Thermal comfort in hospital buildings – A literature review

Feng Yuan[1], Runming Yao[1,2*]; Sasan Sadrizadeh[3]; Baiyi Li[4], Guangyu Cao[5]; Shaoxing Zhang[1], Shan Zhou[1], Hong Liu[1], Anna Bogdan[6]; Cristiana Croitoru[7]; Arsen Krikor Meliko[8]; C. Alan Short[9]; Baizhan Li[1]

[1] Joint International Research Laboratory of Green Buildings and Built Environments (Ministry of Education), Chongqing University, Chongqing, 400045, China

[2] School of the Built Environment, University of Reading, UK

[3] Department of Civil and Architectural Engineering, KTH Royal Institute of Technology, Stockholm, Sweden

[4] School of Architecture and Design, Southwest Jiaotong University, China

[5] Department of Energy and Process Engineering, Norwegian University of Science and Technology, Trondheim, 7491, Norway

[6] Faculty of Building Services, Hydro and Environmental Engineering, Warsaw University of Technology, Poland

[7] Faculty of Building Services, CAMBI Research Center, Technical University of Civil Engineering, Bucharest 020396, Romania

[8] Department of Civil Engineering, Technical University of Denmark - DTU, Denmark

[9] Department of Architecture, University of Cambridge, UK

Corresponding author's email: r.yao@cqu.edu.cn; r.yao@reading.ac.uk

Abbreviation List

ACH	**Air Changes per Hour**
CFD	**Computational Fluid Dynamics**
CMW	**Conduction Mattress Warming**
FAW	**Forced-Air Warming**
HP	**Healthy Person**
HVAC	**Heating, Ventilation, and Air Conditioning**
IAQ	**Indoor Air Quality**
IEQ	**Indoor Environmental Quality**
IPH	**Inadvertent Perioperative Hypothermia**
LAF	**Laminar Air Flow**
LowEx	**Low Exergy**

MV	**Mixing Ventilation**
met	**Metabolic rate, W/m^2**
NPV	**Natural Personalized Ventilation**
NRU	**Neurological Rehabilitation Unit**
OR	**Operating Room**
PCS	**Personal Comfort System**
PE	**Personalized Exhaust**
POV	**Protected Occupied zone Ventilation**
PV	**Personalized Ventilation**
SSIs	**Surgical Site Infections**

Abstract:

Hospital buildings are required to secure a variety of indoor environments according to the diverse requirements of patients and staff. Among these requirements, thermal comfort is an important design criterion for indoor environmental quality that affects patients' healing processes and the wellbeing of medical staff. The patients' thermal comfort is given priority due to their medical conditions and impaired immune systems. Thermal comfort and related contexts have been well-covered in many research articles; however, the number of review articles is limited. The aim of this paper is to conduct a holistic and critical review of existing studies offering insights on future research trends (160 articles were analyzed). The key research themes are identified using scientometric analysis focusing on factors that may improve thermal comfort and prevent patient hypothermia. The primary outcome concludes that ventilation systems play a key role in maintaining acceptable, thermally comfortable conditions for patients and medical staff. It is also found that acceptable thermal comfort is highly case-dependent and varies substantially based on the health condition of the patient as well as the type and level of staff activities. The measures currently mentioned to minimize energy consumption are also discussed. Some interesting issues, including the inaccuracy arising from the use of predicted mean vote (PMV) and the impact of gender, age, and related factors on thermal comfort, have been noted. This review provides insights into the design and assessment of hospital thermal environments.

Keywords: Thermal comfort; Hospital buildings; Improvement measures; Energy efficiency.

1 Introduction

Thermal comfort describes the satisfactory perception of an individual regarding the thermal environment [1]. It is considered as one of the most critical conditions for improving occupants' comfort and satisfaction within the indoor environment.

Hospital buildings are mainly designed to accommodate patients, usually with diverse health conditions which impose specific indoor environmental requirements. At the same time, a comfortable and safe working environment in hospital buildings is necessary for the staff. These requirements make hospital buildings rank among the most energy-intensive of all commercial and residential building types.

According to the application handbook compiled by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) [2], hospital's indoor environment is subdivided into different functional areas, such as surgery and critical care, nursing, ancillary services, administration, diagnostic and treatment, sterilizing and supply, service, etc. . Each functional zone has different requirements for the indoor environment. These characteristics give the hospital building its complexity. Because of the special characteristics of the groups served by hospital buildings, a healthy and comfortable indoor environment plays an important role in stabilizing patients' emotions and enabling staff to work efficiently. Moreover, an improved indoor environment in a hospital building can reduce costs associated with airborne illnesses by 9-20% [3]. There is, therefore, a growing need for maintaining a comfortable indoor environment in hospitals.

