface-supplied diving is done utilizing 2-m tall high-pressure gas cylinders as an air source. A large 35 cfm/150 psi diesel compressor and smaller 14 cfm/125 psi gas compressor are available but used rarely for scientific diving operations. The USAP uses Kirby-Morgan Heliox-18 bandmasks and Superlite-17 helmets. While these units have a greater propensity to freeze and free-flow than Sherwood Maximus scuba regulators, their track record is as good as either the EXO-26 or AGA Divator full-face masks.

POLAR DIVING HAZARDS AND EMERGENCIES

Fast-Ice Diving Hazards

Lighting is often dim under a solid ice cover, particularly early in the austral spring when the sun is low on the horizon. The amount of snow cover and ice thickness will also attenuate light transmission. Microalgal blooms and increasing zooplankton during the austral summer reduces available light, making it difficult for divers to locate buddies, down lines, and underwater landmarks. High visibility early in the austral summer season may make under-ice or benthic objects seem closer than they are. This illusion may entice divers to travel farther from the access hole than is prudent.

The greatest hazard associated with fast-ice diving is the potential loss of the dive hole or lead. Access holes, leads, and cracks in the ice are often highly visible from below because of downwelling daylight streaming through them. However, dive holes may be difficult to see due to conditions of darkness or of covering the holes with portable shelters. Therefore, a well-marked down line is required for fast-ice dives. Divers maintain positive visual contact with the down line during the dive and avoid becoming so distracted by their work that they fail to take frequent note of their position in relation to the access hole or lead. Problems requiring an emergency ascent are serious, since a vertical ascent is impossible except when a diver is directly under the dive hole or lead. Additional safety holes ameliorate the danger of losing the primary dive hole but former dive holes that have frozen over may still look like safety holes from below. To eliminate confusion in a frequently drilled area, all active holes are marked with a down line.

Pack-Ice Diving Hazards

Pack ice is inherently unstable and its conditions can change rapidly, primarily from surface wind conditions. An offshore wind may blow pack ice away from the shoreline and loosen the pack, whereas an onshore wind may move significant quantities of pack ice against shorelines or fast-ice edges, obstructing what may have been clear access areas when divers entered the water. Similarly, increased wind pressure on pack ice may make driving and maneuvering an inflatable Zodiac more difficult or impossible. Under a jumble of pack ice, the topography is reminiscent of cave diving. The condition of the pack must be continually monitored by divers and tenders for changes that may affect dive safety and the entry area must be kept clear. Down lines and tethers can be disturbed by shifting pack ice, forcing dive tenders to be alert in keeping these lines free of moving ice.

Surface swells, even if only light to moderate, may cause pack ice to oscillate up and down. In shallow water, it is possible for a diver to be crushed between rising and falling pack ice and the benthos. At Palmer Station, surges from the calving glacier in Arthur Harbor may create a similar hazard. Divers avoid diving under pack ice if the clearance between the ice and the benthos is 3 m or less. In addition, lighting may be dim under a heavy pack-ice cover.

Open water develops in McMurdo Sound when the fast ice breaks up in late December or early January. In the Palmer region, any existing fast ice usually breaks up by the end of October. Pack ice may be present for another month or two, and intermittently after that, but open water generally characterizes the diving environment after early December. Kongsfjorden in Svalbard has not formed a substantial ice cover since 2005. Climatic conditions will cause variation in annual ice conditions.

Divers operating in open water and from small boats fly a “diver down” or “Alpha” flag to warn other boat traffic in the area. When diving from small boats a rapid exit from the water into the boat may be necessary. Because this can be difficult when fully laden with gear, lines with clips hang over the side of the boat to temporarily secure gear and a ladder facilitates diver exit.

When diving in blue water (a deep open water environment devoid of visual cues as to the diver’s vertical position in the water column) blue water diving guidelines generally apply (Haddock and Heine, 2005). Divers are tethered and wear buoyancy compensators and a down line is deployed if conditions warrant. Divers operating under pack ice in blue water often perceive current increases. Wind action causes the pack to move, which in turn moves the water directly below it. This effect decreases with depth, such that divers in still water at 10 m will have the illusion of movement as the pack ice above them drifts.

Ice-edge diving is usually conducted in blue water, and it tends to be shallow (less than 10 m). The underside of the ice sheet provides a depth reference lacking in ice-free blue water dives. Divers watch continuously for leopard seals known to lunge out of the water to attack people at the ice edge. They may also lurk under the ice waiting for a penguin, or a diver, to enter the water. If penguins in the area demonstrate a reluctance to enter the water, it may be an indication that a leopard seal is nearby.

MARINE LIFE HAZARDS

Few polar animal species are considered dangerous to the diver. Southern elephant seals (*Mirounga leonina*) and Antarctic fur seals (*Arctocephalus gazelli*) may become aggressive during the late spring/early summer breeding season. Crabeater seals (*Lobodon carcinophagus*) have demonstrated curiosity toward divers and aggression to humans on the surface. Leopard seals (*Hydrurga leptonyx*) have been known to attack humans on the surface and have threatened divers in the water. A case report of the single known in-water fatality caused by a leopard seal is described by Muir et al. (2006). Should any aggressive seal approach divers in the water, similar techniques to those protecting against sharks are applied. Polar bears (*Ursus maritimus*) and walrus (*Odobenus rosmarus*) in the Arctic are considered predatory mammals against which diving personnel must be safeguarded. Encounters with all of the aforementioned mammals are usually restricted to areas of open water, ice edges, or pack ice.

Divers in the fast ice around McMurdo may encounter Weddell seals (*Leptonychotes weddelli*) in the water. Occasionally a Weddell seal returning from a dive may surface to breathe in a dive hole to replenish its oxygen stores after a hypoxic diving exposure (Kooyman, 2009, this volume). Usually the seal will vacate the hole once it has taken a few breaths particularly if divers are approaching from below and preparing to surface. Divers must approach such a seal with caution, since an oxygen-hungry seal may aggressively protect its air supply. Weddell seals protecting their surface access will often invert into a head-down, tail-up posture to watch for rivals. Divers entering or exiting the water are particularly vulnerable to aggressive male Weddells, who tend to bite each other in the flipper and genital regions. There are no recorded incidents of killer whale (*Orcinus orca*) attacks on divers.

POLAR DIVING EMERGENCIES

The best method to mitigate scuba diving emergencies is through prevention. Divers must halt operations any time they become unduly stressed because of cold, fatigue, nervousness, or any other physiological reason. Similarly, diving is terminated if equipment difficulties occur, such as free-flowing regulators, tether-system entanglements, leaking drysuits, or buoyancy problems. Emergency situations and accidents stem rarely from a single major cause and they generally result from the accumulation of several minor problems. Maintaining the ability to not panic and to think clearly is the best preparation for the unexpected. Most diving emergencies can be mitigated by assistance from the dive buddy, reinforcing the importance of maintaining contact between two comparably equipped scientific divers while in the water.

Loss of contact with the dive hole may require divers to retrace their path. Scanning the water column for the down line is done slowly and deliberately because the strobe light flash rate is reduced in the cold water. If the hole cannot be found, an alternate access to the surface may have to be located. Often there will be open cracks at the point where fast ice touches a shoreline. Lost divers will have to constantly balance a desirable lower air consumption rate in shallow water with the need for the wider field of vision available from deeper water. Maintaining a safe proximity to the surface access point has made losing the dive hole an extremely unlikely occurrence.

Loss of the tether on a fast-ice dive that requires its use is one of the most serious polar diving emergencies. Lost diver search procedures are initiated immediately (i.e., assumption of a vertical position under the ice where the tethered buddy will swim a circular search pattern just under the ceiling to catch the untethered diver). The danger associated with the loss of a tether in low visibility is mitigated if the divers have previously deployed a series of benthic lines. If a diver becomes disconnected from the tether down current under fast ice, it may be necessary to crawl along the bottom to the down line. To clearly mark the access hole divers deploy a well-marked down line, establish recognizable "landmarks" (such as specific ice formations) under the hole at the outset of the dive, leave a strobe light, a flag, or other highly visible object on the substrate just below the hole or shovel surface snow off the ice in a radiating spoke pattern that points the way to the dive hole.

The under-ice platelet layer can be several meters thick and can become a safety concern if positively buoyant divers become trapped within this layer, become disoriented, and experience difficulty extricating themselves. The most obvious solution is to exhaust air from the drysuit to achieve negative buoyancy. If this is not possible and the platelet layer is not too thick, the diver may stand upside down on the hard under surface of the ice so that the head is out of the platelet ice to orient to the position of the dive hole and buddy. Another concern is that abundant platelet ice dislodged by divers will float up and plug a dive hole.

Fire is one of the greatest hazards to any scientific operation in polar environments. The low humidity ultimately renders any wooden structure susceptible to combustion and once a fire has started, it spreads quickly. Dive teams must always exercise the utmost care when using heat or open flame in a dive hut. If divers recognize during the dive that the dive hut is burning they must terminate the dive and ascend to a safety hole or to the under surface of the ice next to the hole (but not below it) in order to conserve air.

ENVIRONMENTAL PROTECTION

There are research diving sites in Antarctica (e.g., Palmer sewage outfall, McMurdo sewage outfall, and Winter Quarters Bay) that must be treated as contaminated water environments because of the high levels of *E. coli* bacteria (that have been measured up to 100,000/100 ml) or the presence of a hydrogen-sulfide layer (e.g., Lake Vanda). Diving with standard scuba or bandmask, where a diver may be exposed to the water, is prohibited in these areas. Surface-supplied/contaminated-water diving equipment is used at these sites ranging from Heliox-18 bandmasks for use with a vulcanized rubber drysuit to Superlite-17 helmets that mate to special Viking suits.

All researchers must avoid degrading the integrity of the environment in which they work. In particular, polar divers should avoid over-collecting, to not deplete an organism's abundance and alter the ecology of a research site; unduly disturbing the benthos; mixing of water layers such as haloclines; using explosives for opening dive holes; and, spilling oil, gasoline, or other chemicals used with machinery or in research. Increased attention to Antarctic Treaty protocols on environmental protection and implementation of the Antarctic Conservation Act have made human–seal interactions a more sensitive issue. Dive groups should avoid Weddell seal breeding areas during the breeding season and their breathing holes in particular.

PHYSIOLOGICAL CONSIDERATIONS

COLD

Cold ambient temperature is the overriding limiting factor on dive operations, especially for the thermal protection and dexterity of hands. Dives are terminated before a diver's hands become too cold to effectively operate the dive gear or grasp a down line. This loss of dexterity can occur quickly (5–10 min if hands are inadequately protected). Grasping a camera, net, or other experimental apparatus will increase the rate at which a hand becomes cold. Switching the object from hand to hand or attaching it to the down line may allow hands to rewarm. Dry glove systems have greatly improved thermal protection of the hands.

The cold environment can also cause chilling of the diver, resulting in a reduced cognitive ability with progressive cooling. Monitoring the progression of the following symptoms to avoid life-threatening hypothermia is important: cold hands or feet, shivering, increased air consumption, fatigue, confusion, inability to think clearly or perform simple tasks, loss of memory, reduced strength, cessation of shivering while still cold, and finally hypothermia.

Heat loss occurs through inadequate insulation, exposed areas (such as the head under an inadequate hood arrangement), and from breathing cold air. Scuba cylinder air is initially at ambient temperature and chills from expansion as it passes through the regulator. Air consumption increases as the diver cools, resulting in additional cooling with increased ventilation. Significant chilling also occurs during safety stops while the diver is not moving. Polar diving requires greater insulation, which results in decreasing general mobility and increasing the potential for buoyancy problems. This also means that an increased drag and swimming effort, along with the donning and doffing of equipment, all increase fatigue.

SURFACE COLD EXPOSURE

Dive teams are aware that the weather can change quickly in polar environments. While they are in the field, all divers and tenders have in their possession sufficient cold-weather clothing for protection in any circumstance. Possible circumstances include loss of vehicle power or loss of fish hut caused by fire. Boat motor failure may strand dive teams away from the base station. Supervisors/tenders on dives conducted outside must also be prepared for the cooling effects of inactivity while waiting for the divers to surface. In addition, some food and water is a part of every dive team's basic equipment. Besides serving as emergency rations, water is important for diver rehydration after the dive.

HYDRATION

Besides the dehydrating effect of breathing filtered, dry, compressed air on a dive, Antarctica and the Arctic are extremely low-humidity environments where dehydration can be rapid and insidious. Continuous effort is advised to stay hydrated and maintain proper fluid balance.

Urine should be copious and clear and diuretics (coffee, tea, and alcohol) should be avoided before a dive.

Decompression

Mueller (2007) reviewed the effect of cold on decompression stress. The relative contributions of tissue N_2 solubility and tissue perfusion to the etiology of decompression sickness (DCS) are not resolved completely. Over-warming of divers, especially active warming of cold divers following a dive, may induce DCS. Divers in polar environments should, therefore, avoid getting cold during decompression and/or after the dive and if they feel hypothermic, wait before taking hot showers until they have rewarmed themselves, for example, by walking. The effect of cold on bubble grades (as measured by Doppler scores) may be the same for a diver who is only slightly cold as for one who is severely hypothermic. Long-term health effects for divers with a high proportion of coldwater dives should be considered in the future.

Dive computers were examined for use by scientific divers (Lang and Hamilton, 1989) and have now been effectively used in scientific diving programs for almost two decades in lieu of U.S. Navy or other dive tables. Currently, the decompression status of all USAP divers is monitored through the use of dive computers (UWATEC Aladin Pro) and data loggers (Sensus Pro). Battery changes may be needed more frequently because of higher discharge rates in extreme cold. Advantages of dive computers over tables include their display of ascent rates, no-decompression time remaining at depth, and their dive profile downloading function. Generally, no more than two repetitive dives are conducted to depths less than 130fsw (40msw) and reverse dive profiles for no-decompression dives less than 40msw (130fsw) and depth differentials less than 12 msw (40fsw) are authorized (Lang and Lehner, 2000). Oxygen-enriched air (nitrox) capability (Lang, 2006) and rebreather use have, to date, not been requested nor implemented by the USAP Diving Program. Cold and the physical exertion required to deal with heavy gear in polar diving can increase the risk of DCS. Furthermore, because of the polar atmospheric effect, the mean annual pressure altitude at McMurdo Station is 200 meters. Under certain conditions, pressure altitude may be as low as 335 meters at sea level. Surfacing from a long, deep dive (on dive computer sea level settings) to an equivalent altitude of 335 meters may increase the probability of DCS. Safety stops of three to five minutes between 10- to 30-foot (3.3 to 10 m) depths are required for all dives (Lang and Egstrom, 1990).

Acknowledgments

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PAPER 3.

PERFORMANCE OF LIFE-SUPPORT BREATHING APPARATUS FOR UNDER-ICE DIVING OPERATIONS (Submitted to *Diving Hyperb. Med.*)

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Abstract

This study evaluated the under-ice performance of a sampling of commercially available regulators. Single-hose scuba regulators dived in very cold water may suffer first- or second-stage malfunction yielding complete occlusion of air flow or massive freeflow that rapidly expends a diver's air supply. Seventeen divers logged a total of 305 dives in -1.86°C sea water under 6-m thick Antarctic fast ice over two field seasons in 2008 and 2009. Dive profiles had an average depth of 38 msw and dive time of 29 min, including a mandatory 3 min safety stop at 6 msw. Sixty-nine unmodified regulator units (17 models) from 12 different manufacturers underwent standardized pre-dive regulator care and were randomly assigned to divers. Depths and times of onset of second-stage regulator freeflow were recorded. In 305 dives, there were 65 freeflows. The freeflows were not evenly distributed across the regulator brands. Regulator failure rates fell into two categories (<11% and >26%). The regulators classified for the purpose of the test as "better" (< 11% failure rate; DiveRite Jetstream, Sherwood Maximus SRB3600, Poseidon Xstream Deep, Poseidon Jetstream, Sherwood Maximus SRB7600, Poseidon Cyklon, Mares USN22 Abyss) suffered only 9 freeflows out of 146 exposures for a 6% overall freeflow incidence; and those classified as "worse" (> 26% failure rate) suffered 56 freeflows out of 159 exposures (35% freeflow incidence.) The pooled incidences for the seven best performing regulators was significantly different, by Chi-square test, from the ten remaining regulators (P<0.001).

Keywords
Ice diving, regulator freeze-up, freeflow, regulator performance

Introduction

Approximately five decades ago scientists were first able to enter the undersea polar environment using open-circuit scuba to make observations. The history and current practice of scientific diving in Antarctica was recently reviewed and its function highlighted as a research tool.[1,2] Since those first under-ice dives in wetsuits without buoyancy compensators and using double-hose regulators without submersible pressure gauges, technology has advanced tremendously. Novel scientific ice-diving techniques have expanded the working envelope to include use of dive computers, oxygen-enriched air, rebreather units, blue-water diving, and drysuits with dry-glove systems. Within the next decade these limits will be extended to even greater depths and times based on the science need and, with the advent of new technology, greater scientific productivity, while maintaining the scientific diving community's exemplary diving safety record.[3] The primary safety concern currently resides with the identification of the next generation of life-support equipment for under-ice scientific diving. This project aimed to evaluate the under-ice performance of several commercially available regulators to select a successor model to the currently used 1991 Sherwood SRB3600 Maximus regulators.

The primary mission of the National Science Foundation (NSF) U.S. Antarctic Program (USAP) Diving Program is to provide research support and ensure the safety of all under-ice diving operations. The USAP Diving Program issues equipment through its McMurdo Station dive locker to all NSF-authorized scientific divers. USAP's procurement, maintenance, and distribution of approved equipment ensure that NSF scientific divers are appropriately equipped while diving under its auspices.

At its inception in 1947 (through the US Naval Support Force Antarctica) through 1967 the USAP diving program issued double-hose regulators to NSF scientific divers. In 1991, double-hose regulators were retired from service and replaced with single-hose modified Sherwood Maximus SRB3600 regulators (Fig. 1.) A heat retention plate was fitted over the second-stage exhaust valve and around the air delivery lever and the intermediate pressure detuned from 1000 to 860 kPa (10 to 8.6 bar) to reduce the probability of freeflow in supercooled sea water of -1.86°C in McMurdo Sound. The decision to investigate replacement regulators was influenced by the age of the 1991 Sherwood models, their less than optimal breathing characteristics, and the lack of continued parts availability in 2008 to avoid potentially catastrophic regulator failure.

Single-hose scuba regulators dived in very cold water have a probability of experiencing first- or second-stage malfunction yielding complete occlusion of air flow or massive freeflow that rapidly expends a diver's air supply, both conditions referred to as regulator “freeze-up.” Ice crystal build up in the regulator second stage can inhibit the valve from completely seating itself and is the main cause of freeflow. Principal factors contributing to ice crystallization in the regulator second stage include manufacturer's design, materials, and quality control, moisture in the diver’s exhaled breath, adiabatic gas expansion, mass flow, time, temperature, and water leakage into the second stage.

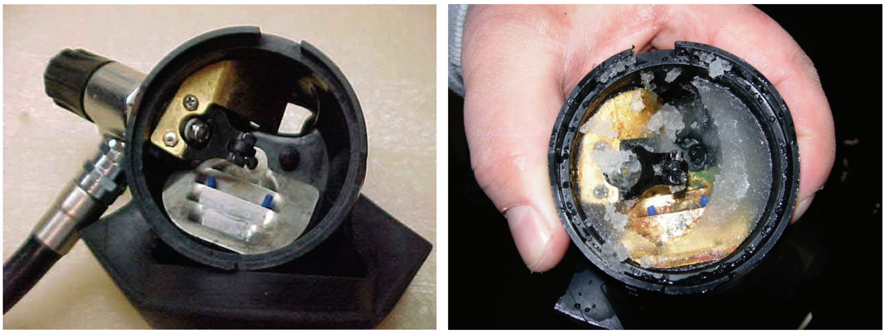
SCIENTIFIC DIVING SAFETY RESEARCH

Scientific diving standards and procedures are an evolving process that receives periodic review and revision through a series of international, interdisciplinary diving safety workshops aimed specifically at addressing the scientific diving community’s needs. Many of the resultant recommendations are further disseminated and adopted by the recreational diving community and scuba training agencies and have been useful to the NSF polar diving program. Diving thermal problems, drysuit diving, ice diving training, and logistics were reviewed for polar scientific diving operations.[4] Subsequently, expert polar diving recommendations were consensually derived nationally for U.S. programs and internationally.[5,6]

OPERATIONAL BACKGROUND

To date, USAP continues to utilize an *ex post facto* data collection method of ice-diving regulator performance.[7,8,9] Alternative regulator models’ performances have not been evaluated systematically due to the existing availability of adequately performing regulators that have enjoyed a high level of non-freezing success. *A priori* evaluation of regulator models that best meet our needs for safety and optimal breathing performance is a prudent management model to avert possibly dangerous consequences to members of our scientific diver population.

To manage NSF's diving research support and occupational risk exposure, an operational framework is required that allows maximum safeguards for the scientific diver and minimizes obstructions to the scientific mission. The Office of Polar Programs’ diving policy has been guided by the American Academy of Underwater Sciences' standards and the federal Occupational Safety and Health Administration (U.S. Department of Labor) regulations for scientific diving. This adherence has greatly reduced liability exposure, and provides for an effective, validated framework for scientific ice divers working under USAP control and supervision. USAP diving requirements as they relate to under-ice life support equipment are detailed and regulators are issued to divers.[2] Divers are required to be equipped with two fully independent regulators attached to their air supply via Y valves (“slingshot valves”) whenever they are diving under a ceiling. USAP-issued Sherwood Maximus SRB3600 regulators are rebuilt at the beginning of each diving season and with over 7,000 dives incurred a freeflow incident rate of 0.3%. [2]



Figures 1a. Sherwood Maximus SRB3600 second stage with heat retention plate on lever and exhaust valve (left); **1b.** Second-stage ice build-up resulting from massive freeflow (right).

OBJECTIVES

In our search for replacement ice-diving regulators for USAP's 1991 model Sherwood Maximus SRB3600 units, the problem has been described as follows: "Because of the pressures of the market place, scuba regulator models typically have a short half-life. However, designing a regulator tolerant to freeze-up is a black art for most manufacturers and even 'minor' cosmetic changes can affect 'freeze-up' risk."[10] When regulators that are known performers in cold water are replaced by new models considerable uncertainty is introduced regarding their continued cold water performance. From what we know about the potential effect of thermal mass, it is certainly possible that a lower thermal mass - 'smaller, lighter' - could yield less heat retention from a diver's breath. Furthermore, if weight is trimmed by use of plastic as opposed to metal, what effect does that have on thermal conductivity? The simple answer is, we do not know. It is hard to predict what the effect of changes in regulator material or design will have on cold-water performance without testing. The ability of the industry to make changes to their products varies tremendously depending upon the government regulatory climate they find themselves in and the perceived safety implications of material changes. The U.S. Navy Experimental Diving Unit similarly points out the need for ice diving field validations of regulators, an experience/facility the U.S. Navy currently does not have, to complement objective and subjective findings and laboratory-derived data from breathing machines in hyperbaric chambers.[11]

This project was guided, in part, by the tendency for regulators to freeflow under polar conditions and the relevant consensus recommendations of the 2007 International Polar Diving Workshop calling for continued data collection on the performance of regulators; field experience or independent lab testing validation prior to adoption of new regulator models for polar diving; a minimum of two independent regulator systems for diving in overhead environments and diver proficiency in switch-over procedures; use of a second-stage isolator valve in conjunction with a first-stage overpressure relief valve to manage regulator freeflow; and, proper pre- and post-dive regulator care.[6]

Methods

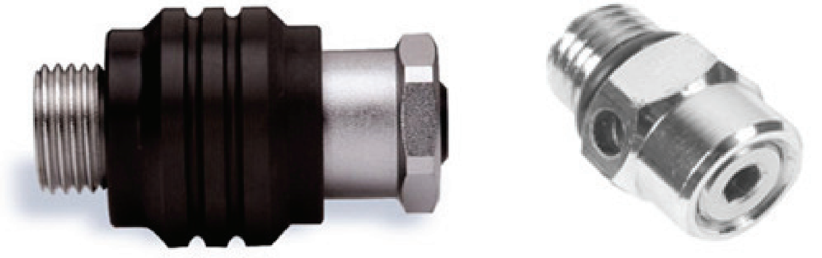
HUMAN RESEARCH PROTECTION

Using the Department of Health and Human Services regulations, the Chesapeake Research Review, Inc. IRB determined on August 20, 2008 that this research project does not constitute human subjects' research.