Over time, some new trends in hospital development related to thermal comfort have appeared. Hospital infrastructure is more important after the outbreak of COVID-19 and needs to be developed to meet people's medical needs [4]. The vulnerable patients in hospitals may be involved in developing more advanced medicine and new treatments for serious illnesses. They will need more dedicated care while simultaneously facing the challenge of creating a more appropriate hospital environment [5]. Besides, as research progresses, many new technologies related to the wellbeing of the patient are emerging, including the new perioperative patient warming blanket - the BARRIER EasyWarm blanket (Mölnlycke Health Care AB, Gothenburg, Sweden), the novel personalized ventilation-exhaust system, innovative low exergy systems, and other new methods [6-9]. The prospects of success of these new technologies and methods require examination.

However, there are very few comprehensive and systematic literature reviews on the topic of thermal comfort in hospital buildings. This study aims to provide a complete picture of thermal comfort-related studies in hospitals, identify the trends and current status of the research, summarize optimization strategies, and provide a future research perspective.

2 Methods

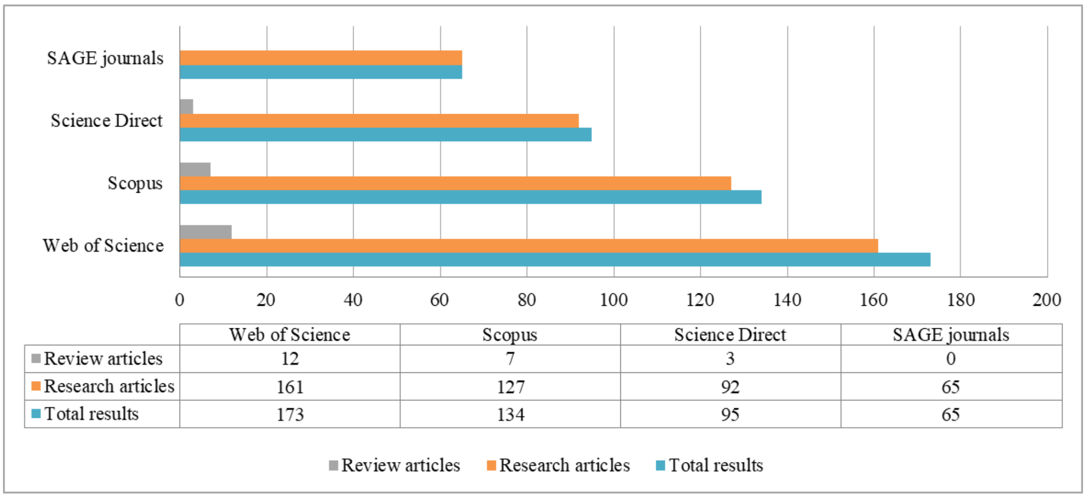
The literature review was conducted by browsing through publications that offer studies related to hospital thermal comfort. First, bibliographies were collected from academic databases. A second refinement used data-driven analysis and science mapping to analyze the bibliographic data [10, 11]. Science mapping is a branch of scientometrics that helps visualize the intellectual, structural, and dynamic patterns of bibliographic records in a research domain [10]. CiteSpace, a freely available scientometric tool, was chosen for this analysis. Then, the studies were analyzed according to the classification results of previous science mapping processes. The publications collected were scanned to recognize potentially insightful patterns from visually encoded signs and synthesize information from various domains.

The following sections describe the main findings of the reviewed bibliographies from each level of hospital thermal comfort or hospital thermal sensation.

2.1 Data collection

The preliminary literature search used a topic search for the terms "hospital thermal comfort" or "hospital thermal sensation" in titles, abstracts, and keywords in the following four academic databases: Web of Science, Scopus, Science Direct, and SAGE journals. The data range was set to "published all years to present". The document type was set to "research and review articles", and the language was limited to "English". Results are presented in Figure 1. Web of Science recorded the largest number (173) of specified type publications related to hospital thermal comfort among the four databases used. However, far fewer results were obtained from Science Direct, SAGE journals, and Scopus so the Web of Science records was chosen to continue this review.

Fig.1: Results from the general literature search on hospital thermal comfort in four databases.

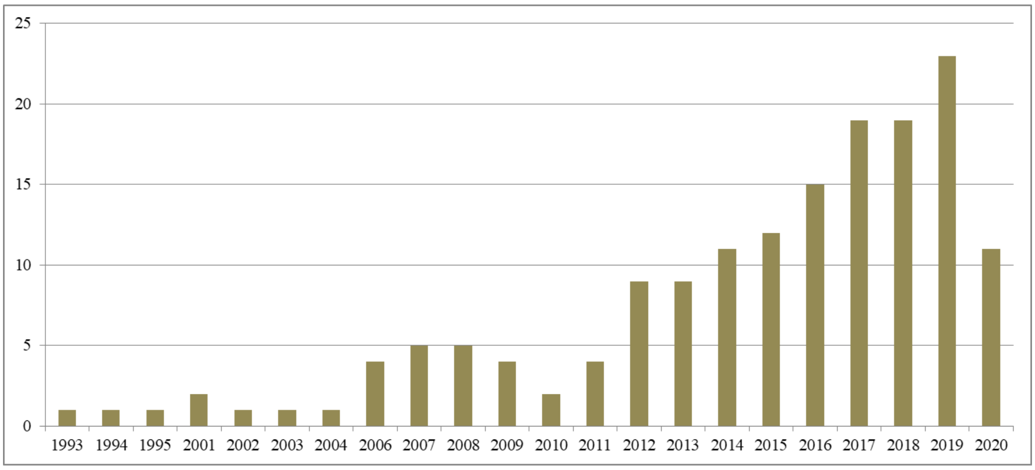


	Web of Science	Scopus	Science Direct	SAGE journals
■ Review articles	12	7	3	0
■ Research articles	161	127	92	65
■ Total results	173	134	95	65

2.2 Scientometric analysis of collected bibliographies

The time distribution of the collected bibliographic records on hospital thermal comfort was studied. Papers earlier than 1975 were excluded due to the time limitation for database inclusion. The earliest related article, discussing the preferred temperature of American surgeons, appeared in 1939 [12]. The number of publications each year is shown in Figure 2. From 1993 to 2020, the number of papers on hospital thermal comfort showed an overall increasing trend. The number of articles published between 2012 and 2019 is much higher than previous years, reaching 23 in 2019. It can be seen that the research activity on hospital thermal comfort from 2012 to 2019 has increased significantly, suggesting that people are paying increasing attention to thermal comfort in hospitals.

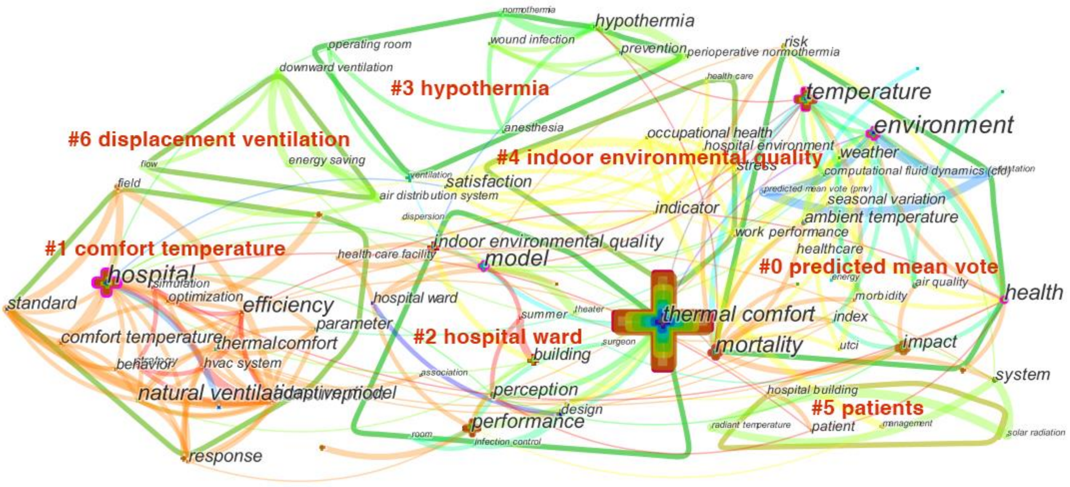
Fig.2: The distribution of the bibliographic records in the chosen database



The keywords and abstracts of 173 bibliographic records were analyzed using CiteSpace. The seven clusters identified are #0 predicted mean vote, #1 comfort temperature, #2 hospital ward, #3 hypothermia, #4 indoor environmental quality, #5 patients, and #6 displacement ventilation, as shown in Figure 3. From the figure, we can see that the predicted mean vote (PMV) appears to be the most important topic among the collected papers and related to cluster #1. Then, the full articles from clusters #0, #1, and #4, followed by clusters #2, #3, #5, and finally cluster #6, were carefully read. Studies irrelevant to hospital thermal comfort, e.g., those about climate change, were then excluded. Finally, data from a total of 62 papers remained on which to base the following discussion.