REGULATORS

All regulators experienced the same diving conditions and pre- and post-dive regulator care was standardized. Regulators were kept warm and dry before a dive and divers did not breathe from the regulator prior to immersion. Regulator purge buttons were not used because large volumes of air exhausted rapidly almost certainly result in a freeflow failure. Drysuit inflator hoses were attached to the back-up regulator in case the air supply to the primary regulator had to be turned off to stem a freeflow. Surgical tubing mouthpiece holders secured the backup regulator (Sherwood SRB3600) second stage to the cylinder harness on the right side of the diver's chest, to be swapped with the freeflowing primary regulator after the flow had been shut off. Regulators were not rinsed with fresh water in between dives; however, with second-stage diaphragm covers removed, regulators were blown dry with low-pressure compressed air.

Each test regulator (except for Poseidon models because of their crimped, versus threaded, hose fittings) was fitted with an isolator valve (Fig. 2a) in line on the intermediate pressure hose adjacent to the second stage. This valve must be used in conjunction with an overpressure relief valve (Fig. 2b) on the regulator's first stage. The isolator valve has 10 mm of horizontal travel towards the regulator mouthpiece to shut off air flow after switching out to the back-up second stage prior to closing the cylinder valve.



Figures 2a and 2b. Zeagle isolator valve (freeflow shut-off device; product no. 333-0233) on the regulator second stage (left) used in conjunction with a first-stage overpressure relief valve (product no. 330-4905; right).

The added breathing resistance (resistive effort, RE) of an isolator valve was measured on an Apeks TX50 and a U.S. Divers Conshelf 14 regulator attached to breathing machines at the Navy Experimental Diving Unit using standard U.S. Navy testing procedures (a depth range of 0-60 msw and ventilation rates of 40 l/min and 62 l/min).

Regulators (69 units from 12 manufacturers) were purchased off the shelf from commercial vendors. Manufacturers were not solicited to submit regulator units. This evaluation was done independently without any modification of the test regulators. Regulator models (Table 1) were selected for ice-diving evaluation based on criteria such as design, materials, manufacturer performance claims and diver reviews. Individual regulator intermediate pressures were recorded after the dive series was performed and with one exception (Zeagle Flathead VI unit, which was disqualified) were within the manufacturers' specified intermediate pressure ranges.

EVALUATION DIVES

Regulators were randomly assigned to seventeen scientific divers who conducted dives in -1.86°C sea water under 6-m thick Antarctic fast ice over two field seasons in 2008 and 2009 in the vicinity of McMurdo Station, Antarctica, through the National Science Foundation's USAP Dive Program. Dive sites were selected at Dayton's Wall and the Jetty near McMurdo Station, and Cape Evans; divers were deployed into the water in groups of 3 or 4.

Table 1. Regulator test units: manufacturer, model, no. of units tested, and intermediate pressures; *all USAP Sherwood regulators are disassembled and rebuilt at the end of the diving season, IP pressure measurement was not done prior to disassembly.

Manufacturer	Regulator Model	No. Units	Intermediate Pressures (kPa)
POSEIDON	Cyklon	3	1140; 1080; 1090
POSEIDON	Xstream Deep	1	990
POSEIDON	Jetstream	3	940; 980; 940
DIVERITE	Jetstream	6	900; 950; 910; 980; 900; 880
DIVERITE	Hurricane	6	950; 970; 970; 970; 980; 1000
MARES	US Navy 22 Abyss	6	900; 920; 900; 910; 900; 890
MARES	V32 Proton Ice Extreme	3	940; 910, 960
AQUA LUNG	Glacia	3	860; 870; 870
APEKS	XTX50	4	960; 1020; 1070; 1010
ZEAGLE	Flathead VI	3	1030; 1030; 2070+
XS SCUBA	Spirit	2	990; 990
SI TECH	S40 Forever	6	550; 570; 560; 550; 550; 540
ATOMIC AQUATICS	M1	5	900; 910; 910; 890; 930
SCUBAPRO	MK17/A700	6	970; 970; 980; 970; 1000; 990
HOLLIS	D212	6	930; 950; 920; 950; 930; 970
SHERWOOD	Maximus SRB7600CE	3	900; 950; 950
SHERWOOD	Maximus SRB3600	3	*

Project divers were selected based on their ice-diving experience and variations in body size, and RMV (Respiratory Minute Volume.) Dives were conducted as no-decompression profiles and recorded with UWATEC One dive computers. Several bounce dives were conducted deeper than 40 m with those regulator models that did not freeflow at shallower depths. After each dive, regulator performance data, dive profile and air consumption were recorded for each diver.

Buoyancy compensators were not used per standard operating procedure of the USAP dive program at McMurdo Station. Diving Unlimited International, Inc. (DUI) weight and trim systems and ankle weights were used by all divers. DUI trilaminate shell drysuits and Viking vulcanized rubber suits were worn in conjunction with dry glove systems. Thermal protection consisted of layers of polypropylene undergarments and a 400 g thinsulate jumpsuit. USAP scientific diving regulations applied during this project as we wished to approximate the dive profiles and scientific work routinely performed under ice.

DIVER CHARACTERISTICS

The combined diver population of 17 divers (9 male, 8 female) was purposefully heterogeneous in body habitus. Average diver height was 176 ± 9.0 cm (mean ± SD) with a range from 163 to 191 cm. Mean diver weight was 76.7 ± 20.5 kg with a range from 53.5 to 127.5 kg.

All project divers met USAP minimum qualifications: one year of diving experience: a) 1-year scuba diving certification; b) 50 logged open water dives; c) 15 logged drysuit dives; and, d) 10 logged drysuit dives in past 6 months. Further, USAP physical qualification was required for all participants prior to deployment to Antarctica under National Science Foundation auspices, including polar dental exam (with pano or full-mouth series and bitewing x-rays), medical history, polar physical examination and required laboratory tests (http://www.usap.gov).

PHYSICAL AND ANTHROPOMETRIC CORRELATIONS

The U.S. Navy showed that freeze-up incidence is related to duration of cold water exposure and ventilation rate.[12,13] Consequently, the correlation of the current results with dive duration and ventilation rate was examined. Standard equations were used to estimate body mass index (BMI) and body surface area (BSA) from diver weight, height and gender.[14,15] Basal oxygen consumption, lean body weight, percent body fat, and predicted vital capacity were also estimated from the basic measurements, including age.[16,17]

REJECTION CRITERIA AND FREEFLOW FAILURE RATE

A priori stopping rules for sequential Bernoulli trials were established to limit the number of freeflow incidences for any given regulator model, while simultaneously allowing the greatest number of regulator tests for the testing time available.[18,19] The stopping rule selected was as follows: if 1/3 or more of the regulator trials resulted in a freeflow, with a minimum of three failures, the trial for that regulator model would be halted. These rules assured that we were 95% confident that the true failure rate would be 10% or greater. Based on Monte Carlo simulation, there is an approximately 2% probability of rejecting a regulator (under the above rules) that has an actual (real world) failure rate of less than 10%. Since the null hypothesis was that the regulator will pass, 2% is the probability of a type 1 error.

STATISTICS

Differences between regulator freeflow incidences were tested by the Chi-square test using Systat, ver. 11, (Systat Software, Inc., Richmond, CA). The Yates correction for continuity was used in calculating this test. An alpha level of 0.05 was used for all statistical tests.

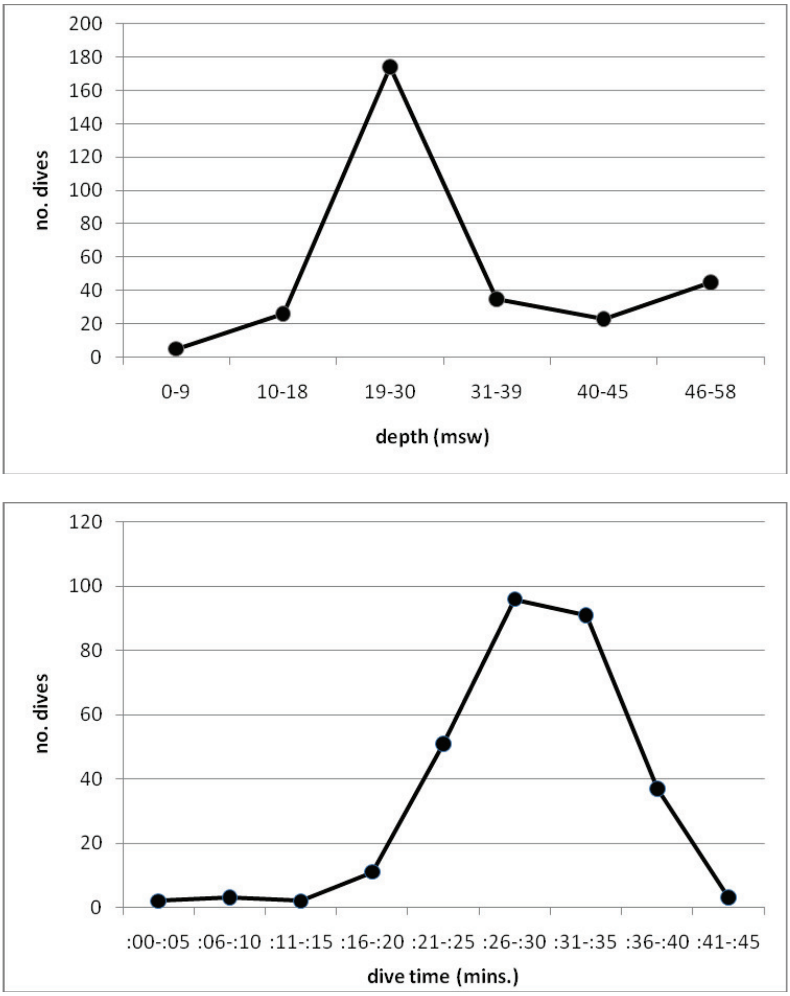
Results

DIVES

A total of 305 dives were conducted (Fig. 3a) by 17 divers for a total dive time of 8,942 mins (Fig. 3b).

FREEFLOW INCIDENT STATISTICS

In 305 dives, there were 65 freeflows. The freeflows were not evenly distributed across the regulator brands. Regulator failure rates by brand fell into two categories (<11% and >26%). The pooled incidences for the seven best performing regulators (DiveRite Jetstream, Sherwood Maximus SRB3600, Poseidon Xstream Deep, Poseidon Jetstream, Sherwood Maximus SRB7600, Poseidon Cyklon, and Mares USN22 Abyss were compared to the ten remaining regulators. The regulators classified for the purpose of the test as “better” (< 11% failure rate) suffered only 9 freeflows out of 146 exposures (6% freeflow incidence);



Figures 3a and 3b. Number of dives (n=305) as a function of dive depth (upper) and dive times (lower).

and those classified as "worse" (> 26% failure rate) suffered 56 freeflows out of 159 exposures (35% freeflow incidence; Fig. 4). Testing on regulators was aborted when the stopping rules were exceeded.

Of the seven better performing regulators, four models suffered no more than 1 freeflow incident out of 60 dives. Those models were the DiveRite Jetstream, Sherwood Maximus SRB3600, Poseidon Xstream, and Poseidon Jetstream (Table 2.)

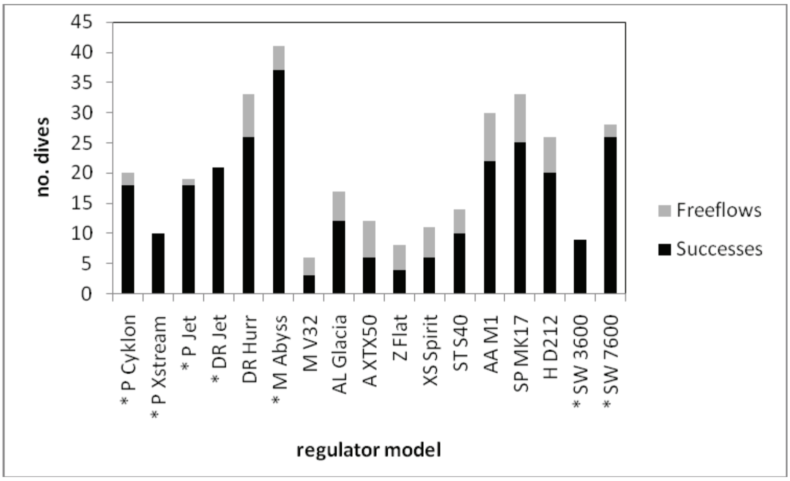


Figure 4. Freeflow incidents by regulator model. * indicates best performing regulators.

The Chi-square value for this categorical comparison was 36.6 (after Yates correction for continuity). With 1 degree of freedom, the Chi-statistic yields a p value <0.001 assuming α = 0.05. The power of the test for an alpha level of 0.05 was 0.999. Statistics supported the conclusion that in the bimodal distribution of regulator freeflows, those regulators with the lower incident rate were less likely to freeflow than the others.

Table 2. Summary of top performing regulators.

Models	**Dives**	**FF**	**% FF**
DiveRite Jetstream	21	0	0.0
Sherwood Maximus SRB3600	9	0	0.0
Poseidon Xstream Deep	10	0	0.0
Poseidon Jetstream	20	1	5.0
Sherwood Maximus SRB7600CE	28	2	7.1
Poseidon Cyklon	21	2	9.5
Mares USN 22 Navy Abyss	37	4	10.8
Total (average)	**146**	**9**	**(4.6)**

FREEFLOW ONSET TIMES AND DEPTHS

The results summarized in Figure 5 represent the onset times (18 ± 9 min, mean ± SD) and Figure 6 the depths (16 ± 10 msw, mean ± SD) at which freeflow events occurred, as reported by the divers.

Testing on regulators was aborted when the freeflow incidence exceeded stopping criteria. Five regulators (SITECH S40 Forever, XS Scuba Spirit, Mares V32 Proton Ice Extreme, Apeks XTX50, and Zeagle Flathead VI) exceeded the stopping rules and were excluded from further testing.

In 2008, phase 1 of this field study narrowed the number of regulator models being considered for the rigorous conditions of the U.S. Antarctic Diving Program from nine models to two: the Poseidon Xstream and the Sherwood Maximus SRB7600. In 2009, phase 2 narrowed the regulator models from seven to two: the DiveRite Jetstream and the Mares Navy 22 Abyss. Ejection of ice spicules from the Poseidon Jetstream into the mouth was a uniform, albeit subjective, objection by all divers.

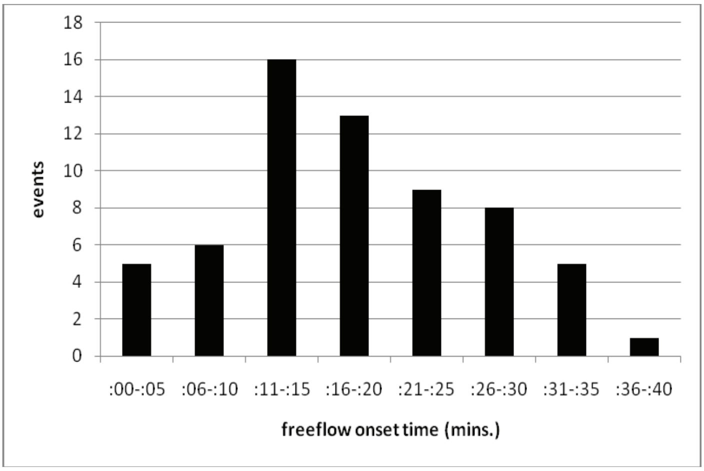


Figure 5. Elapsed dive time when freeflow incident occurred, mean ± SD = 18 ± 9 min, n = 65.

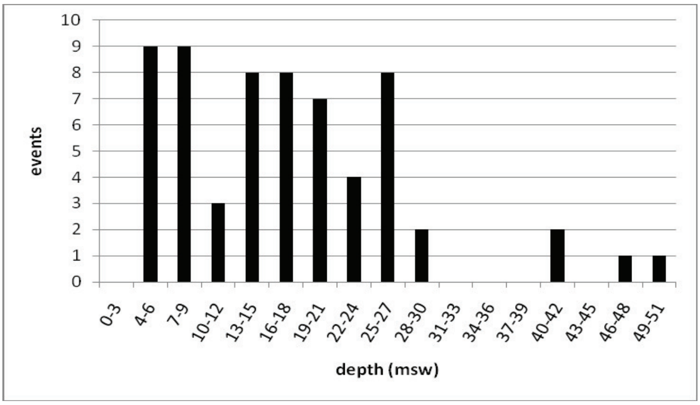


Figure 6. Dive depths when freeflow incident occurred. mean ± SD = 16 ± 10 msw, n = 65.

ISOLATOR VALVE TESTING

The valves used for this study were found to only marginally increase breathing resistance (resistive effort, RE; Fig. 7) but in general the RE lay below the performance goals established by the U.S. Navy for scuba regulators.

PHYSICAL AND ANTHROPOMETRIC FEATURES

Table 3 shows measured and calculated anthropometric characteristics of the divers. The relative freeflow frequency, i.e., the number of freeflows experienced by each diver divided by their total number of dives, is shown in Figure 8. Although the frequency ranged from a minimum of 0.03 to a maximum of 0.48, there were virtually no anthropometric differences between the divers at the extremes (1 and 7) as estimated from their height, weight and gender data (Table 3).

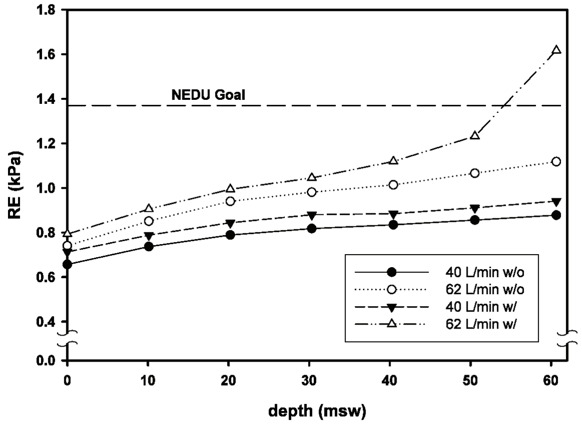


Figure 7. Example of the effect of the isolator valve on resistive effort of an Apeks TX50 scuba regulator at respiratory minute volumes of 40 and 62.5 L/min. Tests were conducted under ambient temperature (~20°C). The triangle symbols indicate tests with the isolator valve in place, and the circles indicate regulator tests without the isolator valve.

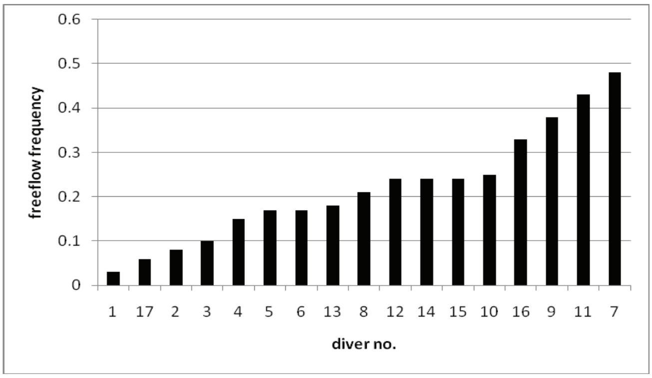


Figure 8. Relative freeflow frequencies for each diver (number of freeflows per total dives).

Discussion

We were fully expecting to find a continuous variation in freezing susceptibility among the regulator brands. What we encountered, a clearly bimodal susceptibility, was surprising. However, that bimodal population lent itself to the classifications of "better" and "worse" regulators for Antarctic service.

All of the candidate regulators were treated equally. The factors known to influence the probability of regulator freeflow are manufacturer's design principles, adiabatic gas expansion, temperature, ventilation rate, dive duration and depth, and water leakage into the second stage.[12,13] Dive duration and gas consumption varied only slightly among the divers. It appears that better insulated divers tolerated longer dives, on average. However, statistically those divers did not have more freeflow incidents than the other divers, and the freeze-ups occurred relatively early in the dives rather than late. There was, in other words, no association between diver body habitus and freeze-up incidence.

Table 3. Anthropometric indices estimated from basic measurements of height, weight, and gender. MBI= body mass index, BSA= body surface area, BOC= basal oxygen consumption, LBW = lean body weight, %BF = percent body fat, VCpred = predicted vital capacity.

diver	BMI	BSA (m^2)	BOC	LBW (kg)	% BF	VCpred (L)
1	25.1	2.1	0.26	67.1	22	5.3
11	25.1	2.1	0.26	65.4	22	5.5
6	20.0	1.6	0.20	43.5	23	3.8
3	26.4	2.2	0.27	69.2	24	5.6
4	24.4	2.0	0.25	62.5	21	5.3
8	23.7	1.9	0.24	59.6	20	5.2
2	20.7	1.8	0.22	48.5	24	4.5
5	21.8	1.7	0.21	44.4	25	4.0
7	30.6	2.4	0.30	78.7	29	5.9
9	37.1	2.5	0.31	79.7	38	5.6
10	26.9	2.3	0.28	73.7	24	5.9
14	20.3	1.6	0.20	41.2	23	3.4
16	20.4	1.7	0.21	45.3	23	4.2
12	20.2	1.6	0.21	43.7	23	3.9
13	23.1	1.7	0.22	47.2	27	4.1
15	22.1	1.7	0.21	46.2	26	4.0
17	24.5	1.9	0.23	57.5	21	4.9

A priori stopping rules for sequential Bernoulli trials were established to limit the number of freeflow incidences for any given regulator model, while simultaneously allowing the greatest number of regulator tests for the testing time available. The stopping rule selected was as follows: if 1/3 or more of the regulator trials resulted in a freeflow, the trial for that regulator would be halted. This rule kept the upper 95% binomial confidence limit at 0.60 or above. For instance, for 5 failures out of 15 trials, the two-sided 95% confidence interval ranged from 0.12 to 0.62. That means we can be 95% sure that based on the limited sample taken, the true percentage of freeflows in a larger population would range from 12% to 62%. For 3 failures out of 9 trials, the confidence interval ranges from 0.07 to 0.70. For 2 out of 6, the range is from 0.04 to 0.78. We were unwilling to allow a regulator to be used for service in Antarctica if there was a 33% incidence of freeflow in our testing, or a 60% or greater chance of it failing in a larger sample.