The country-wise distribution of literature was analyzed based on the 62 selected papers. The analysis results found that among the top five countries with many related articles, the United Kingdom and Italy ranked first, followed by the People's Republic of China, the United States, and Malaysia. At the same time, there were few studies from Africa. In contrast, Europe had the largest number of studies when divided into regions by continent. European healthcare systems started early and have matured considerably through reform and practice. Their experience is instructive and worth learning.

Fig.3: Clusters of data from the 173 papers.



2.3 Themes for discussion and analysis

Clusters #0, #1, and #4, mainly relating to PMV, comfortable temperature, and indoor environmental quality (IEQ), can be discussed from two aspects: influencing factors related to thermal comfort and field surveys of thermal comfort. By reading papers from clusters #2, #3, #5, and #6, patient perioperative hypothermia is a topic of concern. Meanwhile, ventilation is also an important topic to improve indoor air quality. These two topics can be combined and discussed as measures to improve thermal comfort. Some other topics， such as light-touch, low-carbon strategies, innovative systems for integral control of physical hazards and self-protection, and high-quality healthcare delivery for hospital staff, can be a feature of improving thermal comfort. In the reading process, energy-saving based on thermal comfort was found to be an aspect that should not be neglected. Although not many papers are involved, it is worth carrying out the discussion. Based on the cluster mentioned above analysis, four themes form the focus of this study: 1) Influencing factors related to thermal comfort; 2) Field-surveys of thermal comfort; 3) Measures to improve thermal comfort, and 4) Energy-saving based on thermal comfort. Ninety-seven other important works are also included for their historical importance and as reference data to enrich the identified themes. The following themes were chosen to be the focus of the analysis and discussion.

3. Analysis and discussion

3.1 Influencing factors related to thermal comfort

For hospital buildings, maintaining health and comfort is an issue that can never be compromised or neglected. Thermal comfort, acoustics, lighting, electromagnetic frequency levels, potable water surveillance, and indoor air quality (IAQ) constitute the IEQ of a building [13, 14]. Most studies on indoor building environments considered IAQ, lighting, thermal comfort, and acoustics as the main parameters to determine the indoor comfort level [13].

Humans perceive comfort through the interaction of various sensory stimuli and their integration in various environments. The dynamics of indoor environmental conditions, human occupancy, and the operational characteristics of buildings influence thermal comfort and indoor environmental quality [15]. Improving environmental comfort has an advantage in enhancing the health and performance of health providers (doctors, nurses, technicians, and administrative/executive staff) and patients [16, 17].

A comfortable thermal environment helps maintain patients' mood and improves their healing [18]. A variety of environmental factors influences a patient's perception of comfort. Temperature, humidity, illumination, and ventilation systems in hospital buildings have been proposed to affect patients [19]. In addition to the thermal comfort of the patient, there is also a growing body of evidence on the impact of the working environment on healthcare providers' efficiency, productivity, and satisfaction, all of which contribute to patient outcomes. Based on a series of relevant surveys, IAQ, noise level, and thermal comfort are three of the top five factors (a total of 16 physical features investigated) for healthcare providers responsible for healthcare settings [17]. For front-line practitioners, workplace temperature is an essential factor [20]. Meanwhile, in operating rooms (ORs), an analysis showed that the choice of ventilation type had a significant influence on the thermal comfort parameters of medical personnel [21]. Some research has proposed evidence regarding the negative impact on staff, resulting in stress, anxiety, and distractions due to noise; artificial lighting; and improper or inadequate ventilation [20, 22]. Measurement of long-term environmental and operational parameters in a new hospital building in Chicago showed that most of the measured temperatures, relative humidity values, and illuminance levels were within the acceptable thermal comfort range [1]. Indoor temperature, illuminance, and human occupancy/activity were all weakly correlated between rooms. At the same time, relative humidity, humidity ratio, and outdoor air fractions showed strong temporal (seasonal) patterns and strong spatial correlations between rooms [15, 23]. It has been shown that thermal comfort and acoustic comfort may influence each other [24]. An investigation in China studied the interaction between sound and thermal comfort in hospital wards. The results showed that the sound and temperature have an almost equal and stronger effect than humidity on overall comfort.

Meanwhile, a satisfactory thermal environment can improve the evaluation of acoustic comfort, while an unsatisfactory thermal environment has the opposite effect [25]. In some specific circumstances, there are factors unique to a situation that affect thermal comfort. For example, over-crowding was believed to be a significant factor for the low satisfaction level of hospitals in China [26]. Under such conditions, the indoor air quality, acoustic environment, and even the building services are challenging to maintain at a satisfactory level.

While factors inside the room are important, those outside should also be considered. The layout of the hospital's functional areas will influence people's satisfaction with the environment. This is evident in the case of a new consideration of the Neurological Rehabilitation Unit (NRU). The various therapeutic areas are separated from each other, and some rooms have doors for further enclosure, which helps to contain activity-based noise. Meanwhile, the centralized nursing station, decentralized supply rooms, and acuity-adaptable patient rooms create a satisfactory working environment for staff [27]. The design of the hospital's functional areas will also influence people's satisfaction with the environment. The design of Hospital Street can be a good example. Hospital Street, which connects the functional blocks (outpatient and medical-technology spaces), is widely used in the design of large-scale hospitals. And the architectural form is usually a multi-storied atrium, roofed by a transparent building envelope. Its layout also has an increasingly more significant impact on the efficiency and stability of a hospital. An investigation in China showed that the environment of a semi-closed hospital street was over-heated and over-humid, and people experienced discomfort with the visual and acoustic environment under the existing layout [28].

3.2 Field-surveys of thermal comfort

Thermal comfort is a significant factor for a healthy indoor environment. The literature covered is categorized by country, and the basic and detailed information has been summarized in Tables 1 and 2, respectively. The most commonly used methods are objective and subjective data collection.

Patients and medical staff are two commonly studied groups. Visitors are also mentioned in some studies. Staff and patients have different thermal perceptions of the indoor environment. Even though in the same area, different types of personnel have different thermal sensations. Compared to medical staff, patients were more satisfied with indoor conditions, whereas hospital staff preferred the lower temperature to the neutral. The thermal comfort of visitors was also investigated, and they were found to have a different temperature preference to those of staff and patients. The comfort level of some different functional areas has been explored, with wards and operating rooms being the most frequently studied along with special areas, such as the ultrasound suite. Most of the research has been conducted in a single hospital, with only a small number involving multiple hospitals. There are two main types of studies that focus on specific functional areas and specific populations. Some interesting issues such as differences regarding gender or age are exposed, they will also be discussed.

Table 1: Basic information from field-surveys

Country	Year	Subjects	Methods	Functional areas	Main conclusions	Reference
Sweden	2005	Patients and staff	Objective and subjective data collection	Orthopaedic ward	The difference between staff and patient perceptions of the indoor air temperature differed more during winter than summer.	[29]
Japan	2005, 2008	Patients and staff	Objective and subjective data collection	20 sickrooms, nurse stations and corridors.	Introducing humidifiers into a hospital during winter is an effective method of improving low relative humidity environments in sickrooms and of relieving the discomfort of staff members.	[30, 31]
Italy	2013	Patients and staff	Objective and subjective data collection	Orthopaedics, Paediatrics and Internal Medicine wards.	Patients were more satisfied with building-related aspects and indoor conditions than medical staff.	[32]
	2015	Patients and staff	Objective and subjective data collection	8 wards of a public hospital.	PMV model does not seem to prove suitable for the patient population. Gender and age are factors that must be taken into account in the assessment of thermal comfort in the hospital.	[33]
	2019	Pregnant women	Objective and subjective data collection	Obstetrical Ward.	.For pregnant women in a typical sedentary condition when hosted in the inpatient room, the **met(metabolic rate)**value corresponds to 2.17.	[34]

Malaysia	2013	Staff	Objective and subjective data collection	Facility departments (lobby, office, prayer room, kindergarten, and catering area).	The neutral operative temperature based on TSV and PMV regression models are 26.8°C and 25°C, respectively.	[35]
	2013	Non-patient respondents	Objective and subjective data collection	Three offices, pharmacy, radiology, prayer room, kitchen, nursery, lobby, and corridor.	The effective neutral temperatures based on TSV and PMV are 23.4°C and 21.3°C, respectively; Preferred operative and effective temperatures (OT, ET*) are 23.6°C and 20.3°C, respectively.	[36]
	2014	Staff	Objective and subjective data collection	9 hospitals with 41 departments (the staff rooms, nurse counters, and the working space of the hospital personnel).	The adaptive model is $T_n=0.3314T_{out}$ +14.858 and the most comfortable or neutral temperature found from the field study in hospitals was 26.4°C .	[37]
	2019	Patients and visitors	Objective and subjective data collection	Medical, surgical, maternity, and paediatric wards in three private hospitals.	The operative temperature range of 22.0-28.0°C is thermally acceptable to more than 86% of subjects; Mean comfort temperatures for patients and visitors were 25.3°C and 25.5°C, respectively.	[38]