While we would have liked more stringent requirements, this was not possible due to the small available sample size. For instance, the Sherwood Maximus SRB7600CE regulator with 2 freeflows out of 28 trials had a 95% confidence interval ranging from 0.01 to 0.25. The Poseidon Xstream Deep confidence interval ranged from 0 to 0.31. More sophisticated methods have been used to abort Bernoulli trials in diving decompression table testing, which involved hundreds of dives.[18,19]

The U.S. Navy discovered through unpublished testing of prototype heat exchangers that if sufficiently sized they are able to bring super-cooled air up to seawater temperature (-2°C) prior to reaching the second stage. When that happens, freeflows are prevented. This principle was applied in one of the test regulators (Aqua Lung Glacia), but arguably that regulator's heat exchanger was too small for its intended purpose. The intermediate pressure hose connecting the first and second stage regulators is itself a heat exchanger, although one with low efficiency that requires more time to bring internal temperature into equilibrium with external temperature than do high efficiency heat exchangers. Thus, the additional time for heat transfer provided by slow breathing rates may serve favorably in reducing the risk of second stage freeflow. However, without further study, the above comments are merely speculative.

The isolator valve data shows that resistive effort increases, but not by a significant amount unless the diver is breathing very hard very deep, which is operationally not attractive. From diving safety considerations, the addition of the isolator valve to the regulator dramatically increases the margin of safety for ice diving operations.

Conclusions

Regulator freeze-up is a probabilistic event; even the best regulators can fail under polar conditions. In the final consideration of USAP Diving Program regulator replacement acquisition, several subjective factors were also considered: regulator performance observations by test divers, ease of regulator maintenance and servicing, and manufacturer's support. The most important consideration remains a low probability of freeze-up. The combination of laboratory (NEDU) and field testing (McMurdo) of ice-diving regulators points out that if a regulator does not freeflow at all under ice, it should be favorably received. If it also does not freeflow under severe NEDU test conditions, then it is very unlikely to cause air delivery problems for scientists under ice if the units are properly cared for.

In conclusion, the 1991 Sherwood SRB3600 regulators must follow the path of the Royal Aquamaster double-hose ice-diving regulators that were retired from the USAP in 1990. Of the seventeen regulator models tested for ice diving performance and reliability, seven appear worthy of consideration for meeting the scientific diving community and military needs.

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PAPER 4.

The state of oxygen-enriched air (nitrox)

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Key words

Diving, scuba diving, enriched air - nitrox

Abstract

(Lang MA. The state of oxygen-enriched air (nitrox). *Diving and Hyperbaric Medicine*. 2006; 36: 87-93.)

The evolution of the use of oxygen-enriched air (nitrox) in diving can be traced to its origin in 1874, its use in the scientific diving community in 1979, and its introduction on a global scale to the recreational diving community in 1985. As with any emerging technology that has found a broader market appeal, controversies invariably arise. In 2000, the DAN Nitrox Workshop reviewed physiological issues as they pertain to recreational nitrox use such as carbon dioxide retention, oxygen toxicity potential, and narcosis, and nitrox decompression sickness (DCS) incidence rates compared to air. In collaboration with the recreational diving industry, nitrox equipment engineering considerations vis-à-vis the 40%-oxygen-cleaning rule, nitrox training, and operational data were also reviewed. To provide an update on the state of nitrox, the workshop information is synthesized and additional new certification and operational data reviewed for 2000–2005.

Introduction

The use of oxygen-enriched air (nitrox) has been a mainstream recreational diving mode since it was first introduced to sport divers in 1985 by former NOAA Deputy Diving Officer Dick Rutkowski. The mainstream recreational diving training associations (PADI, NAUI, and SSI) now support nitrox training programmes in addition to their traditional open-circuit compressed-air scuba programmes. The training organisations that focus on technical diving (IANTD, ANDI, and TDI) have amassed several additional years of experience in providing nitrox training to the recreational diving community.

In 2000, the DAN Nitrox Workshop[1] was prioritised as a diving safety project of interest to the diving industry by means of Divers Alert Network financial support. As with any emerging technology that has found a broader market appeal, controversies invariably arise. Ignorance, myths, and misconceptions often fuel opposite views. A critical interdisciplinary examination of the current issues surrounding nitrox was in order to disseminate credible diving safety information. This forum was provided to objectively evaluate the available operational and physiological data relating to the use of nitrox, and discuss risk management, equipment, and training parameters.

An approximation of the magnitude of nitrox consumption was essential. This seemed achievable by our ability to provide a denominator of nitrox divers and nitrox dives, as a sub-set of the overall level of recreational diving activity. Many other discussions of nitrox-related topics flowed from these numbers, i.e., comparable incidence rates of decompression sickness (DCS) in nitrox and compressed-air use, and growth of nitrox training and equipment sales.

Physiological issues such as carbon dioxide retention and oxygen toxicity were also in need of critical examination. Nitrox training and equipment issues were discussed to comprehensively address risk management and legal considerations regarding its use. The recreational diver is the ultimate beneficiary of our improved collective knowledge of the state of the art of nitrox diving in 2000. The intermediary beneficiaries of this information are the providers and manufacturers of nitrox products (instructors, equipment manufacturers, dive stores, and nitrox dispensers).

The history of nitrox

Hamilton discussed the evolutionary history of nitrox diving along the following timeline:[2]

1874 H Fleuss probably made the first nitrox dive with a rebreather.

1947 C Lambertsen published the first nitrox paper.[3]

1955 E Lanphier described the use of nitrogen-oxygen mixtures in diving and the equivalent air depth method for using a standard air table with an enriched air mix.[4]

1960s A Galerne used on-line blenders for commercial diving.

1979 M Wells developed NOAA nitrox and equivalent air depth (EAD) tables were published in the NOAA diving manual for scientific diving.

1985 D Rutkowski developed a nitrox training programme for recreational diving.

1989 The Harbor Branch Oceanographic Institution Nitrox Workshop addressed the following issues and rationale:[5]
- oxygen limits
- decompression and the EAD
- nitrox mixing

- terminology: the term 'nitrox', borrowed from habitat diving, implies that nitrogen is the advantage. The US Navy now prefers 'oxygen-nitrogen'. New NOAA designations are NN_{32} and NN_{36}. EAN_x was agreed upon, with 'x' being the percentage of oxygen (O_2). The correct term proposed was 'oxygen-enriched air'.

1991 'Not Invented Here' went to work. Bennett, Bove, and *SkinDiver Magazine* all took stands against nitrox use by recreational divers.[6,7]

1992 The Scuba Diving Resources Group (a committee of the Outdoor Recreation Coalition of America) organised a nitrox workshop in response to nitrox agencies and products being denied access to the Diving Equipment and Marketing Association (DEMA) trade show in Houston.[8] The workshop resulted in the following endorsements:

- the EAD principle
- the NOAA limits for oxygen exposure (but lower limits were encouraged)
- the use of normal DCS treatment procedures for air diving after nitrox dives (the O_2 exposure of recreational nitrox dives should not affect treatment)
- pending testing, mixes up to 40% O_2 could be used in equipment suitable for air provided equipment was clean and O_2-compatible lubricants were used
- dry nitrox would not corrode cylinders and other gear appreciably faster than air
- air for mixing should be 'oil free'
- cylinders used for nitrox should be compatible with O_2
- mixes should be analysed properly before use, and
- mixing in standard cylinders by adding O_2 and topping with air is considered unsafe.

1993 The aquaCorps TEK93 conference took place in San Francisco. A measurable and attainable air quality standard was set by nitrox industry leaders at 0.1 mg/m^3 oil.

1993 The Canadian Forces issued EAD tables, based on the standard air tables, with an upper O_2 limit of 1.5 ATA PO_2 and depth and time limits more stringent than the air tables.[9]

1996 PADI takes the plunge, nitrox has arrived. NAUI, SSI, and even BSAC have nitrox programmes.[10] The diving media have become supportive of nitrox.

1999 A survey by RW Hamilton for the US Navy showed 100,000s of (not well-documented) open-circuit nitrox dives. Commercial diving does not use nitrox much, but it has become fashionable among recreational divers. The DCS incidence record is good, and nitrox dive computers are readily available.

1999 The Occupational Safety and Health Administration (OSHA) was petitioned by PADI and Oceanic in 1995 on behalf of Dixie Divers, Inc. for a recreational nitrox variance for scuba instructors from commercial diving regulations that was approved for:

- PO_2 of 1.4 ATA and a maximum 40 per cent nitrox mix
- 130 feet maximum depth and dives within the no-stop limits
- a stand-by diver, and
- diving within one hour of a chamber.

2001 NOAA diving manual includes a chapter as stand-alone course guide for nitrox diving.

The physiology of nitrox

DECOMPRESSION

Nitrox improves decompression, which is based on the fraction of nitrogen (N_2) only. Therefore, more O_2 and less N_2 is better. Nitrox allows for greater bottom times for no-stop dives. Decompression dives (with required stops) using an enriched-air mix will result in a total decompression time shorter than that required with air. When nitrox is breathed and air decompression tables are used, the decompression times are not affected, but the dives are considered more conservative. This benefit can apply to repetitive dives, flying after diving, and diving at altitude.

OXYGEN TOXICITY

Convulsions from central nervous system (CNS) toxicity can occur without warning and likely lead to loss of the mouthpiece and subsequent drowning. Warning signs and symptoms, if they do occur, include: visual disturbances (including tunnel vision); tinnitus; nausea; twitching or muscle spasms (especially in the face); irritability, restlessness, euphoria or anxiety; and dizziness. Thus, the diver's exposure to high levels of oxygen must be managed by time limits at maximum PO_2 (Table 1.) Standardised recreational nitrox depth limits are 110 feet of sea water (fsw) (EAN_{36}) and 130 fsw (EAN_{32}). Pulmonary or whole-body oxygen toxicity is monitored by oxygen toxicity units (OTU) or units pulmonary toxicity dose (UPTD). Because of the length of exposure time required to elevate oxygen

Table 1
NOAA oxygen exposure limits[12]

PO_2 (ATA)	Maximum single dive (mins)	Maximum 24 hrs (mins)
1.60	45	150
1.50	120	180
1.40	150	180
1.30	180	210
1.20	210	240
1.10	240	270
1.00	300	300

Table 2
PO_2 limits adopted by the Israeli Navy

Degree of retention	End-tidal CO_2 (torr)	Mixed-expired CO_2 (torr)	Maximum PO_2 (ATA)
None	<50	<41	1.6
Moderate	50–55	41–45	1.4
Extreme	>55	>45	1.2

levels, the onset of CNS effects is unlikely to occur in recreational diving applications. Whole-body symptoms include primarily pulmonary effects (coughing, chest pain, and a reduction in vital capacity) and more diffuse symptoms (paraesthesiae, numbness of fingertips and toes, headache, dizziness, nausea, and a reduction in aerobic capacity).

NARCOSIS

Nitrogen narcosis in oxygen-enriched air diving is not a real issue. However, O_2 can be as narcotic as nitrogen[13] but nitrox diving is not efficient at depths where narcosis becomes prominent.

CO_2 RETENTION

CO_2 build-up is not an issue for recreational nitrox mixes, but may be a hazard in the deeper range of nitrox diving.[14] It causes a reduced ventilatory response, such that breathing a dense mix while exercising can lead to unconsciousness. Headaches are a symptom of hypercapnia, caused by dilation of the arterial vessels in the brain. Kerem et al discuss the Israeli Navy experience with pure O_2 rebreathers,which shows victims of CNS O_2 toxicity to be both retainers and late detectors of build-up of inspired CO_2/malfunctioning absorbers. [15] For higher-risk, extreme CO_2 retainers, more conservative PO_2 limits were adopted by the Israeli Navy (Table 2).

NITROX EFFECTS

The late Jon Hardy initiated a study of human function to test nitrox as a product in 1999.[16] Does diving with nitrox as the breathing gas cause:

- less nitrogen narcosis?
- less fatigue?
- less gas consumption?
- better thermal balance?
- less decompression stress?

Initial results showed no variation in gas consumption between air and nitrox under similar conditions. Difficulty was acknowledged in experimentally designing a study to objectively measure fatigue, decompression stress, and thermal balance. Unfortunately, testing of the reduced nitrogen narcosis of nitrox was not completed by Hardy. More recently, in a double-blinded, randomised controlled study, 11 divers carried out dives breathing either air or EAN_{36} at 18 msw in a dry chamber for 40-minute bottom times.[17] Divers were assessed before and after two exercise periods during the dive. These chamber exposures produced no measurable difference in fatigue, attention levels, or ability to concentrate.

Table 3. Manufacturers' nitrox equipment recommendations (modified from Oliver[18])

Company	Maximum fO_2 authorised (%)			
	23.5	<41	<51	100
Apeks		1		
Aqua-Lung		1		
Atomic		1		
Beuchat			2	
Cressi-Sub	x			
Dacor (parent company policy)		2		
Dive-Rite		2		
Genesis		4		
International Divers Inc.		1		
Kirby-Morgan			1	
Mares America		2		
Oceanic			2	
OMS				1
Sherwood Scuba		4		
Scubapro		1		2,4
Thermo valve		2		
Zeagle (policy reevaluated)		3		4

Key code - Enriched Air Nitrox (EAN) Sep 00

x Maximum limit. EAN not recommended.
1 All models are factory-prepared for EAN using O_2 compatible materials.
2 Designated models factory-prepared for EAN using O_2 compatible materials.
3 Standard air components declared acceptable. Viton o-rings available.
4 Conversion components available for installation by technician qualified to prepare for O_2 service.

Nitrox equipment

Oliver summarised the findings and conclusions of the DEMA Manufacturers Committee on oxygen-enriched air and provided manufacturers' recommendations on nitrox and equipment use.[18]

Two major manufacturers (Scubapro and Aqualung) issued technical bulletins in 2001 on the use of their equipment with nitrox:

SCUBAPRO ENGINEERING BULLETIN #271 (05 SEPTEMBER 2001)

- All Scubapro regulators sold after October 2000 are approved for use with nitrox up to 40% O_2 and for an operating pressure not to exceed 3300 psi. The regulators can be used with gases under the restrictions listed above straight out of the box. Specific models are listed by Scubapro.
- For use with gases (other than air) falling outside of the range detailed above (i.e., 40+% O_2, 3300+ psi), the only approved regulator is the MK20 (brass version only) after appropriate cleaning and installation of the nitrox kit, when the operational limit becomes 100% O_2 to 3500 psi.

AQUALUNG AND APEKS REGULATORS

- New Aqualung and Apeks regulators are now EAN compatible up to 40% O_2 right out of the box. See <www.aqualung.com>, technical library–nitrox compatibility and converting existing regulators to EAN_{40} use.
- Owner's responsibility is to maintain cleanliness of the regulator and cleaning procedures (note switches from air to nitrox). Second-stage cleaning prevents cross-contamination.
- Difference in the regulators is in the manufacturing process (i.e., a regulator 'safe' room). Hyperfiltered air (condensed hydrocarbons < 0.1 mg/m^3) is used for testing, as are some oxygen-compatible components.

Table 3 shows updated manufacturers' recommendations.

Nitrox training and operational data

Table 4 lists the nitrox training requirements for the recreational and scientific diving communities.

Table 5 presents updated (until 2005) nitrox instructor and diver certification information since the original data published in 2001. For reference, Table 6 shows total numbers of entry-level open-water scuba certifications as collected by DEMA for 2000–2005.[19] Finally, Table 7 is likewise updated for available nitrox and air exposures and cases of DCS.

Vann concluded that laboratory and open-water experience suggests that nitrox diving may be practised with low risks of DCS and O_2 toxicity.[20] From DAN data on mixed-gas diving dating from 1990 for diving fatalities, from 1995 for diving injuries and from 1997 for safe dives:

- a higher proportion of safe divers used nitrox than of divers who were injured or died
- nitrox divers were older than air divers
- over 60% of nitrox divers who dived safely had specialty training
- safe nitrox diving was most common aboard charter boats and there were no air or nitrox fatalities from liveaboards
- nitrox divers who dived safely dived fewer dives over more days than did air divers
- in general, nitrox divers dived deeper than air divers, regardless of whether they dived safely, were injured, or died
- for either air or nitrox, injured divers and diving fatalities had higher proportions of rapid ascent and running out of gas than did safe divers
- maximum PO_2 was above 1.3 ATA for half of the 74 injured nitrox divers
- while the incidence of O_2 toxicity during nitrox diving is unknown, convulsions and/or unconsciousness were reported for three divers who had a maximum PO_2 of 1.4, 1.6, and 1.9 ATA respectively
- careful depth control is important to avoid excessively high PO_2 during nitrox diving.

Table 4
Recreational and science/government training requirements

	IANTD	ANDI	TDI	PADI	NAUI	SSI	NOAA	NASA	AAUS	UNCW
Max PO_2 limit (ATA)	1.6	1.6	1.6	1.4	1.4	1.6	1.6	1.6	1.6	1.6
O_2 content range (%)	22-40	22-50	22-40	22-40	22-40	22-40	32 & 36	46	22-40	28-40
O_2 cleaning (%)	>40	>21	>40	Mfr	>40	>40	>40	>23	n/a	>40
O_2 limits (ATA)	all agencies NOAA									
OTU/UPTD	300/day	n/a	n/a	n/a	350/day	NOAA	Repex	415/day	Repex	Repex
Mix analysis accuracy	all agencies ± 1%									
EAN_x table/DC	T/DC	T/DC	T/DC	T/DC	T/DC	T/DC	T/DC	T	T/DC	T/DC
Agency tables	Y	Y	NOAA	Y	Y	Y	NOAA	USN	NOAA	USN
Table model	B-PiN_2	B-PiN_2	USN-EAD	Rogers-RDP	RGBM-USN	USN-EAD	USN99-EAD	USN-EAD	mUSN99-EAD	mUSN99-EAD
Encourage DC	Y	Y	Y	Y	Y	Y	N	n/a	n/a	n/a
Prerequisites	none	none	OW	OW	none	OW	n/a	n/a	n/a	n/a

(B – Buhlmann; DC – dive computer; EAD – equivalent air depth; m – modified; Mfr – manufacturer's recommendation; OW – open water certification; RGBM – reduced gradient bubble model; Rogers-RDP – recreational dive planner; USN – US Navy; USN99 – US Navy 1999 dive tables (unpublished))

Table 5
Available nitrox diver certification data up to November 2000 as reported by organisation representatives at the 2001 workshop[1] on oxygen-enriched air diving and then thereafter

Period:		**Until November 2000**		**November 2000 to November 2005**		
Level:	**From**	**Divers**	**Instructors**	**Instructors**	**Divers**	**Region**
NAUI*	1992–	4,472	878	10,221	92,859	Worldwide
PADI	1996–	46,788	7,274	24,817	223,932	Worldwide
SSI	1996–	1570	605	1,500	12,417	USA
IANTD	1991–	64,378	8,140	6,140	89,049	Worldwide
TDI	1994–	66,206	12,823	8,758	51,592	Worldwide
ANDI	1989–	49,118	3,196	5,350	81,200	Worldwide
UNCW	1986–	803	n/a	8	523	USA
NOAA	1981–	139	n/a	n/a	323	USA
NASA	1996–	384	8	n/a	n/a	USA
AAUS	1987–	n/a	n/a	n/a	n/a	USA
TOTAL		**233,858**	**32,924**	**56,794**	**551,895**	

(*NAUI instructor number increase (2000–2005) results from their authorisation to teach nitrox in addition to compressed-air scuba; n/a – data either not tracked organisationally, or not available; nitrox certifications for divers participating in Aggressor and Sea Hunter fleet courses are included in the totals of the training agencies)

Discussion and conclusions

The DAN nitrox workshop concluded the following in 2000 for entry-level, recreational, open-circuit nitrox diving:

- no evidence was presented that showed an increased risk of DCS with the use of oxygen-enriched air (nitrox) versus compressed air
- a maximum PO_2 of 1.6 ATA was accepted based on the history of nitrox use and scientific studies
- routine CO_2 retention screening is not necessary
- O_2 analysers should use a controlled-flow sampling device
- O_2 analysis of the breathing gas should be performed by the blender and/or dispenser and verified by the end user
- training agencies recognise the effectiveness of dive computers
- there is no need to track whole-body exposure to O_2 (OTU/UPTD)
- use of the 'CNS oxygen clock' concept, based on NOAA O_2 exposure limits should be taught. However, it should be noted that CNS oxygen toxicity could occur suddenly and unexpectedly
- no evidence was presented, based on history of use, to show an unreasonable risk of fire or ignition when using up to 40% nitrox with standard scuba equipment. The level of risk is related to specific equipment configurations and the user should rely on the manufacturer's recommendations.

Additional data collected for 2000–2005, while insufficient for statistical purposes (due to some data categories not being tracked organisationally and therefore remaining unknown), serve to show several trends. The certification numbers of nitrox instructors and divers has approximately doubled, and there does not appear to be a commensurate doubling of nitrox DCS incidence rates. However, comparisons of DCS probabilities between compressed air and nitrox remain tenuous at best. Yet, over one million more nitrox dives (from fill data) were done in the last five years than in the history of its use until November 2000. Liveaboard diving operations report almost exclusive nitrox and dive-computer use aboard their vessels. Due to their operations at remote dive locations and given the nature of their captive diver audiences (i.e., adequate time for reporting of DCS symptoms prior to returning to port), one would expect any significant DCS rates from nitrox diving to be readily apparent.

The Diving Equipment and Marketing Association reported almost one million entry-level open-water scuba certifications and the nitrox training organisations reported over 500,000 nitrox certifications. The relationship or overlap between nitrox and open-water certifications cannot be defined at this point in time due to data collection criteria. The maximum PO_2 limit of 1.6 ATA continues to be used

Table 6
Numbers of entry-level, open-water scuba certifications as reported by DEMA (2005) based on records from NAUI, PADI, SDI, and SSI[19]

Year	**No. certifications**
2000	185,714
2001	198,241
2002	183,394
2003	173,476
2004	173,225
2005 (Jan–June)	74,758
Total	**988,808**

Table 7
Available nitrox and air dive data for occurrence of decompression sickness (DCS) as reported at the 2001 workshop[1] and then thereafter

Period:	**Until November 2000**				**November 2000 to November 2005**			
	Nitrox fills	**DCS**	**Air fills**	**DCS**	**Nitrox fills**	**DCS**	**Air fills**	**DCS**
NAUI	17,604	0	n/a	n/a	3,242,309	n/a	n/a	n/a
PADI	n/a	17	n/a	n/a	n/a	n/a	n/a	n/a
SSI	n/a	0	n/a	n/a	n/a	n/a	n/a	n/a
IANTD	1,411,266	0	n/a	n/a	n/a	n/a	n/a	n/a
TDI	n/a	0	n/a	n/a	n/a	n/a	n/a	n/a
ANDI	967,450	0	n/a	n/a	n/a	n/a	n/a	n/a
Ocean Divers	26,000	n/a	235,504	n/a	34,000	0	n/a	n/a
UNCW	23,407	5	21,201	n/a	13,365	0	18,911	1
NOAA	4,894	1	156,697	22	15,618	2	64,757	18
NASA	34,651	0	n/a	n/a	45,635	n/a	0	0
AAUS	18,461	1	442,679	27	52,325	3	518,695	14
Aggressors	33,778	1	n/a	11	127,759	n/a	n/a	n/a
Sea Hunter	30,400	0	n/a	n/a	130,600	0	15,000	0
TOTAL	**2,567,911**	**25**	**856,081**	**60**	**3,661,611**	**5**	**617,363**	**33**

with no documented ill effects. No further issues have arisen from manufacturers with respect to their equipment being used with nitrox without incidental exposure to oxygen content above 40%.

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PAPER 5.

The Future of Diving:

100 Years of Haldane
and Beyond

Michael A. Lang
and Alf. O. Brubakk

Editors

A Smithsonian Contribution to Knowledge

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The Future of Dive Computers

Michael A. Lang and Sergio Angelini

ABSTRACT. The age of electronic diving has arrived with the development of the modern electronic dive computer as the most significant advancement in self-contained diving since the invention of the Aqualung by Jacques Cousteau. Twenty-five years after modern day dive computer introduction several key questions remain surrounding the decompression models used, validation and human testing, acceptable risk, limitations, failures, and operational reliability. A brief history of analog dive computers and electronic digital computers and their function is discussed. Existing decompression models incorporated into dive computers are discussed with comments on the variety of approaches since Haldane. Educated predictions are offered on the functionality, features and configurations of future dive computer evolution based on benefits from advances in consumer electronics technology, and monitoring technology integrated into the dive computer algorithm that allows for a closer approximation of physiological parameters. Final remarks conclude with how advances in diving physiology research based mainly on Haldane's original work in 1908 will shape the dive computer landscape of the future.

INTRODUCTION

Historically, the diving community has depended predominantly on the United States Navy Air Decompression tables, a direct descendant of Haldane's work, which has served divers well for over five decades. Dive computers, utilizing mathematical models of human tissue compartments and gas exchange, allow the constant computation of the diver's decompression status during the dive. They vary in the assumptions incorporated in their models and in their capabilities. As predicted by Lang and Hamilton (1989) these real-time tools now enjoy widespread use in the recreational, scientific and military diving sectors. Logically, dive computer evolution was a natural progression from decompression tables and as they experienced several generations of development. Computers replaced the diver's watch and depth gauge, provided greater accuracy and computerized, real-time, at-depth, continuous dive profile data, eliminating the need for the diver to remember tables and make decompression decisions while under water and while multi-level diving, allowed for longer bottom times than permitted by tables. Many divers are highly motivated in their activities and interested in maximizing underwater time and efficiency. They view decompression requirements as a hindrance and distraction from their dive objectives, yet are generally concerned about safety.

Evaluations of the available databases on pressure-related injuries to examine the effectiveness of dive computers showed that these devices had demonstrable advantages over dive tables. It remains clear that neither tables nor dive computers can eliminate all decompression problems, which have a probabilistic component to their occurrence. However, the current generation of dive computer technology represents an important tool for further improving diver safety. Divers Alert Network has managed to collect 172,000 dive profiles from 1999 to 2009 through its Project Dive Exploration (PDE), a

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worldwide study of recreational diving to record more than one million dives to produce statistically accurate analyses of depth profiles, diver characteristics, and diver behavior. This collection of real-time depth/time profiles for statistical analysis and modeling will assist in characterizing the relationship between diving and health effects, developing flexible, low-risk decompression procedures for multilevel, multiday repetitive diving; and studying the effects of flying after diving.

Since the appearance of the first commercially mass-produced electronic dive computer, the 1983 ORCA Industries' EDGE model, the operational experience with dive computers is enormous, yet some key considerations remain:

1. **Decompression models:** What models are dive computers programmed with? Does it matter? Should the manufacturers specify the model in their brochures? What are the primary criteria for model effectiveness and "acceptability"?
2. **Validation and human testing:** What comprises an acceptable validation protocol? Should all computers be tested on human subjects with Doppler monitoring? If so, what type of dive profiles should be used, and what does this really prove? And the rejection criteria would be what exactly? Comparisons with existing decompression tables demonstrate the range of no-decompression limits (NDLs) for tables and computers. For square-wave dive profiles, NDLs of dive computers are generally more conservative. Multi-level profile comparisons are more tenuous because of mechanical constraints of the organization of dive table limits versus real-time interval updates of dive computers. Should the manufacturer publish validation data or divulge their modifications or adjustments of published algorithms? Should they be evaluated by an independent agency?
3. **Acceptable risk:** It is generally recognized that zero bends is unachievable and that for operational reasons sectors of the diving community accept different DCS rates. What levels of "bends" risk are acceptable?
4. **Limitations:** Should depth and time limitations be imposed on dive computers? If so, how is this determined? Specifically, what is the applicability of dive computers with regard to long shallow dives, short deep "bounce" dives, stage-decompression dives, repetitive multi-day, multi-level dives, reverse dive profiles, variable ascent rates, diving at altitude and desaturation levels for flying after diving.
5. **Dive computer failure:** What is a diver to do regarding decompression during or after a dive should the computer fail? Are there standardized contingency plans to continue diving after a computer failure, or a requirement for a back-up dive computer?
6. **Operational reliability:** The operational experience has been generally good. Are there specific dive computer component or battery failures? Should the manufacturer provide reliability data?

The incidence of decompression sickness would appear to be an appropriate metric to evaluate the efficiency of dive computers. Assuming that the diver wore the computer, actually looked at it during the dive, and the computer can be interrogated by the hyperbaric chamber operator, useful dive profile information can be retrieved and used in treatment decision making protocols.

HISTORY

The introduction of scuba in the mid-1940s changed diving operations that were carried out by hardhat divers using surface-supplied air for dives at single depths for as long as they needed to complete the mission while decompression status was monitored by surface tenders. Scuba divers without surface contact now had to be responsible for their own decompression status under water. Without an unlimited air supply from the surface the repetitive dive concept became an actuality with the exchange of full scuba cylinders. Three-dimensional freedom of movement during a dive led to multi-level dive profiles.

Various mechanical and electrical analog and microprocessor-based digital dive computers to determine a diver's decompression status in real time have been produced since the advent of scuba in the 1950s. Current computers only use depth and time as variables to compute decompression status. Future computers should incorporate individual and environmental variations and additional variables that play a role in decompression sickness susceptibility, and perhaps ultimately monitor actual inert gas levels in the diver.

The U.S. Navy Committee for Undersea Warfare and Underwater Swimmers met in 1951 at Scripps Institution of Oceanography to identify improvements required in scuba diving equipment and how to control the decompression of a non-tethered, free swimming scuba diver. Groves and Monk's (1953) report established the foundation for most of the early designs for decompression devices and presented a preliminary design for a diver-carried pneumatic analog computer which simulated nitrogen uptake and elimination in two theoretical tissue groups and summarized its benefits:

> The gauge automatically takes into account the depth-time history of the entire dive. The resulting continuous 'optimum ascent' should be somewhat more efficient than the usual step-wise ascent, the latter being used only because of its greater simplicity of presentation in tabular form. There are two other situations for which the gauge is conceivably an improvement over the table. For repeated dives the gauge automatically takes into account the residual elevation of nitrogen pressure in the body from the preceding dives. (Divers are known to be more subject to bends on subsequent dives.) In the case of an emergency ascent, such as may be required by an exhaustion of breathing air, the gauge gives some indication of the desirable recompression procedure.

This report also included a basic design for the "Ultimate Gauge," an electrical analog computer that would show both decompression and air consumption status so that the diver would know if the remaining air supply would be sufficient to perform the required decompression schedule.

Searle (1956) indicated in a Navy Experimental Diving Unit report the need for some type of decompression device because of the ever-widening fields of both civilian and military free-swimming diving using self contained breathing apparatus. Particularly when scuba diving was untended from the surface, there arose a very pressing need for a small portable apparatus to be used by the diver to indicate proper decompression and ascent. Huggins (1989) thoroughly reviewed the history of dive computer evolution through 1988.

ANALOG COMPUTERS

1955: Foxboro Decomputer Mark I

Designed by Hugh Bradner and Mead Bradner, manufactured by the Foxboro Company with 40- and 75-minute halftime compartments (both with 1.75:1 surfacing ratios), a pneumatic design, and 5 bellows (Fredrickson, 1956). Nitrogen absorption and elimination from the compartments was simulated by the flow of gas through porous resistors between bellows, which were exposed to the ambient pressure, and bellows sealed in a vacuum, kept under a constant pressure by a spring. Searle's (1956) evaluation reported the actual compartment half-times simulated by the Foxboro Decomputer Mark I as 27.7 and 52 minutes, causing deviations from U.S. Navy Table decompression ranges for some dives. No further development occurred because the U.S. Navy published new air no-decompression/decompression tables and repetitive dive tables in 1957. The Navy apparently rejected the idea of a decompression computer and accepted option "a" of the Groves and Munk report, i.e., depth gauge, watch, tables, and diver wits (Huggins, 1989).

1959: SOS Decompression Meter

Designed by Carlo Alinari, manufactured by SOS Diving Equipment Limited as a one-compartment pneumatic computer with half-time variations with the pressure differential across the ceramic resistor. The ambient pressure increased on the flexible bag, forcing gas through the ceramic resistor (simulating nitrogen uptake and elimination in the body) into the constant volume chamber. The pressure increase was measured by the bourdon tube gauge, indicating the safe ascent depth to the diver. On ascent, the gas pressure in the constant volume chamber became greater than the external pressure and the gas flow reversed (Huggins, 1989). Howard and Schmitt (1975) evaluated ten SOS meters and determined their no-decompression limits to be more conservative than the U.S. Navy limits at depths shallower than 20 msw, but less conservative at deeper depths.

1963: TRACOR Electrical Analog Computer

Developed by Texas Research Associates Inc. as the first electrical analog decompression computer, employing a 10-section ladder network of series resistors and parallel capacitors to simulate nitrogen diffusion within the body. Ambient pressure measurement was supplied by a depth sensor that varied the voltage supplied to the network. Two 1/2D alkaline cells powered an oven that housed the electronics and kept them at a constant 90 °F. Four small mercury batteries were used as the computer network power source. The display was a micro-ammeter calibrated in fsw displaying how many feet the diver could safely ascend. Workman (1963) found that minimal decompression requirements were adequately predicted for schedules throughout the depth range tested (40–190 fsw) for ascent rates of 20 and 60 fpm. Longer and deeper exposures were not provided adequate depth and total decompression time at stops compared to the U.S. Navy air decompression tables. Continuous ascent decompression predicted by the TRACOR computer was inadequate both in depth and duration of total decompression time. Temperature dependency of the instrument was excessive, particularly for cold exposures, and resulted in widely varying decompression requirements for the same dive schedule. Workman (1963) further suggested that a mechanical analog computer could be used to avoid the instability and breakdowns that occurred in the electrical circuitry.

1962: DCIEM Analog Computer Series (Nishi, 1989)

Developed by D.J. Kidd and R.A. Stubbs at the Defence and Civil Institute for Environmental Medicine (DCIEM) with four compartments to simulate the nitrogen absorption and elimination in the diver. Initial versions' compartments were arranged in parallel, the final design's arranged in series, resulting in the Kidd-Stubbs decompression model (Kidd and Stubbs, 1966). The MARK V S was the first thoroughly tested, successful decompression computer. The four serial compartments gave effective half-times of 5 to over 300 mins (Nishi, 1978). The display consisted of a depth gauge face with two needles: one to indicate the diver's present depth, and the other to indicate the depth to which the diver could safely ascend (Huggins, 1989). The unit was small enough to fit into a housing 9 cm in diameter and 18 cm long, which could be easily carried by a scuba diver. Another version of the device, called the MARK VI S, was designed utilizing the same algorithm for hyperbaric chamber use. The MARK V S was produced by Spar Aerospace in the late 1960s for sale to industrial and military agencies with operational depth limits to 60 msw. In 1970, Spar developed a smaller and lighter version operational to 90 msw. Due to the complexity of construction, high manufacturing costs, and extensive maintenance and calibration requirements, the MARK VS computer was not a commercially viable product for recreational divers.

1973: GE Decompression Meter

Designed by Borom and Johnson (1973) utilizing semipermeable silicon membranes to simulate nitrogen diffusion. These membranes operated better than porous resistors because the simulated half-time of a compartment did not vary with depth (as in the SOS meter). A four-chamber device was built to simulate the U.S. Navy Air Decompression Tables using compartment half-times of 24, 39, 90 and 144 mins. Initial evaluations by GE showed that the membrane-based decompression meter concept was sound. The size of the unit could be reduced and temperature dependence was "well within satisfactory limits." However, no information on any subsequent development and testing was available (Huggins, 1989).

1975: Farallon Decomputer

Manufactured by Farallon Industries, the device was a pneumatic analog computer utilizing four semipermeable membranes (two for gas uptake, 2 for elimination) that simulated two theoretical tissue groups. Air from the collapsible gas chamber flowed through the "fast tissue" (large) and "slow tissue" (small) membranes when exposed to elevated pressures. The increased pressure within the mechanism caused the pistons to move along the display color-coded green, yellow, and red, indicating the diver's decompression status. When the ambient pressure was reduced to a lower pressure than inside the tissue simulator, the air flowed out through the "repetitive dive membrane." Both compartments had offgasing membranes that simulated a slow offgasing rate. Testing at Scripps Institution of Oceanography determined that the Farallon Decomputer failed to "approximate" the U.S. Navy Air Decompression limits and repetitive dives proved even less acceptable, was too permissive, and developed too much mechanical deterioration with use (Flynn, 1978).

Digital Computers

The dive computer consists of a watertight housing with a through-hull pressure transducer that transforms pressure sensed through an analog-digital converter to the microprocessor, powered by a battery. Read-only memory, random-access memory and a clock feed into the microprocessor, which outputs information to the diver via the computer's display (Fig. 1). Huggins (1989) outlined the evolution of a series of digital dive computers once the microprocessor revolution was underway in the mid 1970s. DCIEM unveiled the XDC Digital Decompression Computer Series using the Kidd-Stubbs model. The XDC3 Cyberdiver was actually the first diver-carried microprocessor-based underwater decompression computer. Like the Cyberdiver, the DACOR Dive Computer suffered from very high power consumption and was a US Navy dive table reader. Thalmann (et al., 1980; 1983; 1984) and Presswood et al. (1986) worked on developing an E-L (exponential linear) decompression model and algorithm to program into an Underwater Decompression Computer to be used with the USN constant partial pressure of oxygen closed-circuit mixed gas system. This model assumed that nitrogen absorbed by tissues at an exponential rate (as in Haldanean models), discharged at a slower linear rate. In 1996, Thalmann's VVAL 18 model was tested in the USN's Cochran Navy dive computer.

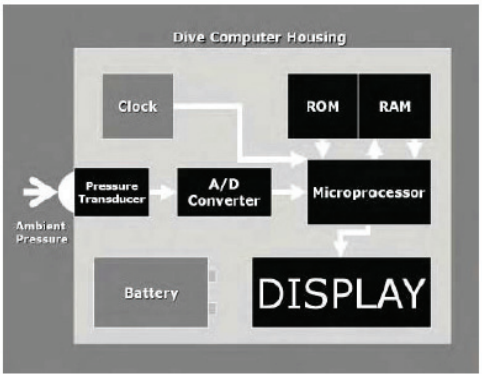

FIGURE 1. Dive computer schematic.

ORCA Industries, Inc. released the EDGE (Electronic Dive Guide) in 1983, the world's first commercially successful, mass produced electronic dive computer that paved the way into this new approach to decompression status monitoring. The ORCA 12-compartment model (half times from 5 to 480 mins) was based on no-decompression limits (to 130fsw) determined, in part, by Doppler ultrasonic bubble detection (Spencer, 1976). The EDGE display was perhaps one of the most innovative to date, divided into graphical and digital information split into two sections by a curve (limit-line) representing the maximum pressure (M-values) allowed in the twelve compartments. One glance by the diver established whether all compartment bars were above the limit-line, indicating a no-decompression dive. The SkinnyDipper (also distributed as a private labeling, Sigmatech, by Sherwood Scuba) from ORCA Industries utilized the same decompression model as the EDGE, but its simpler display scheme consisted of three numerical segments and no graphics. The SME-ML, a nine-compartment Haldanean model with half-times ranging from 2.5 to 480 mins, is also based on Doppler research and was manufactured by SUUNTO of Finland. It stored ten hours of dive information that could be recalled at any time after the dive. The Datamaster II (also distributed as the DataScan II by U.S. Divers Co.) was manufactured by Oceanic using a pseudo-Haldanean decompression model of six compartments with half-times of 5 to 120 mins. This model allowed no off-gassing from the compartments until reaching the surface. The Datamaster II lead the way in calculating air consumption, tank pressure and air time remaining.

In 1979, the Hans Hass Decobrain I was a Swiss table-based computer for high-altitude diving that could perform multi-level computations using the table's repetitive group designators but only by using the 80-minute half-time compartment, which easily put it "out of range" as a decompression device. In 1985, the Decobrain II by Divetronic was based on Bühlmann's 16-compartment Swiss model (ZHL-16) developed with compartment half-times ranging from 4 to 635 mins and designed for altitude diving up to 4500 meters above sea level. Time to fly information was first introduced. The DACOR Microbrain (also manufactured by Divetronics) used six compartments (4.5 to 395 minute half-times) that corresponded to the 16-compartment Swiss model. The Aladin (Uwatec), G.U.I.D.E. (Beuchat) and the Black Fox (Parkway) is the same unit manufactured by Uwatec with a 6-compartment version of the Swiss decompression model utilizing four sets of M-values based on the altitude ranges of the dive. The Uwatec computer could be interrogated and the log entries for the last five dives recalled by activating two wet switches. The Aladin Pro Plus in 1987 was likely the second commercially successful mass-produced dive computer.

Huggins (1989) aptly concludes

> It is interesting to speculate about the present state of scuba diving if the Foxboro Decomputer Mark I had performed properly and had been adopted for U.S. Navy use in 1956. If so, the present U.S. Navy air decompression tables might not have been computed and the standard tool used to determine decompression status might have been a dive computer. Dive computer technology would be far more advanced, and more information and studies about the effects of multi-level diving would be available today.

DECOMPRESSION MODELS

In 1908 John Scott Haldane published a paper (Boycott et al., 1908) that to date represents the most significant milestone in decompression physiology. A multitude of researchers (Hills, 1966; Workman, 1963, 1965; Bühlmann, 1990) and many others over the years have published numerous versions of decompression models which, by and large, are all intrinsically linked to this century-old publication.

As a diver descends in the water column and is exposed to increased ambient pressure, the partial pressure of the inhaled inert gas is higher than that of the dissolved inert gas in the various bodily tissues. This imbalance leads to inert gas travelling from the lungs via the blood stream throughout the body, where it is absorbed in the various tissues at a rate which is a function of the tissue itself (e.g., muscle tissue will "load" up with inert gas faster than fat tissue). The characteristic by which a tissue loads with inert gas is defined by the term "half time", an artificial parameter that defines the time required for a tissue to equilibrate to within 50% of the imposed external pressure.

Similarly, as the diver ascends at the end of the dive and is exposed to a diminishing ambient pressure, the partial pressure of inert gas in a tissue will become higher than the partial pressure of the inhaled inert gas (supersaturation), and hence the inert gas transfer process is inverted. Excess inert gas is returned from the tissues via the blood stream to the lungs, from where it is eliminated by exhalation. The key concept in every form of Haldanean implementation is that decompression sickness is preceded by inert gas bubbles forming due to excessive supersaturation. Therefore, a successful decompression strategy involves controlling the supersaturation in each tissue within defined values. The various versions of Haldanean models differ primarily in the number of tissues considered, their half times and their tolerance to supersaturation (up to the tipping point of bubble formation) and mathematical tricks are applied to cover a variety of influencing factors (e.g., cold, workload, repetitive diving). The primary reason for the success of Haldanean models is that, in spite of their simplistic approach, a vast amount of data exists to which the models have been fitted. Similar to the flower-like trajectory of Mars around the Earth in a Ptolemaic view, enough empirical observation and data fitting can make any model yield excellent results within its tested range.

During the 1980s the prevailing opinion was that bubbles formed during almost all dives, even those not producing any sign or symptom of decompression sickness. This prompted a new wave in decompression modeling that implicitly included bubble formation and growth, and its consequences to the diver. As a main departure from the Haldanean model, inert gas was not only present in dissolved form, but also in free form as a bubble. David Yount proposed a free-phase decompression model, the Variable Permeability Model (Yount and Hoffman, 1986), Michael Gernhardt the Tissue Bubble Dynamics Model (Gernhardt, 1991), and Wayne Gerth and Richard Vann (Gerth and Vann, 1997) the Probabilistic Gas and Bubble Dynamics Model. The most widely implemented model in a simplified version in a variety of dive computers is the Reduced Gradient Bubble Model (Wienke, 1990). Gutvik and Brubakk (2009) are the proponents of Copernicus, and Lewis and Crow (2008) presented an introduction to their Gas Formation Model (GFM). Whereas Yount and Hoffman, and Wienke consider supersaturation as a mechanism to begin bubble formation, Gernhardt, Gerth and Vann, and Gutvik and Brubakk track bubbles from their initial form as microscopic nuclei and follow their evolution and growth as the dive progresses. These latter models are of considerable higher mathematical complexity and cannot be solved within the realm of a modern microprocessor.

The overarching goal of future dive computer models should be to more closely reflect the individual physiology of the diver, evolving as a true electronic instrument designed to solve a physiological problem. Moon et al. (1995) reinforced that the probabilistic models on which tables and computers are based should reflect the individual reality of the divers, to enable them to conduct their dives in accordance with their individual characteristics.

ASCENT RATES, REPETITIVE DIVING, TIME TO FLY, AND MIXED GAS FUNCTIONS

Divers must adhere to the manufacturer's recommended ascent rate, whether variable or uniform, which is an integral component of the algorithm's tissue tension calculations. Training in, and understanding of, proper ascent techniques is fundamental to safe diving practice, including mastering proper buoyancy control, weighting and a controlled ascent with a "hovering" safety stop in the 10–30 fsw zone for 3–5 min (Lang and Egstrom, 1990). It is in the ascent phase of the dive that computers reveal one of their strengths. Existing computers have maximum ascent rates that do not exceed 60 fsw/min from depth and many are limited to 30 fsw/min in shallower water. Future dive computer models may favor slower rates but we make the observation that operationally, the 30 fsw/min is achievable and effective, while slower rates most likely are not.

Multi-level, multiday repetitive computer diving within the tested envelope is the mainstream practice today, and it appears to be less stressful than square wave profile diving. Deep repetitive dives with short surface intervals should nevertheless be given special consideration. Because of limited analysis of the existing profile databases, no firm conclusions have been reached regarding repetitive diving limits to date (Lang and Vann, 1992). The maximum depth sequence of repetitive dive profiles is not restricted by dive computers. Lang and Lehner (2000) found that there was no physiological reason for prohibiting reverse dive profiles for no-decompression dives less than 40 msw (130 fsw) and depth differentials less than 12 msw (40 fsw) because this was never a rule in either U.S. Navy or commercial diving, but more of an operational constraint of the organization of depth/time profiles in a square-wave table format.

There exists no dependable distinction between "safe to fly" and "not safe to fly" in dive computers. There is a gradual reduction of risk for which the diver needs to choose an acceptable degree (e.g., wait at least 24 hours, the longer the wait, the further the reduction in probability of decompression sickness). Lang and Hamilton (1989) provide examples of dive computer computations for "time to fly" that include offgasing to 1–2 fsw (2–4 psi) over ambient pressure, waiting until 12 hrs have elapsed after the last dive, or not exceeding 0.58 bar as maximum ceiling setting (against a minimum aircraft cabin pressure of 0.75 bar).

Adjusting oxygen fractions in dive computer software from 0.21 to standard oxygen-enriched air (nitrox) of 0.32 or 0.36 is simple and an available function of most computers. Huggins (2006) evaluated several dive computers capable of calculating heliox and trimix dive profiles (the EMC-20H by Cochran Undersea Technology, the HS Explorer by HydroSpace Engineering, the NiTek He by Dive Rite, and the VR3 by Delta P Technology). The decompression software that purportedly emulated these four dive computers was used to calculate the response to specific 300 fsw/20 min total bottom time (TBT) dive scenarios, including decompression gas switches. Huggins opined that in surface-supplied mixed-gas operations diver-carried dive computers are best used as a backup and that the major control of decompression should be assigned to the surface-support personnel using a preplanned set of heliox or trimix tables that the dive computer emulates.