Poland	2015	Surgical staff(surgeons , nurses and surgeon's assistants , anaesthetists)	Thermal environment measurements	37 ORs in 7 Warsaw hospitals.	The thermal environment in most of measured ORs was assessed as ‘warm’ or ‘slightly warm’ for nurses, surgeon’s assistants, and surgeons, while quite comfortable for anaesthetists.	[39]
Madagascar	2017	Patients	Questionnaires, interviews and physical parameter measurements	5 big hospitals.	Voters' mind state as non-negligible parameter in adaptive comfort; 90% of the patients reported a comfortable temperature range between 22.4°C and 25.3°C.	[40]
Thailand	2017	Patients, visitors, and staff	Objective and subjective data collection	Public waiting areas, nurse stations, and clinical examination rooms in five OPD clinics (medicine (Med); ear, nose and throat (ENT); and dentistry (Dent)).	The acceptable temperature ranges for the patient, visitor, and medical staff are at 21.8–27.9, 22.0–27.1, and 24.1–25.6°C, respectively.	[41]
Netherlands	2018	Nursing staff	Objective and subjective data collection	Two wards of a hospital (patient rooms, reception, meeting room, break room, and medicine room).	The optimal thermal sensation for the nurses would be closer to ‘slightly cool’ than neutral.	[42]

Netherlands	2018	Nursing staff and office workers	Objective and subjective data collection	Hospital wards (the reception, medicine room, nurses' break-room, corridors, and some patient rooms with different bed numbers and different orientations were covered).	The thermal environment in the hospital wards was perceived as slightly warm while the office workers rated their environment on the cool side.	[43]
UK	2019	The ultrasound area	Objective data collection	Waiting/reception area and staff break room associated with the ultrasound scanning rooms.	Several low-level solutions such as improved signage, access to water, and the allocation of vulnerable patients to morning clinics are suggested.	[44]
Italy and Denmark	2020	Physiotherapists and patients	Objective and subjective data collection	Four physiotherapy centers (“Bolzano 1”,“Bolzano 2”, “Copenhagen 1”, “Copenhagen 2”).	Patients preferred temperature ranges of 22.5–24.5°C and 20–22.5°C, respectively, during static and dynamic treatments, while therapists seemed to better adapt to the environment by adjusting their clothing level.	[45]
Saudi Arabia	2020	Patients	Objective and subjective data collection	Medical and surgical wards.	Using PMV or a non-patient-specific temperature caanot reflect patients thermal desire in hospitals.	[46]

Table 2: Detailed information from field-surveys

Monitoring parameters	Number of participants	Sampling period	Demographic characteristics	Reference
Indoor air temperature, relative air humidity, globe temperature, carbon dioxide concentration, PM2.5 dust concentration, sound pressure level, and illuminance	35 patients and 40 employees (assistant nurses, nurses and administrative staff).	Summer (the end of August and the beginning of September in 2003 and Winter (February 2004).	-	[29]
Indoor air temperature and relative humidity	36 patients and 45 staff members (nurses or nurses' aides).	From the 30th of November to the 25th of January (8 weeks).	Age(mean±SD): Patients:71.0±13.6 Staff: 38.7±11.5 ; Main diseases of patients: Stroke etc.(66%) bone fracture etc.(28%), other(6%)	[30, 31]
Continuous monitoring: indoor air temperature, relative humidity (RH) and illumination. Spot measurements: included plane radiant temperature, and mean air velocity	55 staff members (26 from Orthopaedics, 16 from Internal Medicine, and 13 from Paediatrics) and 35 patients (20 from Orthopaedics and 15 from Internal Medicine).	March 31st-June 10$^{th.}$.	-	[32]
Indoor air temperature, globe temperature, air velocity, and relative humidity.	30 patients and 19 medical staff.	October and November 2011.	Gender (number of people): Patients: male(13) female(17) Staff: male(2) female(17) Age: (number of people): Patients: Under 65(16) Over 65 (14) Staff: Under 65(19) Over 65(0).	[33]
Indoor air temperature, mean radiant temperature, relative humidity, and airspeed.	55 pregnant women.	24th of November 2017.	Age range: 20-35.	[34]