THE FUTURE: FUNCTIONALITY, FEATURES AND CONFIGURATIONS

The dive computer of the future will benefit from advances in science and technology. These can be grouped into three distinct categories: benefits from advances in consumer electronics technology, monitoring technology integrated in the algorithm, and advances in decompression physiology research.

BENEFITS FROM ADVANCES IN CONSUMER ELECTRONICS TECHNOLOGY

The combined worldwide sales of dive computers from all manufacturers does not exceed 500,000 units per year, while Apple alone sold over 30 million iPhones in the first 12 months. It becomes obvious then that dive computers do not drive new technologies, but rather benefit from a trickledown effect. In a world dominated by PDAs, Smartphones and iPods, not only is the technological development unbridled, but the cost of these new technologies keeps declining and becoming more affordable. Hence, in spite of the relatively small volumes of dive computer produced, we can expect to start seeing more and more advanced embedded technologies. Other outdoor activities, such as hiking, climbing and camping, are also promoters of new technologies that can find an application within a dive computer.

High Resolution Color Display

Barring a few exceptions dive computers today utilize a segment display. In these types of displays, information is presented by "turning on" certain segments within a large array. Due to the constraints of fitting a wide variety of information on a small display, segment displays typically present only numbers and symbols. Advantages of this technology are low energy consumption and very sharp representation. The main disadvantage, however, is the inability to show anything other than what is "preprogrammed" into the display. This means that any interaction between the diver and the computer takes place through a display of numbers and symbols. In an emergency situation, the diver sees blinking symbols and/or numbers and from this has to infer the nature of the emergency and take appropriate action. The possibility exists that, if the diver does not recognize or otherwise understand the meaning of the blinking symbol, this can lead to an increase in stress in the diver and could potentially precipitate a risky situation.

The switch to a high resolution color display is the most obvious consequence of the proliferation of PDAs and Smartphones. Color dot-matrix displays can play an important role in enhancing the safety of the dive in many ways:

a. Before the dive: menu navigation via text in a language of choice means simplicity and clarity in setting up the computer for the dive;
b. During the dive: one obvious advantage is the clear

representation of all relevant information, possibly with a choice of font size and in a pattern customized by the user. In addition, the combination of text and color can be tremendously helpful in alerting the diver of a potentially risky situation by describing the exact nature of the problem and recommending a course of action. For instance, a diver on nitrox exceeding the maximum operating depth of the breathing gas would see a clear text message such as MAX OPERATING DEPTH EXCEEDED (the nature of the problem) followed by a clear text message such as ASCEND TO 40 MSW (the recommended course of action). A dive computer with a standard segment display cannot do more than beep madly and show blinking symbols; and,

c. After the dive: logbook viewing function with several pages of information, including a graphic representation of the dive.

Rechargeable Battery

Today's computers function well with replaceable batteries, allowing between 100 and 800 dives before the battery runs out. In most cases replacing the battery is a very simple process which, combined with a battery price of a few dollars/euros, makes this an attractive solution. Reliability, an important factor in a life support system, is also very high in this configuration. Color displays, however, require higher energy consumption and thus the switch to a rechargeable battery becomes necessary. With a typical lifetime of 500 charge/discharge cycles and assuming 5 to 10 dives on each full charge, this would allow 2500 to 5000 dives before the battery needs to be replaced. Charging of the battery can take place via a USB cable connected to a PC or directly to a power outlet, or, as in the case of the UEMIS Scuba Diver Assistant, via solar cells.

GPS Receiver

GPS receiver use has become wide spread in outdoor instruments and the automotive industry, where its role is of much higher importance and obvious benefit than in a dive computer. GPS works only through air, hence on the surface, and therefore an application in a dive computer might seem inappropriate. However, it would allow divers to locate dive sites simply by recording their GPS coordinates. Additionally, at the end of the dive, the emerging diver would be able to estimate the distance and direction from the point of entry (boat or shore), which could be useful in a situation of low visibility.

Underwater Communication and Navigation

Communicating underwater with the dive buddy or even all the way to the dive vessel would represent an enormous step forward in diver safety (but perhaps not necessarily in dive enjoyment, because many divers love diving for the peace and quiet provided by the silent world). Furthermore, with the proliferation of navigation systems in automotive technology, it seems only logical to have similar gadgets guiding us through a dive. Data transmission underwater over a certain distance requires the use of ultrasound technology. Radio frequency, as utilized for instance for the transmission of tank information from a sensor on the first stage regulator to the dive computer, is strongly attenuated by water and thus would require too much power to be useful over a longer distance. Ultrasound, on the other hand, can travel very far underwater with relatively little power. Unfortunately, ultrasound is not necessarily a universal technology in consumer electronics, hence its integration in a dive computer may not be in the near future. Attempts have been made though, and for professional use there are voice communication systems which, though bulky, function rather well. GPS-like underwater navigation would require the reproduction of a satellite system for triangulation (set of buoys that translate the GPS signal from the surface to an ultrasound signal underwater) and, as such, would be costly and cumbersome. Simpler devices, which only show the direction and distance to the boat, have been introduced several years ago (Uwatec NEVERLOST, Desert Star Systems DIVETRACKER) but have not enjoyed extensive market penetration.

EPIRB

Emergency Position Indicating Radio Beacon (EPIRB) is a distress signal technology utilized in the maritime industry. EPIRBs are tracking transmitters that aid in the detection and location of boats, aircraft, and people in distress. Strictly speaking, they are radio beacons that interface with Cospas-Sarsat, the international satellite system for search and rescue (SAR). When activated, such beacons send out a distress signal that, when detected by non-geostationary satellites, can be located through triangulation. Often using the initial position provided via the satellite system, the distress signals from the beacons can be homed in on by SAR aircraft and ground search parties who can in turn come to the aid of the concerned boat, aircraft, or people. For instance, should a diver get carried away by a current during a drift dive, an EPIRB built into the dive computer would allow for a relatively quick location and rescue. The related technology is unfortunately rather costly and most divers may never need to be rescued at sea.

BENEFITS FROM MONITORING TECHNOLOGY INTEGRATED INTO THE ALGORITHM

The principal objective of a dive computer is to recommend an ascent schedule as a result of the diver's exposure to a specific depth/time profile. The depth defines the inert gas partial pressure in the inhaled breathing gas which, combined with the length of the exposure (time at depth), drives the inert gas uptake into the diver's tissues. Clearly, perfusion (blood circulation through the body) plays a significant role in that it transports the inert gas through the body from and to the lungs. Consequently, a change in perfusion during the dive, as may be induced by exercise (increased perfusion) or exposure to cold (vasoconstriction in the arms or legs, hence a reduced perfusion), is expected to play a role in the ongasing and offgasing of inert gas. In particular, if the perfusion was increased during the deeper parts of the dive when much inert gas uptake is occurring, and/or the perfusion were reduced during the shallower parts towards the end of the dive, when inert gas elimination is occurring, the simplistic approach of considering only inert gas partial pressures may not be sufficient. In today's dive computers evidently enough conservatism is built in to cover these effects, as evidenced by the relatively low incidence rates of decompression sickness.

There are attempts to account for changes in perfusion. One approach is to lump any deviation from a "normal" exposure into additional conservatism in the model ("personal factors"). The clear disadvantage of this method is that the diver needs to define and predict before the dive whether strenuous exercise or chilling is expected to occur. The other approach, followed at the moment only by UWATEC and UEMIS, is to evaluate changes in perfusion based on actual measurements during the dive. An increase in workload is measured either by heart rate monitoring (UWATEC) or by a change in breathing pattern (UWATEC and UEMIS). Cold water effects, which theoretically could lead to a reduction in perfusion during the decompression phase of the dive, are based on the concept that the colder the water, the more vasoconstriction plays a role (Angelini, 2007). A thermally insulated diver, however, may be warmer in 4 °C water than a poorly protected diver in the Caribbean, and here a pre-dive set cold factor could be more practical.

Regardless, in spite of the theoretical validity of the effect of changes in perfusion during the dive, the actual implementation within a decompression model has not been experimentally validated or clinically proven. A thorough review of cold as decompression sickness stress factor was performed by Mueller (2007). One can argue that diving is a reasonably safe activity and that therefore these model complications are uncalled for. Another point of view is that this is an indication of excessive conservatism in today's models so that, with proper implementation of these phenomena, a diver could enjoy more freedom.

However, as advances in science and decompression physiology are made, we propose the continued development of the following technologies:

1. **Heart rate monitoring.** There is a proliferation of heart-rate monitoring devices in most outdoor and fitness activities. As people become more aware of the importance of exercise to their well being, they also discover heart rate monitoring as an excellent tool for fitness evaluation. Recording the heart rate during a dive can be useful, besides from an implementation of workload-related nitrogen calculations, to become aware of how the body responds to the environment, leading to either increased comfort and enjoyment (recorded heart rate is low and consistent) or the avoidance of certain types of stressful dives (high and/or erratic heart rate).
2. **Skin temperature measurements.** Vasoconstriction is the result of the brain's recognition that the core body temperature is diminishing. In order to maintain the function of critical body parts the brain reduces blood circulation to the limbs (arms and legs) with their large surface to volume ratio to reduce heat loss and protect the heart, lungs, and brain. Skin temperature measurements transmitted to the dive computer would allow for a quantification of the cooling. In addition to an implementation of vasoconstriction in the decompression model, this could be very important as an alarm trigger for approaching hypothermia. Hypothermia is an acute danger when pain and feeling of cold disappears once the body gives up on shivering as a mechanism of generate warmth.
3. **Oxygen saturation measurement.** This is of primary interest to free divers because the risk of oxygen depletion and consequent shallow-water blackout is high. Nevertheless, this and other blood monitoring technologies could find applications in scuba or rebreather diving.
4. **Inert gas bubble detection.** Inert gas uptake and consequent offgasing is in and of itself not the cause of decompression sickness. Problems can occur when the combination of excessive amounts of inert gas dissolved in the body and a diminishing ambient pressure lead to the gas coming out of solution and forming free gas bubbles in the body. Some decompression models attempt to describe this free gas formation, with all the complexity that follows from the physics associated with such an event. It would be very useful if it were possible to detect bubble formation during the dive, integrated into a feedback loop into the decompression algorithm (regardless of the nature of the algorithm itself). There exist, however, two rather large obstacles to this. First, the bubble detection technology existing today is based on ultrasound or Doppler monitoring, both requiring rather cumbersome equipment that could hardly be placed on a diver during the dive. The second problem is that bubbles really do not grow to a discernible level until 20 to 40 minutes after the dive, so that in-water detection might only be useful in extreme dives in which something went seriously wrong. On the other hand, this line of thinking could lead to the development of a similar or new kind of technology aimed at detecting a physiologically viable parameter that gives an indication of decompression stress in the body. Any parameter that gives online feedback into a decompression model as to the state of the diver with respect to potential DCS would be a tremendous benefit.

Benefits from Advances in Decompression Physiology Research

As described above, decompression models in existence today are, aside from a few mathematical manipulations, almost entirely based on the ideas of John Scott Haldane presented in the historic 1908 paper (Doolette, 2009). Actual bubble models that carry out the pertinent bubble-dynamics calculations (and the related non-linear differential equations) are too complex to be managed by the limited processing power of a dive computer microprocessor. Even if this were to be solved, what remains is the need to validate such a radically different approach to decompression. There is an attempt by the Norwegian University for Science and Technology to build a complete bubble model under the project name Copernicus. As much as the earth-centered planetary model was intrinsically flawed yet allowed reasonable ocean navigation via immense empirical observations of the movements of the stars (made to fit this wrong model), a sun-centered planetary system yielded much better and accurate results allowing for significant broadening of the range of validity of the model itself. Haldanean theory, which does not consider inert gas in free form, and consequently its effects on the human body, has been refined over a century with the input of Workman (1963), Bühlmann (1990), Thalmann et al. (1980) and Thalmann (1983; 1984) to name a few, and provides us today with an extremely valuable and powerful tool in spite of its underlying wrong assumption. Copernicus, the decompression model, is the attempt to find the sun-centered model for decompression physiology, yet at the moment the wealth of data with which the existing models have been refined gives the Haldanean-based models a clear advantage. Science and its related research should nevertheless persist in the pursuit of the "truth". A full bubble model availability within a few years would be very welcome. Such a model should incorporate those aspects of relevance in approximating the human body such as body fat, age, gender, and fitness level.

CONCLUSION

Electronic dive computers have for all practical purposes replaced dive tables in recreational and scientific diving and are increasingly implemented in particular segments of the military diving community. For the commercial diving industry and its standard operating methods of surface-supplied/controlled diving or saturation diving, a dive computer's advantages in monitoring decompression status appear to be minimal. It would not be unreasonable to state that regardless of the number of algorithm variations incorporated in modern dive computers, they all appear to fall within an acceptable window of effectiveness based on available databases of pressure-related injuries. It is also clear that neither tables nor dive computers can eliminate all decompression problems, but if utilized conservatively, computers have emerged as an important tool for the improvement of diver safety.

All things considered, the dive computer's functions of ascent rate monitoring, real-time computation of nitrogen balances, air consumption monitoring and profile downloading capability form a solid, reliable basis for advancements that will emerge in the future. Benefits from advances in consumer electronics technology will undoubtedly incorporate features such as high resolution color display, rechargeable battery, GPS receiver, underwater communication and navigation, and EPIRB. Further, benefits from monitoring technology integrated in the dive computer algorithm will surely include heart rate monitoring, skin temperature measurements, oxygen saturation monitoring, and perhaps even inert gas bubble detection. We can only imagine the progress that John Scott Haldane's brilliant decompression insight would have made had the dive computer tools available to us now and in the future been available to him 100 years ago.

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86. Jie Ming Shen: BLOOD FLOW VELOCITY AND RESPIRATORY STUDIES.
87. Piotr Kruszewski: SUNCT SYNDROME WITH SPECIAL REFERENCE TO THE AUTONOMIC NERVOUS SYSTEM.
88. Mette Haase Moen: ENDOMETRIOSIS.
89. Anne Vik: VASCULAR GAS EMBOLISM DURING AIR INFUSION AND AFTER DECOMPRESSION IN PIGS.
90. Lars Jacob Stovner: THE CHIARI TYPE I MALFORMATION.
91. Kjell Å. Salvesen: ROUTINE ULTRASONOGRAPHY *IN UTERO* AND DEVELOPMENT IN CHILDHOOD.

1994

92. Nina-Beate Liabakk: DEVELOPMENT OF IMMUNOASSAYS FOR TNF AND ITS SOLUBLE RECEPTORS.
93. Sverre Helge Torp: *erb*B ONCOGENES IN HUMAN GLIOMAS AND MENINGIOMAS.
94. Olav M. Linaker: MENTAL RETARDATION AND PSYCHIATRY: Past and present.
95. Per Oscar Feet: INCREASED ANTIDEPRESSANT AND ANTIPANIC EFFECT IN COMBINED TREATMENT WITH DIXYRAZINE AND TRICYCLIC ANTIDEPRESSANTS.
96. Stein Olav Samstad: CROSS SECTIONAL FLOW VELOCITY PROFILES FROM TWO-DIMENSIONAL DOPPLER ULTRASOUND: Studies on early mitral blood flow.
97. Bjørn Backe: STUDIES IN ANTENATAL CARE.
98. Gerd Inger Ringdal: QUALITY OF LIFE IN CANCER PATIENTS.
99. Torvid Kiserud: THE *DUCTUS VENOSUS* IN THE HUMAN FETUS.
100. Hans E. Fjøsne: HORMONAL REGULATION OF PROSTATIC METABOLISM.
101. Eylert Brodtkorb: CLINICAL ASPECTS OF EPILEPSY IN THE MENTALLY RETARDED.
102. Roar Juul: PEPTIDERGIC MECHANISMS IN HUMAN SUBARACHNOID HEMORRHAGE.
103. Unni Syversen: CHROMOGRANIN A: Physiological and Clinical Role.

1995

104. Odd Gunnar Brakstad: THERMOSTABLE NUCLEASE AND THE *nuc* GENE IN THE DIAGNOSIS OF *Staphylococcus aureus* INFECTIONS.
105. Terje Engan: NUCLEAR MAGNETIC RESONANCE (NMR) SPECTROSCOPY OF PLASMA IN MALIGNANT DISEASE.

106. Kirsten Rasmussen: VIOLENCE IN THE MENTALLY DISORDERED.
107. Finn Egil Skjeldestad: INDUCED ABORTION: Timetrends and determinants.
108. Roar Stenseth: THORACIC EPIDURAL ANALGESIA IN AORTOCORONARY BYPASS SURGERY.
109. Arild Faxvaag: STUDIES OF IMMUNE CELL FUNCTION IN MICE INFECTED WITH MURINE RETROVIRUS.

1996

110. Svend Aakhus: NONINVASIVE COMPUTERIZED ASSESSMENT OF LEFT VENTRICULAR FUNCTION AND SYSTEMIC ARTERIAL PROPERTIES: Methodology and some clinical applications.
111. Klaus-Dieter Bolz: INTRAVASCULAR ULTRASONOGRAPHY.
112. Petter Aadahl: CARDIOVASCULAR EFFECTS OF THORACIC AORTIC CROSS-CLAMPING.
113. Sigurd Steinshamn: CYTOKINE MEDIATORS DURING GRANULOCYTOPENIC INFECTIONS.
114. Hans Stifoss-Hanssen: SEEKING MEANING OR HAPPINESS?
115. Anne Kvikstad: LIFE CHANGE EVENTS AND MARITAL STATUS IN RELATION TO RISK AND PROGNOSIS OF CANCER.
116. Torbjørn Grøntvedt: TREATMENT OF ACUTE AND CHRONIC ANTERIOR CRUCIATE LIGAMENT INJURIES: A clinical and biomechanical study.
117. Sigrid Hørven Wigers: CLINICAL STUDIES OF FIBROMYALGIA WITH FOCUS ON ETIOLOGY, TREATMENT AND OUTCOME.
118. Jan Schjøtt: MYOCARDIAL PROTECTION: Functional and metabolic characteristics of two endogenous protective principles.
119. Marit Martinussen: STUDIES OF INTESTINAL BLOOD FLOW AND ITS RELATION TO TRANSITIONAL CIRCULATORY ADAPATION IN NEWBORN INFANTS.
120. Tomm B. Müller: MAGNETIC RESONANCE IMAGING IN FOCAL CEREBRAL ISCHEMIA.
121. Rune Haaverstad: OEDEMA FORMATION OF THE LOWER EXTREMITIES.
122. Magne Børset: THE ROLE OF CYTOKINES IN MULTIPLE MYELOMA, WITH SPECIAL REFERENCE TO HEPATOCYTE GROWTH FACTOR.
123. Geir Smedslund: A THEORETICAL AND EMPIRICAL INVESTIGATION OF SMOKING, STRESS AND DISEASE: Results from a population survey.

1997

124. Torstein Vik: GROWTH, MORBIDITY, AND PSYCHOMOTOR DEVELOPMENT IN INFANTS WHO WERE GROWTH RETARDED *IN UTERO*.
125. Siri Forsmo: ASPECTS AND CONSEQUENCES OF OPPORTUNISTIC SCREENING FOR CERVICAL CANCER: Results based on data from three Norwegian counties.
126. Jon S. Skranes: CEREBRAL MRI AND NEURODEVELOPMENTAL OUTCOME IN VERY LOW BIRTH WEIGHT (VLBW) CHILDREN: A follow-up study of a geographically based year cohort of VLBW children at ages one and six years.
127. Knut Bjørnstad: COMPUTERIZED ECHOCARDIOGRAPHY FOR EVALUTION OF CORONARY ARTERY DISEASE.
128. Grethe Elisabeth Borchgrevink: DIAGNOSIS AND TREATMENT OF WHIPLASH/NECK SPRAIN INJURIES CAUSED BY CAR ACCIDENTS.
129. Tor Elsås: NEUROPEPTIDES AND NITRIC OXIDE SYNTHASE IN OCULAR AUTONOMIC AND SENSORY NERVES.
130. Rolf W. Gråwe: EPIDEMIOLOGICAL AND NEUROPSYCHOLOGICAL PERSPECTIVES ON SCHIZOPHRENIA.
131. Tonje Strømholm: CEREBRAL HAEMODYNAMICS DURING THORACIC AORTIC CROSSCLAMPING: An experimental study in pigs.

1998

132. Martinus Bråten: STUDIES ON SOME PROBLEMS RELATED TO INTRAMEDULLARY NAILING OF FEMORAL FRACTURES.
133. Ståle Nordgård: PROLIFERATIVE ACTIVITY AND DNA CONTENT AS PROGNOSTIC INDICATORS IN ADENOID CYSTIC CARCINOMA OF THE HEAD AND NECK.
134. Egil Lien: SOLUBLE RECEPTORS FOR TNF AND LPS: Release pattern and possible significance in disease.
135. Marit Bjørgaas: HYPOGLYCAEMIA IN CHILDREN WITH *DIABETES MELLITUS*.
136. Frank Skorpen: GENETIC AND FUNCTIONAL ANALYSES OF DNA REPAIR IN HUMAN CELLS.

137. Juan A. Pareja: SUNCT SYNDROME. ON THE CLINICAL PICTURE: Its distinction from other, similar headaches.
138. Anders Angelsen: NEUROENDOCRINE CELLS IN HUMAN PROSTATIC CARCINOMAS AND THE PROSTATIC COMPLEX OF RAT, GUINEA PIG, CAT AND DOG.
139. Fabio Antonaci: CHRONIC PAROXYSMAL HEMICRANIA AND *HEMICRANIA CONTINUA*: TWO DIFFERENT ENTITIES?
140. Sven M. Carlsen: ENDOCRINE AND METABOLIC EFFECTS OF METFORMIN WITH SPECIAL EMPHASIS ON CARDIOVASCULAR RISK FACTORS.

1999

141. Terje A. Murberg: DEPRESSIVE SYMPTOMS AND COPING AMONG PATIENTS WITH CONGESTIVE HEART FAILURE.
142. Harm-Gerd Karl Blaas: THE EMBRYONIC EXAMINATION: Ultrasound studies on the development of the human embryo.
143. Noèmi Becser Andersen: THE CEPHALIC SENSORY NERVES IN UNILATERAL HEADACHES: Anatomical background and neurophysiological evaluation.
144. Eli-Janne Fiskerstrand: LASER TREATMENT OF PORT WINE STAINS: A study of the efficacy and limitations of the pulsed dye laser; clinical and morphological analyses aimed at improving the therapeutic outcome.
145. Bård Kulseng: A STUDY OF ALGINATE CAPSULE PROPERTIES AND CYTOKINES IN RELATION TO INSULIN-DEPENDENT *DIABETES MELLITUS*.
146. Terje Haug: STRUCTURE AND REGULATION OF THE HUMAN UNG GENE ENCODING URACIL-DNA GLYCOSYLASE.
147. Heidi Brurok: MANGANESE AND THE HEART: A magic metal with diagnostic and therapeutic possibilities.
148. Agnes Kathrine Lie: DIAGNOSIS AND PREVALENCE OF HUMAN PAPILLOMAVIRUS INFECTION IN CERVICAL INTRAEPITHELIAL NEOPLASIA: Relationship to cell cycle regulatory proteins and HLA DQBI genes.
149. Ronald Mårvik: PHARMACOLOGICAL, PHYSIOLOGICAL AND PATHOPHYSIOLOGICAL STUDIES ON ISOLATED STOMACHS.
150. Ketil Jarl Holen: THE ROLE OF ULTRASONOGRAPHY IN THE DIAGNOSIS AND TREATMENT OF HIP DYSPLASIA IN NEWBORNS.
151. Irene Hetlevik: THE ROLE OF CLINICAL GUIDELINES IN CARDIOVASCULAR RISK INTERVENTION IN GENERAL PRACTICE.
152. Katarina Tunòn: ULTRASOUND AND PREDICTION OF GESTATIONAL AGE.
153. Johannes Soma: INTERACTION BETWEEN THE LEFT VENTRICLE AND THE SYSTEMIC ARTERIES.
154. Arild Aamodt: DEVELOPMENT AND PRE-CLINICAL EVALUATION OF A CUSTOM-MADE FEMORAL STEM.
155. Agnar Tegnander: DIAGNOSIS AND FOLLOW-UP OF CHILDREN WITH SUSPECTED OR KNOWN HIP DYSPLASIA.
156. Bent Indredavik: STROKE UNIT TREATMENT: Short and long-term effects.
157. Jolanta Vanagaite Vingen: PHOTOPHOBIA AND PHONOPHOBIA IN PRIMARY HEADACHES.

2000

158. Ola Dalsegg Sæther: PATHOPHYSIOLOGY DURING PROXIMAL AORTIC CROSS-CLAMPING CLINICAL AND EXPERIMENTAL STUDIES.
159. xxxxxxxxx (blind number)
160. Christina Vogt Isaksen: PRENATAL ULTRASOUND AND POSTMORTEM FINDINGS: A ten-year correlative study of fetuses and infants with developmental anomalies.
161. Holger Seidel: HIGH-DOSE METHOTREXATE THERAPY IN CHILDREN WITH ACUTE LYMPHOCYTIC LEUKEMIA: Dose, concentration, and effect considerations.
162. Stein Hallan: IMPLEMENTATION OF MODERN MEDICAL DECISION ANALYSIS INTO CLINICAL DIAGNOSIS AND TREATMENT.
163. Malcolm Sue-Chu: INVASIVE AND NON-INVASIVE STUDIES IN CROSS-COUNTRY SKIERS WITH ASTHMA-LIKE SYMPTOMS.
164. Ole-Lars Brekke: EFFECTS OF ANTIOXIDANTS AND FATTY ACIDS ON TUMOR NECROSIS FACTOR-INDUCED CYTOTOXICITY.

165. Jan Lundbom: AORTOCORONARY BYPASS SURGERY: Clinical aspects, cost considerations and working ability.
166. John-Anker Zwart: LUMBAR NERVE ROOT COMPRESSION: Biochemical and neurophysiological aspects.
167. Geir Falck: HYPEROSMOLALITY AND THE HEART.
168. Eirik Skogvoll: CARDIAC ARREST: Incidence, Intervention and Outcome.
169. Dalius Bansevicius: SHOULDER-NECK REGION IN CERTAIN HEADACHES AND CHRONIC PAIN SYNDROMES.
170. Bettina Kinge: REFRACTIVE ERRORS AND BIOMETRIC CHANGES AMONG UNIVERSITY STUDENTS IN NORWAY.
171. Gunnar Qvigstad: CONSEQUENCES OF HYPERGASTRINEMIA IN MAN.
172. Hanne Ellekjær: EPIDEMIOLOGICAL STUDIES OF STROKE IN A NORWEGIAN POPULATION: Incidence, Risk Factors and Prognosis.
173. Hilde Grimstad: VIOLENCE AGAINST WOMEN AND PREGNANCY OUTCOME.
174. Astrid Hjelde: SURFACE TENSION AND COMPLEMENT ACTIVATION: Factors influencing bubble formation and bubble effects after decompression.
175. Kjell A. Kvistad: MR IN BREAST CANCER: A clinical study.
176. Ivar Rossvoll: ELECTIVE ORTHOPAEDIC SURGERY IN A DEFINED POPULATION: Studies on demand, waiting time for treatment and incapacity for work.
177. Carina Seidel: PROGNOSTIC VALUE AND BIOLOGICAL EFFECTS OF HEPATOCYTE GROWTH FACTOR AND SYNDECAN-1 IN MULTIPLE MYELOMA.

2001

178. Alexander Wahba: THE INFLUENCE OF CARDIOPULMONARY BYPASS ON PLATELET FUNCTION AND BLOOD COAGULATION: Determinants and clinical consequences.
179. Marcus Schmitt-Egenolf: THE RELEVANCE OF THE MAJOR HISTOCOMPATIBILITY COMPLEX FOR THE GENETICS OF PSORIASIS.
180. Odrun Arna Gederaas: BIOLOGICAL MECHANISMS INVOLVED IN 5-AMINOLEVULINIC ACID-BASED PHOTODYNAMIC THERAPY.
181. Pål Richard Romundstad: CANCER INCIDENCE AMONG NORWEGIAN ALUMINIUM WORKERS.
182. Henrik Hjorth-Hansen: NOVEL CYTOKINES IN GROWTH CONTROL AND BONE DISEASE OF MULTIPLE MYELOMA.
183. Gunnar Morken: SEASONAL VARIATION OF HUMAN MOOD AND BEHAVIOUR.
184. Bjørn Olav Haugen: MEASUREMENT OF CARDIAC OUTPUT AND STUDIES OF VELOCITY PROFILES IN AORTIC AND MITRAL FLOW USING TWO- AND THREE-DIMENSIONAL COLOUR FLOW IMAGING.
185. Geir Bråthen: THE CLASSIFICATION AND CLINICAL DIAGNOSIS OF ALCOHOL-RELATED SEIZURES.
186. Knut Ivar Aasarød: RENAL INVOLVEMENT IN INFLAMMATORY RHEUMATIC DISEASE: A study of renal disease in Wegener's Granulomatosis and in Primary Sjögren's Syndrome.
187. Trude Helen Flo: RECEPTORS INVOLVED IN CELL ACTIVATION BY DEFINED URONIC ACID POLYMERS AND BACTERIAL COMPONENTS.
188. Bodil Kavli: HUMAN URACIL-DNA GLYCOSYLASES FROM THE UNG GENE: Structural basis for substrate specificity and repair.
189. Liv Thommesen: MOLECULAR MECHANISMS INVOLVED IN TNF- AND GASTRIN-MEDIATED GENE REGULATION.
190. Turid Lingaas Holmen: SMOKING AND HEALTH IN ADOLESCENCE: The Nord-Trøndelag Health Study, 1995-97.
191. Øyvind Hjertner: MULTIPLE MYELOMA: Interactions between malignant plasma cells and the bone microenvironment.
192. Asbjørn Støylen: STRAIN RATE IMAGING OF THE LEFT VENTRICLE BY ULTRASOUND: Feasibility, clinical validation and physiological aspects.
193. Kristian Midthjell: DIABETES IN ADULTS IN NORD-TRØNDELAG: Public health aspects of diabetes mellitus in a large, non-selected Norwegian population.
194. Guanglin Cui: FUNCTIONAL ASPECTS OF THE ECL CELL IN RODENTS.
195. Ulrik Wisløff: CARDIAC EFFECTS OF AEROBIC ENDURANCE TRAINING: Hypertrophy, contractility and calcium handling in normal and failing heart.

196. Øyvind Halaas: MECHANISMS OF IMMUNOMODULATION AND CELL-MEDIATED CYTOTOXICITY INDUCED BY BACTERIAL PRODUCTS.
197. Tore Amundsen: PERFUSION MR IMAGING IN THE DIAGNOSIS OF PULMONARY EMBOLISM.
198. Nanna Kurtze: THE SIGNIFICANCE OF ANXIETY AND DEPRESSION IN FATIGUE AND PATTERNS OF PAIN AMONG INDIVIDUALS DIAGNOSED WITH FIBROMYALGIA: Relations with quality of life, functional disability, lifestyle, employment status, co-morbidity and gender.
199. Tom Ivar Lund Nilsen: PROSPECTIVE STUDIES OF CANCER RISK IN NORD-TRØNDELAG - THE HUNT STUDY: Associations with anthropometric, socioeconomic, and lifestyle risk factors.
200. Asta Kristine Håberg: A NEW APPROACH TO THE STUDY OF MIDDLE CEREBRAL ARTERY OCCLUSION IN THE RAT USING MAGNETIC RESONANCE TECHNIQUES.

2002

201. Knut Jørgen Arntzen: PREGNANCY AND CYTOKINES.
202. Henrik Døllner: INFLAMMATORY MEDIATORS IN PERINATAL INFECTIONS.
203. Asta Bye: LOW FAT, LOW LACTOSE DIET USED AS PROPHYLACTIC TREATMENT OF ACUTE INTESTINAL REACTIONS DURING PELVIC RADIOTHERAPY: A prospective randomised study.
204. Sylvester Moyo: STUDIES ON *STREPTOCOCCUS AGALACTIAE* (GROUP B STREPTOCOCCUS) SURFACE-ANCHORED MARKERS WITH EMPHASIS ON STRAINS AND HUMAN SERA FROM ZIMBABWE.
205. Knut Hagen: HEAD-HUNT: The epidemiology of headache in Nord-Trøndelag.
206. Li Lixin: ON THE REGULATION AND ROLE OF UNCOUPLING PROTEIN-2 IN INSULIN PRODUCING ß-CELLS.
207. Anne Hildur Henriksen: SYMPTOMS OF ALLERGY AND ASTHMA VERSUS MARKERS OF LOWER AIRWAY INFLAMMATION AMONG ADOLESCENTS.
208. Egil Andreas Fors: NON-MALIGNANT PAIN IN RELATION TO PSYCHOLOGICAL AND ENVIRONMENTAL FACTORS: Experiental and clinical studies of pain with focus on fibromyalgia.
209. Pål Klepstad: MORPHINE FOR CANCER PAIN.
210. Ingunn Bakke: MECHANISMS AND CONSEQUENCES OF PEROXISOME PROLIFERATOR-INDUCED HYPERFUNCTION OF THE RAT GASTRIN PRODUCING CELL.
211. Ingrid Susann Gribbestad: MAGNETIC RESONANCE IMAGING AND SPECTROSCOPY OF BREAST CANCER.
212. Rønnaug Astri Ødegård: PREECLAMPSIA: Maternal risk factors and fetal growth.
213. Johan Haux: STUDIES ON CYTOTOXICITY INDUCED BY HUMAN NATURAL KILLER CELLS AND DIGITOXIN.
214. Turid Suzanne Berg-Nielsen: PARENTING PRACTICES AND MENTALLY DISORDERED ADOLESCENTS.
215. Astrid Rydning: BLOOD FLOW AS A PROTECTIVE FACTOR FOR THE STOMACH MUCOSA: An experimental study on the role of mast cells and sensory afferent neurons.

2003

216. Jan Pål Loennechen: HEART FAILURE AFTER MYOCARDIAL INFARCTION: Regional differences, myocyte function, gene expression, and response to Cariporide, Losartan, and exercise training.
217. Elisabeth Qvigstad: EFFECTS OF FATTY ACIDS AND OVER-STIMULATION ON INSULIN SECRETION IN MAN.
218. Arne Åsberg: EPIDEMIOLOGICAL STUDIES IN HEREDITARY HEMOCHROMATOSIS: Prevalence, morbidity and benefit of screening.
219. Johan Fredrik Skomsvoll: REPRODUCTIVE OUTCOME IN WOMEN WITH RHEUMATIC DISEASE: A population-registry based study of the effects of inflammatory rheumatic disease and connective tissue disease on reproductive outcome in Norwegian women in 1967-1995.
220. Siv Mørkved: URINARY INCONTINENCE DURING PREGNANCY AND AFTER DELIVERY: Effect of pelvic floor muscle training in prevention and treatment.
221. Marit S. Jordhøy: THE IMPACT OF COMPREHENSIVE PALLIATIVE CARE.
222. Tom Christian Martinsen: HYPERGASTRINEMIA AND HYPOACIDITY IN RODENTS: Causes and consequences.
223. Solveig Tingulstad: CENTRALIZATION OF PRIMARY SURGERY FOR OVARIAN CANCER: Feasibility and impact on survival.

224. Haytham Eloqayli: METABOLIC CHANGES IN THE BRAIN CAUSED BY EPILEPTIC SEIZURES.
225. Torunn Bruland: STUDIES OF EARLY RETROVIRUS-HOST INTERACTIONS: Viral determinants for pathogenesis and the influence of sex on the susceptibility to Friend murine leukaemia virus infection.
226. Torstein Hole: DOPPLER ECHOCARDIOGRAPHIC EVALUATION OF LEFT VENTRICULAR FUNCTION IN PATIENTS WITH ACUTE MYOCARDIAL INFARCTION.
227. Vibeke Nossum: THE EFFECT OF VASCULAR BUBBLES ON ENDOTHELIAL FUNCTION.
228. Sigurd Fasting: ROUTINE BASED RECORDING OF ADVERSE EVENTS DURING ANAESTHESIA: Application in quality improvement and safety.
229. Solfrid Romundstad: EPIDEMIOLOGICAL STUDIES OF MICROALBUMINURIA: The Nord-Trøndelag Health Study 1995-97 (HUNT 2).
230. Geir Torheim: PROCESSING OF DYNAMIC DATA SETS IN MAGNETIC RESONANCE IMAGING.
231. Catrine Ahlén: SKIN INFECTIONS IN OCCUPATIONAL SATURATION DIVERS IN THE NORTH SEA AND THE IMPACT OF THE ENVIRONMENT.
232. Arnulf Langhammer: RESPIRATORY SYMPTOMS, LUNG FUNCTION AND BONE MINERAL DENSITY IN A COMPREHENSIVE POPULATION SURVEY. The N-Trøndelag Health Study 1995-97; The bronchial obstruction in Nord-Trøndelag study.
233. Einar Kjelsås: EATING DISORDERS AND PHYSICAL ACTIVITY IN NON-CLINICAL SAMPLES.
234. Arne Wibe: RECTAL CANCER TREATMENT IN NORWAY: Standardisation of surgery and quality assurance.

2004

235. Eivind Witsø: BONE GRAFT AS AN ANTIBIOTIC CARRIER.
236. Anne Mari Sund: DEVELOPMENT OF DEPRESSIVE SYMPTOMS IN EARLY ADOLESCENCE.
237. Hallvard Lærum: EVALUATION OF ELECTRONIC MEDICAL RECORDS: A clinical task perspective.
238. Gustav Mikkelsen: ACCESSIBILITY OF INFORMATION IN ELECTRONIC PATIENT RECORDS: An evaluation of the role of data quality.
239. Steinar Krokstad: SOCIOECONOMIC INEQUALITIES IN HEALTH AND DISABILITY: Social epidemiology in the Nord-Trøndelag Health Study (Hunt), Norway.
240. Arne Kristian Myhre: NORMAL VARIATION IN ANOGENITAL ANATOMY AND MICROBIOLOGY IN NON-ABUSED PRESCHOOL CHILDREN.
241. Ingunn Dybedal: NEGATIVE REGULATORS OF HEMATOPOIETEC STEM AND PROGENITOR CELLS.
242. Beate Sitter: TISSUE CHARACTERIZATION BY HIGH RESOLUTION MAGIC ANGLE SPINNING MR SPECTROSCOPY.
243. Per Arne Aas: MACROMOLECULAR MAINTENANCE IN HUMAN CELLS: Repair of uracil in DNA and methylations in DNA and RNA.
244. Anna Bofin: FINE NEEDLE ASPIRATION CYTOLOGY IN THE PRIMARY INVESTIGATION OF BREAST TUMOURS AND IN THE DETERMINATION OF TREATMENT STRATEGIES.
245. Jim Aage Nøttestad: DEINSTITUTIONALIZATION AND MENTAL HEALTH CHANGES AMONG PEOPLE WITH MENTAL RETARDATION.
246. Reidar Fossmark: GASTRIC CANCER IN JAPANESE COTTON RATS.
247. Wibeke Nordhøy: MANGANESE AND THE HEART: Intracellular MR relaxation and water exchange across the cardiac cell membrane.

2005

248. Sturla Molden: QUANTITATIVE ANALYSES OF SINGLE UNITS RECORDED FROM THE HIPPOCAMPUS AND ENTORHINAL CORTEX OF BEHAVING RATS.
249. Wenche Brenne Drøyvold: EPIDEMIOLOGICAL STUDIES ON WEIGHT CHANGE AND HEALTH IN A LARGE POPULATION: The Nord-Trøndelag Health Study (HUNT).
250. Ragnhild Støen: ENDOTHELIUM-DEPENDENT VASODILATION IN THE FEMORAL ARTERY OF DEVELOPING PIGLETS.
251. Aslak Steinsbekk: HOMEOPATHY IN THE PREVENTION OF UPPER RESPIRATORY TRACT INFECTIONS IN CHILDREN.
252. Hill-Aina Steffenach: MEMORY IN HIPPOCAMPAL AND CORTICO-HIPPOCAMPAL CIRCUITS.
253. Eystein Stordal: ASPECTS OF THE EPIDEMIOLOGY OF DEPRESSIONS BASED ON SELF-RATING IN A LARGE GENERAL HEALTH STUDY (THE HUNT-2 STUDY).
254. Viggo Pettersen: FROM MUSCLES TO SINGING: The activity of accessory breathing muscles and thorax movement in classical singing.

255. Marianne Fyhn: SPATIAL MAPS IN THE HIPPOCAMPUS AND ENTORHINAL CORTEX.
256. Robert Valderhaug: OBSESSIVE-COMPULSIVE DISORDER AMONG CHILDREN AND ADOLESCENTS: Characteristics and psychological management of patients in outpatient psychiatric clinics.
257. Erik Skaaheim Haug: INFRARENAL ABDOMINAL AORTIC ANEURYSMS: Comorbidity and results following open surgery.
258. Daniel Kondziella: GLIAL-NEURONAL INTERACTIONS IN EXPERIMENTAL BRAIN DISORDERS.
259. Vegard Heimly Brun: ROUTES TO SPATIAL MEMORY IN HIPPOCAMPAL PLACE CELLS.
260. Kenneth McMillan: PHYSIOLOGICAL ASSESSMENT AND TRAINING OF ENDURANCE AND STRENGTH IN PROFESSIONAL YOUTH SOCCER PLAYERS.
261. Marit Sæbø Indredavik: MENTAL HEALTH AND CEREBRAL MAGNETIC RESONANCE IMAGING IN ADOLESCENTS WITH LOW BIRTH WEIGHT.
262. Ole Johan Kemi: ON THE CELLULAR BASIS OF AEROBIC FITNESS, INTENSITY-DEPENDENCE AND TIME-COURSE OF CARDIOMYOCYTE AND ENDOTHELIAL ADAPTATIONS TO EXERCISE TRAINING.
263. Eszter Vanky: POLYCYSTIC OVARY SYNDROME: Metformin treatment in pregnancy.
264. Hild Fjærtoft: EXTENDED STROKE UNIT SERVICE AND EARLY SUPPORTED DISCHARGE: Short and long-term effects.
265. Grete Dyb: POSTTRAUMATIC STRESS REACTIONS IN CHILDREN AND ADOLESCENTS.
266. Vidar Fykse: SOMATOSTATIN AND THE STOMACH.
267. Kirsti Berg: OXIDATIVE STRESS AND THE ISCHEMIC HEART: A study in patients undergoing coronary revascularization.
268. Björn Inge Gustafsson: THE SEROTONIN PRODUCING ENTEROCHROMAFFIN CELL AND EFFECTS OF HYPERSEROTONINEMIA ON HEART AND BONE.

2006

269. Torstein Baade Rø: EFFECTS OF BONE MORPHOGENETIC PROTEINS, HEPATOCYTE GROWTH FACTOR AND INTERLEUKIN-21 IN MULTIPLE MYELOMA.
270. May-Britt Tessem: METABOLIC EFFECTS OF ULTRAVIOLET RADIATION ON THE ANTERIOR PART OF THE EYE.
271. Anne-Sofie Helvik: COPING AND EVERYDAY LIFE IN A POPULATION OF ADULTS WITH HEARING IMPAIRMENT.
272. Therese Standal: MULTIPLE MYELOMA: The interplay between malignant plasma cells and the bone marrow microenvironment.
273. Ingvild Saltvedt: TREATMENT OF ACUTELY SICK, FRAIL ELDERLY PATIENTS IN A GERIATRIC EVALUATION AND MANAGEMENT UNIT: Results from a prospective randomised trial.
274. Birger Henning Endreseth: STRATEGIES IN RECTAL CANCER TREATMENT: Focus on early rectal cancer and the influence of age on prognosis.
275. Anne Mari Aukan Rokstad: ALGINATE CAPSULES AS BIOREACTORS FOR CELL THERAPY.
276. Mansour Akbari: HUMAN BASE EXCISION REPAIR FOR PRESERVATION OF GENOMIC STABILITY.
277. Stein Sundstrøm: IMPROVING TREATMENT IN PATIENTS WITH LUNG CANCER: Results from two multicentre randomised studies.
278. Hilde Pleym: BLEEDING AFTER CORONARY ARTERY BYPASS SURGERY: Studies on hemostatic mechanisms, prophylactic drug treatment and effects of autotransfusion.
279. Line Merethe Oldervoll: PHYSICAL ACTIVITY AND EXERCISE INTERVENTIONS IN CANCER PATIENTS.
280. Boye Welde: THE SIGNIFICANCE OF ENDURANCE TRAINING, RESISTANCE TRAINING AND MOTIVATIONAL STYLES IN ATHLETIC PERFORMANCE AMONG ELITE JUNIOR CROSS-COUNTRY SKIERS.
281. Per Olav Vandvik: IRRITABLE BOWEL SYNDROME IN NORWAY: Studies of prevalence, diagnosis and characteristics in general practice and in the population.
282. Idar Kirkeby-Garstad: CLINICAL PHYSIOLOGY OF EARLY MOBILIZATION AFTER CARDIAC SURGERY.
283. Linn Getz: SUSTAINABLE AND RESPONSIBLE PREVENTIVE MEDICINE: Conceptualising ethical dilemmas arising from clinical implementation of advancing medical technology.

284. Eva Tegnander: DETECTION OF CONGENITAL HEART DEFECTS IN A NON-SELECTED POPULATION OF 42,381 FETUSES.
285. Kristin Gabestad Nørsett: GENE EXPRESSION STUDIES IN GASTROINTESTINAL PATHOPHYSIOLOGY AND NEOPLASIA.
286. Per Magnus Haram: GENETIC VS. AQUIRED FITNESS: Metabolic, vascular and cardiomyocyte adaptations.
287. Agneta Johansson: GENERAL RISK FACTORS FOR GAMBLING PROBLEMS AND THE PREVALENCE OF PATHOLOGICAL GAMBLING IN NORWAY.
288. Svein Artur Jensen: THE PREVALENCE OF SYMPTOMATIC ARTERIAL DISEASE OF THE LOWER LIMB.
289. Charlotte Björk Ingul: QUANITIFICATION OF REGIONAL MYOCARDIAL FUNCTION BY STRAIN RATE AND STRAIN FOR EVALUATION OF CORONARY ARTERY DISEASE: Automated versus manual analysis during acute myocardial infarction and dobutamine stress echocardiography.
290. Jakob Nakling: RESULTS AND CONSEQUENCES OF ROUTINE ULTRASOUND SCREENING IN PREGNANCY: A geographic-based population study.
291. Anne Engum: DEPRESSION AND ANXIETY: Their relations to thyroid dysfunction and diabetes in a large epidemiological study.
292. Ottar Bjerkeset: ANXIETY AND DEPRESSION IN THE GENERAL POPULATION: Risk factors, intervention and outcome, the Nord-Trøndelag Health Study (HUNT).
293. Jon Olav Drogset: RESULTS AFTER SURGICAL TREATMENT OF ANTERIOR CRUCIATE LIGAMENT INJURIES: A clinical study.
294. Lars Fosse: MECHANICAL BEHAVIOUR OF COMPACTED MORSELLISED BONE: An experimental *in vitro* study.
295. Gunilla Klensmeden Fosse: MENTAL HEALTH OF PSYCHIATRIC OUTPATIENTS BULLIED IN CHILDHOOD.
296. Paul Jarle Mork: MUSCLE ACTIVITY IN WORK AND LEISURE AND ITS ASSOCIATION TO MUSCULOSKELETAL PAIN.
297. Björn Stenström: LESSONS FROM RODENTS. I: Mechanisms of obesity surgery: role of stomach. II: Carcinogenic effects of *Helicobacter pylori* and snus in the stomach.