Indoor air temperature, mean radiant temperature, humidity, air velocity, CO_2, light level, and noise.	110 subjects	May and June 2011	Gender: male(24.5%); female(75.5%) Age:<20(5.5%) 20-30(60%) 30-40(21%) >40(13.5%).	[35]
Indoor air temperature, globe temperature, relative humidity, air velocity, light level, noise, and CO_2.	188 respondents	May 2011 and February 2012	Gender: male(28.2%) female(71.8%).	[36]
Indoor air temperature, globe temperature, relative humidity, and air velocity.	293 workers	2009 and 2010	Gender ratio: male:female(1:2.5). Age range: 23-45.	[37]
Indoor air temperature, relative humidity, globe temperature, and air movement.	389 responses (305 patients and 84 visitors).	Over 29 days, from January 2016 to March 2017 (January −March 2016 (15 days), June −August 2016 (9 days), and June −August 2016, and March 2017 (5 days).	Average ages :patients(36), visitors(38). Gender: patients(57% females) visitors(63% females). Current health condition: 81%(‘fair’ and ‘good’) 19% (‘bad’ and ‘very bad’).	[38]

Indoor air temperature, wet-bulb temperature, mean radiant temperature, air velocity, relative humidity.	-	July - September 2014	-	[39]
Indoor air temperature, air speed, and relative humidity.	Questionnaires:100 patients; Interviews: 198; A total of 298 voters.	10 days September 2016 8 days December 2016	Gender: Male (48%); Female(52%). Age range: 13-89.. Height range(m): 1.55-1.78. Weight range(kg): 33-90.	[40]
Indoor air temperature, relative humidity, carbon dioxide concentration, sound level and illuminance, globe temperature, and wind velocity.	928 occupants (451 patients, 331 visitors and 146 medical staff).	July to November 2015 and March to May 2016	Gender: Male(35%) Female(65%) Average age: patients(47) visitors(42) Staff (31)	[41]
Indoor air temperature, globe temperature, omni-directional air velocity, RH, CO_2 concentration, and particulate levels.	Summer: 89 responses, Autumn:43 responses.	July 11th - July 29th (Summer) October 7th-November 11th (Autumn), 2016.	Summer: Age range: 21-30 (75.3%), Female 64.0%, Autumn: Age 21-30 (53.5%), Female 76.7%.	[42]

Indoor air temperature, relative humidity, globe temperature, air velocity, and CO_2 concentration.	96 usable responses.	During 11–29 July (First period) and 7 October–11 November (Second period), 2016.	Age range (number of people): <20 (1); 21-30 (75); 31-40 (12); 41-50 (15); 51-60(6); >60 (1) Gender(number of people): Male 20, Female 90.	[43]
Indoor air temperature and relative humidity.	-	225 clinic hours.	-	[44]
Long-term measurements: indoor air temperature and humidity. Short term measurements: indoor air temperature, relative humidity, mean radiant temperature, and air speed.	Therapists (186), Patients before therapy (273), Patients after static therapy (77), Patients after dynamic therapy (181).	October 15th 2018- April 15th, 2019 ("Bolzano 1","Bolzano 2") February 5th 2019- March 13th 2019 ("Copenhagen 1") February 4th 2019 - March 21st 2019 ("Copenhagen 2").	Gender: Therapists (Female:64% Male:36%) Patients (Female:60% Male:40%) Age: Therapists (20-29:23% 30-39:31% 40-49:31% 50-59:14% 60-69 1%), Patients (9-19:3% 20-29:5% 30-39:4% 40-49:10% 50-59: 14% 60-69: 28% 70-79: 24% 80-89:9% 90-99:3%) Health status of patients: Weak(4%), Slightly weak (40%), Healthy (56%).	[45]
Indoor air temperature, mean radiant temperature, relative humidity, and air velocity.	120 subjects	Summer of 2017 (May, June, and July).	Gender: Female:49% Male:51%. Age range: 18-24(9%) 25-34(18%), 35-44(23%), 45-54(15%), 55-64(19%), 65-74(9%), >74(7%).	[46]

3.2.1 Thermal comfort research in different functional areas

Concerning the various functional areas, most of the attention is currently focused on ward rooms and ORs, with some studies conducted in hospital streets and ultrasound areas.