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298. Haakon R. Skogseth: INVASIVE PROPERTIES OF CANCER - A TREATMENT TARGET? *In vitro* studies in human prostate cancer cell lines.
299. Janniche Hammer: GLUTAMATE METABOLISM AND CYCLING IN MESIAL TEMPORAL LOBE EPILEPSY.
300. May Britt Drugli: YOUNG CHILDREN TREATED BECAUSE OF ODD/CD: Conduct problems and social competencies in day-care and school settings.
301. Arne Skjold: MAGNETIC RESONANCE KINETICS OF MANGANESE DIPYRIDOXYL DIPHOSPHATE (MnDPDP) IN HUMAN MYOCARDIUM. Studies in healthy volunteers and in patients with recent myocardial infarction.
302. Siri Malm: LEFT VENTRICULAR SYSTOLIC FUNCTION AND MYOCARDIAL PERFUSION ASSESSED BY CONTRAST ECHOCARDIOGRAPHY.
303. Valentina Maria do Rosario Cabral Iversen: MENTAL HEALTH AND PSYCHOLOGICAL ADAPTATION OF CLINICAL AND NON-CLINICAL MIGRANT GROUPS.
304. Lasse Løvstakken: SIGNAL PROCESSING IN DIAGNOSTIC ULTRASOUND: Algorithms for real-time estimation and visualization of blood flow velocity.
305. Elisabeth Olstad: GLUTAMATE AND GABA: Major players in neuronal metabolism.
306. Lilian Leistad: THE ROLE OF CYTOKINES AND PHOSPHOLIPASE A2S IN ARTICULAR CARTILAGE CHONDROCYTES IN RHEUMATOID ARTHRITIS AND OSTEOARTHRITIS.
307. Arne Vaaler: EFFECTS OF PSYCHIATRIC INTENSIVE CARE UNIT IN AN ACUTE PSYCIATHRIC WARD.
308. Mathias Toft: GENETIC STUDIES OF LRRK2 AND PINK1 IN PARKINSON'S DISEASE.
309. Ingrid Løvold Mostad: IMPACT OF DIETARY FAT QUANTITY AND QUALITY IN TYPE 2 DIABETES WITH EMPHASIS ON MARINE N-3 FATTY ACIDS.
310. Torill Eidhammer Sjøbakk: MR DETERMINED BRAIN METABOLIC PATTERN IN PATIENTS WITH BRAIN METASTASES AND ADOLESCENTS WITH LOW BIRTH WEIGHT.
311. Vidar Beisvåg: PHYSIOLOGICAL GENOMICS OF HEART FAILURE: From technology to physiology.

312. Olav Magnus Søndenå Fredheim: HEALTH-RELATED QUALITY OF LIFE ASSESSMENT AND ASPECTS OF THE CLINICAL PHARMACOLOGY OF METHADONE IN PATIENTS WITH CHRONIC NON-MALIGNANT PAIN.
313. Anne Brantberg: FETAL AND PERINATAL IMPLICATIONS OF ANOMALIES IN THE GASTROINTESTINAL TRACT AND THE ABDOMINAL WALL.
314. Erik Solligård: GUT LUMINAL MICRODIALYSIS.
315. Elin Tollefsen: RESPIRATORY SYMPTOMS IN A COMPREHENSIVE POPULATION BASED STUDY AMONG ADOLESCENTS 13-19 YEARS. YOUNG-HUNT 1995-97 AND 2000-01; The Nord-Trøndelag Health Studies (HUNT).
316. Anne-Tove Brenne: GROWTH REGULATION OF MYELOMA CELLS.
317. Heidi Knobel: FATIGUE IN CANCER TREATMENT: Assessment, course and etiology.
318. Torbjørn Dahl: CAROTID ARTERY STENOSIS: Diagnostic and therapeutic aspects.
319. Inge-Andre Rasmussen, Jr.: FUNCTIONAL AND DIFFUSION TENSOR MAGNETIC RESONANCE IMAGING IN NEUROSURGICAL PATIENTS.
320. Grete Helen Bratberg: PUBERTAL TIMING – ANTECEDENT TO RISK OR RESILIENCE ? Epidemiological studies on growth, maturation and health risk behaviours; The YOUNG HUNT study, Nord-Trøndelag, Norway.
321. Sveinung Sørhaug: THE PULMONARY NEUROENDOCRINE SYSTEM: Physiological, pathological and tumorigenic aspects.
322. Olav Sande Eftedal: ULTRASONIC DETECTION OF DECOMPRESSION-INDUCED VASCULAR MICROBUBBLES.
323. Rune Bang Leistad: PAIN, AUTONOMIC ACTIVATION AND MUSCULAR ACTIVITY RELATED TO EXPERIMENTALLY-INDUCED COGNITIVE STRESS IN HEADACHE PATIENTS.
324. Svein Brekke: TECHNIQUES FOR ENHANCEMENT OF TEMPORAL RESOLUTION IN THREE-DIMENSIONAL ECHOCARDIOGRAPHY.
325. Kristian Bernhard Nilsen: AUTONOMIC ACTIVATION AND MUSCLE ACTIVITY IN RELATION TO MUSCULOSKELETAL PAIN.
326. Anne Irene Hagen: HEREDITARY BREAST CANCER IN NORWAY: Detection and prognosis of breast cancer in families with BRCA1 gene mutation.
327. Ingebjørg S. Juel: INTESTINAL INJURY AND RECOVERY AFTER ISCHEMIA: An experimental study on restitution of the surface epithelium, intestinal permeability, and release of biomarkers from the mucosa.
328. Runa Heimstad: POST-TERM PREGNANCY.
329. Jan Egil Afset: ROLE OF ENTEROPATHOGENIC *ESCHERICHIA COLI* IN CHILDHOOD DIARRHOEA IN NORWAY.
330. Bent Håvard Hellum: *IN VITRO* INTERACTIONS BETWEEN MEDICINAL DRUGS AND HERBS ON CYTOCHROME P-450 METABOLISM AND P-GLYCOPROTEIN TRANSPORT.
331. Morten André Høydal: CARDIAC DYSFUNCTION AND MAXIMAL OXYGEN UPTAKE MYOCARDIAL ADAPTATION TO ENDURANCE TRAINING.

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332. Andreas Møllerløkken: REDUCTION OF VASCULAR BUBBLES: Methods to prevent the adverse effects of decompression.
333. Anne Hege Aamodt: COMORBIDITY OF HEADACHE AND MIGRAINE IN THE NORD-TRØNDELAG HEALTH STUDY 1995-97.
334. Brage Høyem Amundsen: MYOCARDIAL FUNCTION QUANTIFIED BY SPECKLE TRACKING AND TISSUE DOPPLER ECHOCARDIOGRAPHY: Validation and application in exercise testing and training.
335. Inger Anne Næss: INCIDENCE, MORTALITY AND RISK FACTORS OF FIRST VENOUS THROMBOSIS IN A GENERAL POPULATION: Results from the second Nord-Trøndelag Health Study (HUNT2).
336. Vegard Bugten: EFFECTS OF POSTOPERATIVE MEASURES AFTER FUNCTIONAL ENDOSCOPIC SINUS SURGERY.
337. Morten Bruvold: MANGANESE AND WATER IN CARDIAC MAGNETIC RESONANCE IMAGING.
338. Miroslav Fris: THE EFFECT OF SINGLE AND REPEATED ULTRAVIOLET RADIATION ON THE ANTERIOR SEGMENT OF THE RABBIT EYE.

339. Svein Arne Aase: METHODS FOR IMPROVING QUALITY AND EFFICIENCY IN QUANTITATIVE ECHOCARDIOGRAPHY: Aspects of using high frame rate.
340. Roger Almvik: ASSESSING THE RISK OF VIOLENCE: Development and validation of the brøset violence checklist.
341. Ottar Sundheim: STRUCTURE-FUNCTION ANALYSIS OF HUMAN ENZYMES INITIATING NUCLEOBASE REPAIR IN DNA AND RNA.
342. Anne Mari Undheim: SHORT AND LONG-TERM OUTCOME OF EMOTIONAL AND BEHAVIOURAL PROBLEMS IN YOUNG ADOLESCENTS WITH AND WITHOUT READING DIFFICULTIES.
343. Helge Garåsen: THE TRONDHEIM MODEL. Improving the professional communication between the various levels of health care services and implementation of intermediate care at a community hospital could provide better care for older patients: short- and long-term effects.
344. Olav A. Foss: THE ROTATION RATIOS METHOD: A method to describe altered spatial orientation in sequential radiographs from one pelvis.
345. Bjørn Olav Åsvold: THYROID FUNCTION AND CARDIOVASCULAR HEALTH.
346. Torun Margareta Melø: NEURONAL GLIAL INTERACTIONS IN EPILEPSY.
347. Irina Poliakova Eide: FETAL GROWTH RESTRICTION AND PRE-ECLAMPSIA: Some characteristics of feto-maternal interactions in decidua basalis.
348. Torunn Askim: RECOVERY AFTER STROKE: Assessment and treatment with focus on motor function.
349. Ann Elisabeth Åsberg: NEUTROPHIL ACTIVATION IN A ROLLER PUMP MODEL OF CARDIOPULMONARY BYPASS: Influence on biomaterial, platelets and complement.
350. Lars Hagen: REGULATION OF DNA BASE EXCISION REPAIR BY PROTEIN INTERACTIONS AND POST TRANSLATIONAL MODIFICATIONS.
351. Sigrun Beate Kjøtrød: POLYCYSTIC OVARY SYNDROME: Metformin treatment in assisted reproduction.
352. Steven Keita Nishiyama: PERSPECTIVES ON LIMB-VASCULAR HETEROGENEITY: Implications for human aging, sex, and exercise.
353. Sven Peter Näsholm: ULTRASOUND BEAMS FOR ENHANCED IMAGE QUALITY.
354. Jon Ståle Ritland: PRIMARY OPEN-ANGLE GLAUCOMA AND EXFOLIATIVE GLAUCOMA: Survival, comorbidity and genetics.
355. Sigrid Botne Sando: ALZHEIMER'S DISEASE IN CENTRAL NORWAY: Genetic and educational aspects.
356. Parvinder Kaur: CELLULAR AND MOLECULAR MECHANISMS BEHIND METHYLMERCURY-INDUCED NEUROTOXICITY.
357. Ismail Cüneyt Güzey: DOPAMINE AND SEROTONIN RECEPTOR AND TRANSPORTER GENE POLYMORPHISMS AND EXTRAPYRAMIDAL SYMPTOMS: Studies in Parkinson's disease and in patients treated with antipsychotic or antidepressant drugs.
358. Brit Dybdahl: EXTRA-CELLULAR INDUCIBLE HEAT-SHOCK PROTEIN 70 (Hsp70): A role in the inflammatory response?
359. Kristoffer Haugarvoll: IDENTIFYING GENETIC CAUSES OF PARKINSON'S DISEASE IN NORWAY.
360. Nadra Nilsen: TOLL-LIKE RECEPTOR 2: Expression, regulation and signaling.
361. Johan Håkon Bjørngaard: PATIENT SATISFACTION WITH OUTPATIENT MENTAL HEALTH SERVICES: The influence of organizational factors.
362. Kjetil Høydal: EFFECTS OF HIGH INTENSITY AEROBIC TRAINING IN HEALTHY SUBJECTS AND CORONARY ARTERY DISEASE PATIENTS: The importance of intensity, duration and frequency of training.
363. Trine Karlsen: TRAINING IS MEDICINE: Endurance and strength training in coronary artery disease and health.
364. Marte Thuen: MANGANASE-ENHANCED AND DIFFUSION TENSOR MR IMAGING OF THE NORMAL, INJURED AND REGENERATING RAT VISUAL PATHWAY.
365. Cathrine Broberg Vågbø: DIRECT REPAIR OF ALKYLATION DAMAGE IN DNA AND RNA BY 2-OXOGLUTARATE- AND IRON-DEPENDENT DIOXYGENASES.
366. Arnt Erik Tjønna: AEROBIC EXERCISE AND CARDIOVASCULAR RISK FACTORS IN OVERWEIGHT AND OBESE ADOLESCENTS AND ADULTS.

367. Marianne W. Furnes: FEEDING BEHAVIOR AND BODY WEIGHT DEVELOPMENT: Lessons from rats.
368. Lene N. Johannessen: FUNGAL PRODUCTS AND INFLAMMATORY RESPONSES IN HUMAN MONOCYTES AND EPITHELIAL CELLS.
369. Anja Bye: GENE EXPRESSION PROFILING OF INHERITED AND ACQUIRED MAXIMAL OXYGEN UPTAKE: Relations to the metabolic syndrome.
370. Oluf Dimitri Røe: MALIGNANT MESOTHELIOMA - VIRUS, BIOMARKERS AND GENES: A translational approach.
371. Ane Cecilie Dale: DIABETES MELLITUS AND FATAL ISCHEMIC HEART DISEASE: Analyses from the HUNT1 and 2 studies.
372. Jacob Christian Hølen: PAIN ASSESSMENT IN PALLIATIVE CARE: Validation of methods for self-report and behavioural assessment.
373. Erming Tian: THE GENETIC IMPACTS IN THE ONCOGENESIS OF MULTIPLE MYELOMA.
374. Ole Bosnes: KLINISK UTPRØVING AV NORSKE VERSJONER AV NOEN SENTRALE TESTER PÅ KOGNITIV FUNKSJON.
375. Ola M. Rygh: 3D ULTRASOUND BASED NEURONAVIGATION IN NEUROSURGERY: A clinical evaluation.
376. Astrid Kamilla Stunes: ADIPOKINES, PEROXISOME PROFILERATOR ACTIVATED RECEPTOR (PPAR) AGONISTS AND SEROTONIN: Common regulators of bone and fat metabolism.
377. Silje Engdal: HERBAL REMEDIES USED BY NORWEGIAN CANCER PATIENTS AND THEIR ROLE IN HERB-DRUG INTERACTIONS.
378. Kristin Offerdal: IMPROVED ULTRASOUND IMAGING OF THE FETUS AND ITS CONSEQUENCES FOR SEVERE AND LESS SEVERE ANOMALIES.
379. Øivind Rognmo: HIGH-INTENSITY AEROBIC EXERCISE AND CARDIOVASCULAR HEALTH.
380. Jo-Åsmund Lund: RADIOTHERAPY IN ANAL CARCINOMA AND PROSTATE CANCER.

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381. Tore Grüner Bjåstad: HIGH FRAME RATE ULTRASOUND IMAGING USING PARALLEL BEAMFORMING.
382. Erik Søndenaa: INTELLECTUAL DISABILITIES IN THE CRIMINAL JUSTICE SYSTEM.
383. Berit Rostad: SOCIAL INEQUALITIES IN WOMEN'S HEALTH, HUNT 1984-86 AND 1995-97, THE NORD-TRØNDELAG HEALTH STUDY (HUNT).
384. Jonas Crosby: ULTRASOUND-BASED QUANTIFICATION OF MYOCARDIAL DEFORMATION AND ROTATION.
385. Erling Tronvik: MIGRAINE, BLOOD PRESSURE AND THE RENIN-ANGIOTENSIN SYSTEM.
386. Tom Christensen: BRINGING THE GP TO THE FOREFRONT OF EPR DEVELOPMENT.
387. Håkon Bergseng: ASPECTS OF GROUP B STREPTOCOCCUS (GBS) DISEASE IN THE NEWBORN: Epidemiology, characterisation of invasive strains and evaluation of intrapartum screening.
388. Ronny Myhre: GENETIC STUDIES OF CANDIDATE TENE3S IN PARKINSON'S DISEASE.
389. Torbjørn Moe Eggebø: ULTRASOUND AND LABOUR.
390. Eivind Wang: TRAINING IS MEDICINE FOR PATIENTS WITH PERIPHERAL ARTERIAL DISEASE.
391. Thea Kristin Våtsveen: GENETIC ABERRATIONS IN MYELOMA CELLS.
392. Thomas Jozefiak: QUALITY OF LIFE AND MENTAL HEALTH IN CHILDREN AND ADOLESCENTS: Child and parent perspectives.
393. Jens Erik Slagsvold: N-3 POLYUNSATURATED FATTY ACIDS IN HEALTH AND DISEASE: Clinical and molecular aspects.
394. Kristine Misund: A STUDY OF THE TRANSCRIPTIONAL REPRESSOR ICER: Regulatory networks in gastrin-induced gene expression.
395. Franco M. Impellizzeri: HIGH-INTENSITY TRAINING IN FOOTBALL PLAYERS: Effects on physical and technical performance.
396. Kari Hanne Gjeilo: HEALTH-RELATED QUALITY OF LIFE AND CHRONIC PAIN IN PATIENTS UNDERGOING CARDIAC SURGERY.
397. Øyvind Hauso: NEUROENDOCRINE ASPECTS OF PHYSIOLOGY AND DISEASE.
398. Ingvild Bjellmo Johnsen: INTRACELLULAR SIGNALING MECHANISMS IN THE INNATE IMMUNE RESPONSE TO VIRAL INFECTIONS.

399. Linda Tømmerdal Roten: GENETIC PREDISPOSITION FOR DEVELOPMENT OF PREEMCLAMPSIA: Candidate gene studies in the HUNT (Nord-Trøndelag Health Study) population.
400. Trude Teoline Nausthaug Rakvåg: PHARMACOGENETICS OF MORPHINE IN CANCER PAIN.
401. Hanne Lehn: MEMORY FUNCTIONS OF THE HUMAN MEDIAL TEMPORAL LOBE STUDIED WITH fMRI.
402. Randi Utne Holt: ADHESION AND MIGRATION OF MYELOMA CELLS: *In vitro* studies.
403. Trygve Solstad: NEURAL REPRESENTATIONS OF EUCLIDEAN SPACE.
404. Unn-Merete Fagerli: MULTIPLE MYELOMA CELLS AND CYTOKINES FROM THE BONE MARROW ENVIRONMENT: Aspects of growth regulation and migration.
405. Sigrid Bjørnelv: EATING AND WEIGHT PROBLEMS IN ADOLESCENTS: THE YOUNG HUNT-STUDY.
406. Mari Hoff: CORTICAL HAND BONE LOSS IN RHEUMATOID ARTHRITIS: Evaluating digital x-ray radiogrammetry as outcome measure of disease activity, response variable to treatment and predictor of bone damage.
407. Siri Bjørgen: AEROBIC HIGH INTENSITY INTERVAL TRAINING IS AN EFFECTIVE TREATMENT FOR PATIENTS WITH CHRONIC OBSTRUCTIVE PULMONARY DISEASE.
408. Susanne Lindqvist: VISION AND BRAIN IN ADOLESCENTS WITH LOW BIRTH WEIGHT.
409. Torbjørn Hergum: 3D ULTRASOUND FOR QUANTITATIVE ECHOCARDIOGRAPHY.
410. Jørgen Urnes: PATIENT EDUCATION IN GASTRO-OESOPHAGEAL REFLUX DISEASE: Validation of a digestive symptoms and impact questionnaire and a randomised controlled trial of patient education.
411. Elvar Eyjolfsson: 13C NMRS OF ANIMAL MODELS OF SCHIZOPHRENIA.
412. Marius Steiro Fimland: CHRONIC AND ACUTE NEURAL ADAPTATIONS TO STRENGTH TRAINING.
413. Øyvind Støren: RUNNING AND CYCLING ECONOMY IN ATHLETES: Determining factors, training interventions and testing.
414. Håkon Hov: HEPATOCYTE GROWTH FACTOR AND ITS RECEPTOR C-MET: Autocrine growth and signaling in multiple myeloma cells.
415. Maria Radtke: ROLE OF AUTOIMMUNITY AND OVERSTIMULATION FOR BETA-CELL DEFICIENCY: Epidemiological and therapeutic perspectives.
416. Liv Bente Romundstad: ASSISTED FERTILIZATION IN NORWAY: Safety of the reproductive technology.
417. Erik Magnus Berntsen: PREOPERATIVE PLANNING AND FUNCTIONAL NEURONAVIGATION WITH FUNCTIONAL MRI AND DIFFUSION TENSOR TRACTOGRAPHY IN PATIENTS WITH BRAIN LESIONS.
418. Tonje Strømmen Steigedal: MOLECULAR MECHANISMS OF THE PROLIFERATIVE RESPONSE TO THE HORMONE GASTRIN.
419. Vidar Rao: EXTRACORPOREAL PHOTOCHEMOTHERAPY IN PATIENTS WITH CUTANEOUS T CELL LYMPHOMA OR GRAFT VERSUS HOST DISEASE.
420. Torkild Visnes: DNA EXCISION REPAIR OF URACIL AND 5-FLUOROURACIL IN HUMAN CANCER CELL LINES.

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421. John Munkhaugen: BLOOD PRESSURE, BODY WEIGHT, AND KIDNEY FUNCTION IN THE NEAR-NORMAL RANGE: Normality, risk factor or morbidity?
422. Ingrid Castberg: PHARMACOKINETICS, DRUG INTERACTIONS AND ADHERENCE TO TREATMENT WITH ANTIPSYCHOTICS: Studies in a naturalistic setting.
423. Jian Xu: BLOOD-OXYGEN-LEVEL DEPENDENT FUNCTIONAL MAGNETIC RESONANCE IMAGING AND DIFFUSION TENSOR IMAGING IN TRAUMATIC BRAIN INJURY RESEARCH.
424. Sigmund Simonsen: ACCEPTABLE RISK AND THE REQUIREMENT OF PROPORTIONALITY IN EUROPEAN BIOMEDICAL RESEARCH LAW: What does the requirement that biomedical research shall not involve risks and burdens disproportionate to its potential benefits mean?
425. Astrid Woodhouse: MOTOR CONTROL IN WHIPLASH AND CHRONIC NON-TRAUMATIC NECK PAIN.
426. Line Rørstad Jensen: EVALUATION OF TREATMENT EFFECTS IN CANCER BY MR IMAGING AND SPECTROSCOPY.
427. Trine Moholdt: AEROBIC EXERCISE IN CORONARY HEART DISEASE.

428. Øystein Olsen: ANALYSIS OF MANGANESE ENHANCED MRI OF THE NORMAL AND INJURED RAT CENTRAL NERVOUS SYSTEM.
429. Bjørn H. Grønberg: PEMETREXED IN THE TREATMENT OF ADVANCED LUNG CANCER.
430. Vigdis Schnell Husby: REHABILITATION OF PATIENTS UNDERGOING TOTAL HIP ARTHROPLASTY WITH FOCUS ON MUSCLE STRENGTH, WALKING AND AEROBIC ENDURANCE PERFORMANCE.
431. Torbjørn Øien: CHALLENGES IN PRIMARY PREVENTION OF ALLERGY: The prevention of allergy among children in Trondheim (PACT) study.
432. Kari Anne Indredavik Evensen: BORN TOO SOON OR TOO SMALL: Motor problems in adolescence.
433. Lars Adde: PREDICTION OF CEREBRAL PALSY IN YOUNG INFANTS: Computer-based assessment of general movements.
434. Magnus Fasting: PRE- AND POSTNATAL RISK FACTORS FOR CHILDHOOD ADIPOSITY.
435. Vivi Talstad Monsen: MECHANISMS OF ALKYLATION DAMAGE REPAIR BY HUMAN AlkB HOMOLOGUES.
436. Toril Skandsen: MODERATE AND SEVERE TRAUMATIC BRAIN INJURY: Magnetic resonance imaging findings, cognition and risk factors for disability.
437. Ingeborg Smidesang: ALLERGY-RELATED DISORDERS AMONG 2-YEAR OLDS AND ADOLESCENTS IN MID-NORWAY: Prevalence, severity and impact, the PACT study 2005, the YOUNG HUNT study 1995-97.
438. Vidar Halsteinli: MEASURING EFFICIENCY IN MENTAL HEALTH SERVICE DELIVERY: A study of outpatient units in Norway.
439. Karen Lehrmann Ægidius: THE PREVALENCE OF HEADACHE AND MIGRAINE IN RELATION TO SEX HORMONE STATUS IN WOMEN, THE HUNT 2 STUDY.
440. Madelene Ericsson: EXERCISE TRAINING IN GENETIC MODELS OF HEART FAILURE.
441. Marianne Klokk: THE ASSOCIATION BETWEEN SELF-REPORTED ECZEMA AND COMMON MENTAL DISORDERS IN THE GENERAL POPULATION: The Hordaland Health Study (HUSK).
442. Tomas Ottemo Stølen: IMPAIRED CALCIUM HANDLING IN ANIMAL AND HUMAN CARDIOMYOCYTES REDUCE CONTRACTILITY AND INCREASE ARRHYTHMIA POTENTIAL: Effects of aerobic exercise training.
443. Bjarne Hansen: ENHANCING TREATMENT OUTCOME IN COGNITIVE BEHAVIOURAL THERAPY FOR OBSESSIVE COMPULSIVE DISORDER: The importance of cognitive factors.
444. Mona Løvlien: WHEN EVERY MINUTE COUNTS: From symptoms to admission for acute myocardial infarction with special emphasis on gender differences.
445. Karin Margaretha Gilljam: DNA REPAIR PROTEIN COMPLEXES, FUNCTIONALITY AND SIGNIFICANCE FOR REPAIR EFFICIENCY AND CELL SURVIVAL.
446. Anne Byriel Walls: NEURONAL GLIAL INTERACTIONS IN CEREBRAL ENERGY AND AMINO ACID HOMEOSTASIS: Implications of glutamate and GABA.
447. Cathrine Fallang Knetter: MECHANISMS OF TOLL-LIKE RECEPTOR 9 ACTIVATION.
448. Marit Følsvik Svindseth: A STUDY OF HUMILIATION, NARCISSISM AND TREATMENT OUTCOME IN PATIENTS ADMITTED TO PSYCHIATRIC EMERGENCY UNITS.
449. Karin Elvenes Bakkelund: GASTRIC NEUROENDOCRINE CELLS: Role in gastric neoplasia in man and rodents.
450. Kirsten Brun Kjelstrup: DORSOVENTRAL DIFFERENCES IN THE SPATIAL REPRESENTATION AREAS OF THE RAT BRAIN.
451. Roar Johansen: MR EVALUATION OF BREAST CANCER PATIENTS WITH POOR PROGNOSIS.
452. Rigmor Myran: POST-TRAUMATIC NECK PAIN: Epidemiological, neuroradiological and clinical aspects.
453. Krisztina Kunszt Johansen: GENEALOGICAL, CLINICAL AND BIOCHEMICAL STUDIES IN LRRK2 ASSOCIATED PARKINSON’S DISEASE.
454. Pål Gjerden: THE USE OF ANTICHOLINERGIC ANTIPARKINSON AGENTS IN NORWAY: Epidemiology, toxicology and clinical implications.
455. Else Marie Huuse: ASSESSMENT OF TUMOR MICROENVIRONMENT AND TREATMENT EFFECTS IN HUMAN BREAST CANCER XENOGRAFTS USING MR IMAGING AND SPECTROSCOPY.

456. Khalid S. Ibrahim: INTRAOPERATIVE ULTRASOUND ASSESSMENT IN CORONARY ARTERY BYPASS SURGERY WITH SPECIAL REFERENCE TO CORONARY ANASTOMOSES AND THE ASCENDING AORTA.
457. Bjørn Øglænd: ANTHROPOMETRY, BLOOD PRESSURE AND REPRODUCTIVE DEVELOPMENT IN ADOLESCENCE OF OFFSPRING OF MOTHERS WHO HAD PREECLAMPSIA IN PREGNANCY.
458. John Olav Roaldset: RISK ASSESSMENT OF VIOLENT, SUICIDAL AND SELF-INJURIOUS BEHAVIOUR IN ACUTE PSYCHIATRY: A bio-psycho-social approach.
459. Håvard Dalen: ECHOCARDIOGRAPHIC INDICES OF CARDIAC FUNCTION: Normal values and associations with cardiac risk factors in a population free from cardiovascular disease, hypertension and diabetes: the HUNT 3 study.
460. Beate André: CHANGE CAN BE CHALLENGING: Introduction to changes and implementation of computerized technology in health care.
461. Latha Nrugham: ASSOCIATES AND PREDICTORS OF ATTEMPTED SUICIDE AMONG DEPRESSED ADOLESCENTS: A 6-year prospective study.
462. Håvard Bersås Nordgaard: TRANSIT-TIME FLOWMETRY AND WALL SHEAR STRESS ANALYSIS OF CORONARY ARTERY BYPASS GRAFTS: A clinical and experimental study.

Cotutelle with University of Ghent: Abigail Emily Swillens: A MULTIPHYSICS MODEL FOR IMPROVING THE ULTRASONIC ASSESSMENT OF LARGE ARTERIES.

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463. Marte Helene Bjørk: DO BRAIN RHYTHMS CHANGE BEFORE THE MIGRAINE ATTACK? A longitudinal controlled EEG study.
464. Carl-Jørgen Arum: A STUDY OF UROTHELIAL CARCINOMA: Gene expression profiling, tumorigenesis and therapies in orthotopic animal models.
465. Ingunn Harstad: TUBERCULOSIS INFECTION AND DISEASE AMONG ASYLUM SEEKERS IN NORWAY: Screening and follow-up in public health care.
466. Leif Åge Strand: EPIDEMIOLOGICAL STUDIES AMONG ROYAL NORWEGIAN NAVY SERVICEMEN: Cohort establishment, cancer incidence and cause-specific mortality.
467. Katrine Høyer Holgersen: SURVIVORS IN THEIR THIRD DECADE AFTER THE NORTH SEA OIL RIG DISASTER OF 1980: Long-term perspectives on mental health.
468. Marianne Wallenius: PREGNANCY-RELATED ASPECTS OF CHRONIC INFLAMMATORY ARTHRITIDES: Disease onset postpartum, pregnancy outcomes and fertility; data from a Norwegian patient registry linked to the medical birth registry of Norway.
469. Ole Vegard Solberg: 3D ULTRASOUND AND NAVIGATION: Applications in laparoscopic surgery.
470. Inga Ekeberg Schjerve: EXERCISE-INDUCED IMPROVEMENT OF MAXIMAL OXYGEN UPTAKE AND ENDOTHELIAL FUNCTION IN OBESE AND OVERWEIGHT INDIVIDUALS ARE DEPENDENT ON EXERCISE-INTENSITY.
471. Eva Veslemøy Tyldum: CARDIOVASCULAR FUNCTION IN PREECLAMPSIA WITH REFERENCE TO ENDOTHELIAL FUNCTION, LEFT VENTRICULAR FUNCTION AND PRE-PREGNANCY PHYSICAL ACTIVITY.
472. Benjamin Garzón Jiménez de Cisneros: CLINICAL APPLICATIONS OF MULTIMODAL MAGNETIC RESONANCE IMAGING.
473. Halvard Knut Nilsen: ASSESSING CODEINE TREATMENT TO PATIENTS WITH CHRONIC NON-MALIGNANT PAIN: Neuropsychological functioning, driving ability and weaning.
474. Eiliv Brenner: GLUTAMATE-RELATED METABOLISM IN ANIMAL MODELS OF SCHIZOPHRENIA.
475. Egil Jonsbu: CHEST PAIN AND PALPITATIONS IN A CARDIAC SETTING: Psychological factors, outcome and treatment.
476. Mona Høysæter Fenstad: GENETIC SUSCEPTIBILITY TO PREECLAMPSIA: Studies on the Nord-Trøndelag Health Study (HUNT) cohort, an Australian/New Zealand family cohort and decidua basalis tissue.
477. Svein Erik Gaustad: CARDIOVASCULAR CHANGES IN DIVING: From human response to cell function.
478. Karin Torvik: PAIN AND QUALITY OF LIFE IN PATIENTS LIVING IN NURSING HOMES.
479. Arne Solberg: OUTCOME ASSESSMENTS IN NON-METASTATIC PROSTATE CANCER.

480. Henrik Sahlin Pettersen: CYTOTOXICITY AND REPAIR OF URACIL AND 5-FLUOROURACIL IN DNA.
481. Pui-Lam Wong: PHYSICAL AND PHYSIOLOGICAL CAPACITY OF SOCCER PLAYERS: Effects of strength and conditioning.
482. Ole Solheim: ULTRASOUND GUIDED SURGERY IN PATIENTS WITH INTRACRANIAL TUMOURS.
483. Sten Roar Snare: QUANTITATIVE CARDIAC ANALYSIS ALGORITHMS FOR POCKET-SIZED ULTRASOUND DEVICES.
484. Marit Skyrud Bratlie: LARGE-SCALE ANALYSIS OF ORTHOLOGS AND PARALOGS IN VIRUSES AND PROKARYOTES.
485. Anne Elisabeth F. Isern: BREAST RECONSTRUCTION AFTER MASTECTOMY, RISK OF RECURRENCE AFTER DELAYED LARGE FLAP RECONSTRUCTION, AESTHETIC OUTCOME, PATIENT SATISFACTION, QUALITY OF LIFE AND SURGICAL RESULTS: Histopathological findings and follow-up after prophylactic mastectomy in hereditary breast cancer.
486. Guro L. Andersen: CEREBRAL PALSY IN NORWAY: Subtypes, severity and risk factors.
487. Frode Kolstad: CERVICAL DISC DISEASE: Biomechanical aspects.
488. Bente Nordtug: CARING BURDEN OF COHABITANTS LIVING WITH PARTNERS SUFFERING FROM CHRONIC OBSTRUCTIVE PULMONARY DISEASE OR DEMENTIA.
489. Mariann Gjervik Heldahl: EVALUATION OF NEOADJUVANT CHEMOTHERAPY IN LOCALLY ADVANCED BREAST CANCER BASED ON MR METHODOLOGY.
490. Lise Tevik Løvseth: THE SUBJECTIVE BURDEN OF CONFIDENTIALITY.
491. Marie Hjelmseth Aune: INFLAMMATORY RESPONSES AGAINST GRAM NEGATIVE BACTERIA INDUCED BY TLR4 AND NLRP12.
492. Tina Strømdal Wik: EXPERIMENTAL EVALUATION OF NEW CONCEPTS IN HIP ARTHROPLASTY.
493. Solveig Sigurdardottir: CLINICAL ASPECTS OF CEREBRAL PALSY IN ICELAND: A population-based study of preschool children.
494. Arne Reimers: CLINICAL PHARMACOKINETICS OF LAMOTRIGINE.
495. Monica Wegling: KULTURMENNESKETS BYRDE OG SYKDOMMENS VELSIGNELSE: Kan medisinsk utredning og intervensjon ha en selvstendig funksjon uavhengig av det kurative?
496. Silje Alvestad: ASTROCYTE-NEURON INTERACTIONS IN EXPERIMENTAL MESIAL TEMPORAL LOBE EPILEPSY: A study of underlying mechanisms and possible biomarkers of epileptogenesis.
497. Javaid Nauman: RESTING HEART RATE - A MATTER OF LIFE OR DEATH: Prospective studies of resting heart rate and cardiovascular risk (the HUNT study, Norway).
498. Thuy Nguyen: THE ROLE OF C-SRC TYROSINE KINASE IN ANTIVIRAL IMMUNE RESPONSES.
499. Trine Naalsund Andreassen: PHARMACOKINETIC, PHARMACODYNAMIC AND PHARMACOGENETIC ASPECTS OF OXYCODONE TREATMENT IN CANCER PAIN.
500. Eivor Alette Laugsand: SYMPTOMS IN PATIENTS RECEIVING OPIOIDS FOR CANCER PAIN: Clinical and pharmacogenetic aspects.
501. Dorthe Stensvold: PHYSICAL ACTIVITY, CARDIOVASCULAR HEALTH AND LONGEVITY IN PATIENTS WITH METABOLIC SYNDROME.
502. Stian Thoresen Aspenes: PEAK OXYGEN UPTAKE AMONG HEALTHY ADULTS: Cross-sectional descriptions and prospective analyses of peak oxygen uptake, physical activity and cardiovascular risk factors in healthy adults (20-90 years).
503. Reidar Alexander Vigen: PATHOBIOLOGY OF GASTRIC CARCINOIDS AND ADENOCARCINOMAS IN RODENT MODELS AND PATIENTS: Studies of gastrocystoplasty, gender-related factors, and autophagy.
504. Halvard Høilund-Kaupang: MODELS AND METHODS FOR INVESTIGATION OF REVERBERATIONS IN NONLINEAR ULTRASOUND IMAGING.
505. Audhild Løhre: WELLBEING AMONG SCHOOL CHILDREN IN GRADES 1-10: Promoting and adverse factors.
506. Torgrim Tandstad: VOX POPULI: Population-based outcome studies in testicular cancer.
507. Anna Brenne Grønskag: THE EPIDEMIOLOGY OF HIP FRACTURES AMONG ELDERLY WOMEN IN NORD-TRØNDELAG: HUNT 1995-97, The Nord-Trøndelag Health Study.
508. Kari Ravndal Risnes: BIRTH SIZE AND ADULT MORTALITY: A systematic review and a long-term follow-up of nearly 40 000 individuals born at St. Olav University Hospital in Trondheim 1920-1960.

509. Hans Jakob Bøe: LONG-TERM POSTTRAUMATIC STRESS AFTER DISASTER: A controlled study of survivors' health 27 years after the capsized North Sea oil rig.
510. Cathrin Barbara Canto, Cotutelle with University of Amsterdam: LAYER SPECIFIC INTEGRATIVE PROPERTIES OF ENTORHINAL PRINCIPAL NEURONS.
511. Ioanna Sandvig: THE ROLE OF OLFACTORY ENSHEATHING CELLS, MRI, AND BIOMATERIALS IN TRANSPLANT-MEDIATED CNS REPAIR.
512. Karin Fahl Wader: HEPATOCYTE GROWTH FACTOR, C-MET AND SYNDECAN-1 IN MULTIPLE MYELOMA.
513. Gerd Tranø: FAMILIAL COLORECTAL CANCER.
514. Bjarte Bergstrøm: INNATE ANTIVIRAL IMMUNITY: Mechanisms of the RIG-I-mediated response.
515. Marie Søfteland Sandvei: INCIDENCE, MORTALITY, AND RISK FACTORS FOR ANEURYSMAL SUBARACHNOID HEMORRHAGE: Prospective analyses of the HUNT and Tromsø studies.
516. Mary-Elizabeth Bradley Eilertsen: CHILDREN AND ADOLESCENTS SURVIVING CANCER: Psychosocial health, quality of life and social support.
517. Takaya Saito: COMPUTATIONAL ANALYSIS OF REGULATORY MECHANISM AND INTERACTIONS OF MICRORNAS.

Godkjent for disputas, publisert post mortem: Eivind Jullumstrø: COLORECTAL CANCER AT LEVANGER HOSPITAL 1980-2004.

518. Christian Gutvik: A PHYSIOLOGICAL APPROACH TO A NEW DECOMPRESSION ALGORITHM USING NONLINEAR MODEL PREDICTIVE CONTROL.
519. Ola Storrø: MODIFICATION OF ADJUVANT RISK FACTOR BEHAVIOURS FOR ALLERGIC DISEASE AND ASSOCIATION BETWEEN EARLY GUT MICROBIOTA AND ATOPIC SENSITIZATION AND ECZEMA: Early life events defining the future health of our children.
520. Guro Fanneløb Giskeødegård: IDENTIFICATION AND CHARACTERIZATION OF PROGNOSTIC FACTORS IN BREAST CANCER USING MR METABOLOMICS.
521. Gro Christine Christensen Løhaugen: BORN PRETERM WITH VERY LOW BIRTH WEIGHT: Never ending cognitive consequences?
522. Sigrid Nakrem: MEASURING QUALITY OF CARE IN NURSING HOMES: What matters?
523. Brita Pukstad: CHARACTERIZATION OF INNATE INFLAMMATORY RESPONSES IN ACUTE AND CHRONIC WOUNDS.

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524. Hans H. Wasmuth: ILEAL POUCHES.
525. Inger Økland: BIASES IN SECOND-TRIMESTER ULTRASOUND DATING RELATED TO PREDICTION MODELS AND FETAL MEASUREMENTS.
526. Bjørn Mørkedal: BLOOD PRESSURE, OBESITY, SERUM IRON AND LIPIDS AS RISK FACTORS OF ISCHAEMIC HEART DISEASE.
527. Siver Andreas Moestue: MOLECULAR AND FUNCTIONAL CHARACTERIZATION OF BREAST CANCER THROUGH A COMBINATION OF MR IMAGING, TRANSCRIPTOMICS AND METABOLOMICS
528. Guro Aune: CLINICAL, PATHOLOGICAL, AND MOLECULAR CLASSIFICATION OF OVARIAN CARCINOMA
529. Ingrid Alsos Lian: MECHANISMS INVOLVED IN THE PATHOGENESIS OF PRE-ECLAMPSIA AND FETAL GROWTH RESTRICTION. Transcriptional analyses of placental and decidual tissue.
530. Karin Solvang-Garten: X-RAY REPAIR CROSS-COMPLEMENTING PROTEIN 1: The role as a scaffold protein in base excision repair and single strand break repair.
531. Toril Holien: BONE MORPHOGENETIC PROTEINS AND MYC IN MULTIPLE MYELOMA.
532. Rooyen Mavenyengwa: *STREPTOCOCCUS AGALACTIAE* IN PREGNANT WOMEN IN ZIMBABWE: Epidemiology and serotype marker characteristics.
533. Tormod Rimehaug: EMOTIONAL DISTRESS AND PARENTING AMONG COMMUNITY AND CLINIC PARENTS
534. Maria Dung Cao: MR METABOLIC CHARACTERIZATION OF LOCALLY ADVANCED BREAST CANCER: Treatment effects and prognosis.
535. Mirta Mittelstedt Leal de Sousa: PROTEOMICS ANALYSIS OF PROTEINS INVOLVED IN DNA BASE REPAIR AND CANCER THERAPY.

536. Halfdan Petursson: THE VALIDITY AND RELEVANCE OF INTERNATIONAL CARDIOVASCULAR DISEASE PREVENTION GUIDELINES FOR GENERAL PRACTICE.
537. Marit By Rise: LIFTING THE VEIL FROM USER PARTICIPATION IN CLINICAL WORK: What is it and does it work?
538. Lene Thoresen: NUTRITION CARE IN CANCER PATIENTS - NUTRITION ASSESSMENT: Diagnostic criteria and the association to survival and health-related quality of life in patients with advanced colorectal carcinoma.
539. Berit Doseth: PROCESSING OF GENOMIC URACIL IN MAN AND MOUSE.
540. Gro Falkenér Bertheussen: PHYSICAL ACTIVITY AND HEALTH IN A GENERAL POPULATION AND IN CANCER SURVIVORS: Methodological, observational and clinical aspects.
541. Anne Kari Knudsen: CANCER PAIN CLASSIFICATION.
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543. Harald Edvard Mølmen Hansen: CARDIOVASCULAR EFFECTS OF HIGH INTENSITY AEROBIC INTERVAL TRAINING IN HYPERTENSITIVE PATIENTS, HEALTHY AGED AND YOUNG PERSONS.
544. Sasha Gulati: SURGICAL RESECTION OF HIGH-GRADE GLIOMAS.
545. John Chr. Fløvig: FREQUENCY AND EFFECT OF SUBSTANCES AND PSYCHOACTIVE MEDICATIONS THE WEEK BEFORE ADMISSION TO AN ACUTE PSYCHIATRIC DEPARTMENT.
546. Kristin Moksnes Husby: OPTIMIZING OPIOID TREATMENT FOR CANCER PAIN: Clinical and pharmacological aspects.
547. Audun Hanssen-Bauer: X-RAY REPAIR CROSS-COMPLEMENTING PROTEIN 1 ASSOCIATED MULTIPROTEIN COMPLEXES IN BASE EXCISION REPAIR.
548. Marit Saunes: ECZEMA IN CHILDREN AND ADOLESCENTS: Epidemiology, course and impact; the prevention of allergy among children in Trondheim (PACT) Study, YOUNG-HUNT 1995-97.
549. Guri Kaurstad: CARDIOMYOCYTE FUNCTION AND CALCIUM HANDLING IN ANIMAL MODELS OF INBORN AND ACQUIRED MAXIMAL OXYGEN UPTAKE.
550. Kristian Svendsen: METHODOLOGICAL CHALLENGES IN PHARMACOEPIDEMIOLOGICAL STUDIES OF OPIOID CONSUMPTION.
551. Signe Nilssen Stafne: EXERCISE DURING PREGNANCY.
552. Marius Widerøe: MAGNETIC RESONANCE IMAGING OF HYPOXIC-ISCHEMIC BRAIN INJURY DEVELOPMENT IN THE NEWBORN RAT: Manganese and diffusion contrasts.
553. Andreas Radtke: MOLECULAR METHODS FOR TYPING *STREPTOCOCCUS AGALACTIAE* WITH SPECIAL EMPHASIS ON THE DEVELOPMENT AND VALIDATION OF A MULTI-LOCUS VARIABLE NUMBER OF TANDEM REPEATS ASSAY (MLVA).
554. Thor Wilhelm Bjelland: PHARMACOLOGICAL ASPECTS OF THERAPEUTIC HYPOTHERMIA.
555. Caroline Hild Hakvåg Pettersen: THE EFFECT OF OMEGA-3 POLYUNSATURATED FATTY ACIDS ON HUMAN CANCER CELLS: Molecular mechanisms involved.
556. Inga Thorsen Vengen: INFLAMMATION AND ATHEROSCLEROSIS: Risk associations in the HUNT surveys.
557. Elisabeth Balstad Magnussen: PREECLAMPSIA, PRETERM BIRTH AND MATERNAL CARDIOVASCULAR RISK FACTORS.
558. Monica Unsgaard-Tøndel: MOTOR CONTROL EXERCISES FOR PATIENTS WITH LOW BACK PAIN.
559. Lars Erik Sande Laugsand: INSOMNIA AND RISK FOR CARDIOVASCULAR DISEASE.
560. Kjersti Grønning: PATIENT EDUCATION AND CHRONIC INFLAMMATORY POLYARTHRITIS: Coping and effect.
561. Hanne Gro Wenzel: PRE- AND POST-INJURY HEALTH IN PERSONS WITH WHIPLASH, THE HUNT STUDY: Exploration of the functional somatic model for chronic whiplash.
562. Øystein Grimstad: TOLL-LIKE RECEPTOR-MEDIATED INFLAMMATORY RESPONSES IN KERATINOCYTES.
563. Håkon Olav Leira: DEVELOPMENT OF AN IMAGE-GUIDANCE RESEARCH SYSTEM FOR BRONCHOSCOPY.
564. Michael A. Lang: DIVING IN EXTREME ENVIRONMENTS: The scientific diving experience.