The study of thermal comfort in wards is a hot topic. To compare the views of patients and staff in the wards, De Giuli *et al.* used innovative statistical nonparametric methods to conduct an investigation [32]. Staff mostly complained about lack of privacy, room size, number of shared spaces, poor air quality, and acoustic discomfort. Patients expressed a higher level of satisfaction with building-related aspects and perceived a lower frequency of environmental discomfort. Differences in satisfaction between different types of wards were also noted. In building-related aspects, Orthopaedics had the highest level of staff satisfaction, while Internal Medicine had the lowest frequency of discomfort [32]. Studies about thermal perceptions of patients and staff were also undertaken. By using objective and subjective data collection methods, a study showed that the optimal thermal sensation for the nurses would be closer to "slightly cool" than “neutral” [42]. Another study compared the feedback of nursing staff in hospital wards and the workers in an office. The thermal environment in hospital wards was perceived as slightly warm, while the office workers rated their environment on the cool side [43]. The comfort temperature for patients and visitors was investigated in tropical hospitals by field survey assessments. The operative temperature range of 22.0-28.0°C is thermally acceptable to more than 86% of subjects. The mean comfort operative temperatures were estimated to be 25.3°C for patients and 25.5°C for visitors [38].

Maintaining thermal comfort in the OR is complicated and challenging. While the patient’s safety is a priority, the thermal comfort of medical staff should be weighted equally because their comfort has an indirect influence on the quality of their work [47-49]. In ORs, the specific tasks undertaken by medical staff limit their ability to adapt. Studies have confirmed the effectiveness of the PMV model for evaluating thermal conditions on surgical wards [48, 50]. The variance between survey results and PMV measurements did not exceed 5% in these studies. Therefore, the PMV index can be used to provide optimum levels of accuracy for evaluating OR thermal environment conditions, which are comparable to thermal perception data from the questionnaires [39]. Due to the different types of OR staff, differences in thermal sensation exist. The nurses feel a slightly cold sensation under the air supply diffuser, and their neutral comfort zone is located in the air stagnation zones close to the walls, while the surgeons feel the opposite [51]. A survey in Polish ORs found that the thermal environment was assessed as "warm" by surgeons, as "slightly warm" by nurses and surgeons' assistants, and as “comfortable” by anesthetists [39].

Some research on other areas in hospitals has been conducted. The ambient temperature and humidity in sickrooms, nurse stations, and corridors were measured during winter. The data showed that the humidity level was low, which would promote the spread of influenza viruses. Introducing humidifiers into a hospital during winter is an effective method of improving low relative humidity environments in sickrooms and of relieving the discomfort of staff members [30, 31]. A case study conducted in the ultrasound suite of the Maternity and Gynecology building showed that most rooms had already breached standard overheating thresholds, and anthropogenic and waste heat from equipment had a noticeable effect on indoor temperatures. Several low-level solutions such as improved signage, access to water, and the allocation of vulnerable patients to morning clinics are suggested [44]. The thermal comfort in four physiotherapy centers in Northern Italy and Denmark was investigated during the heating season. Patients preferred temperature ranges of 22.5-24.5°C and 20-22.5°C during static and dynamic treatments, respectively, while therapists seemed to better adapt to the environment by adjusting their clothing level [45].

3.2.2 Thermal comfort research on different people

Hospital thermal comfort research focuses typically on two groups of people: patients and hospital staff.

Three thermal comfort surveys for medical staff have been conducted in different areas in Malaysian hospitals. The results have confirmed that the preferred temperature is lower than a neutral temperature. The effective neutral temperatures based on TSV and PMV are 23.4°C and 21.3°C, respectively. The preferred operative and effective temperatures (OT, ET*) are 23.6°C and 20.3°C, respectively [35, 36]. By conducting regression analysis between the neutral temperature and outdoor temperature, the adaptive thermal comfort model, $T_n = 0.3314\ T_{out} + 14.858$ was successfully developed based on a large field study in nine hospitals with 293 workers [37].

Some studies are related to thermal comfort for patients. A case study was conducted to evaluate patients' thermal comfort in naturally ventilated hospital buildings in Madagascar. The mean neutral temperature was different for women and men. Almost 90% of the patients reported a comfortable temperature range between 22.4°C and 25.3°C [40]. A study conducted by Alotaibi *et al*. [46] revealed that patients have diverse preferences for their indoor environment. The large range of neutral temperatures also emphasized the diversity in thermal requirements. Special patient groups in the hospital, such as pregnant women, were studied as subjects. The research revealed that for pregnant women in a typical sedentary condition when hosted in an inpatient room, the met value corresponds to 2.17 [34].

Comparisons of the thermal preference of different people have also been conducted. A study showed that staff and patients' perception of the indoor air temperature differed more during winter than summer, despite the physical measurements showing that the temperatures were similar in both seasons [29]. A survey in Bangkok concluded that the acceptable temperature range for the patients, visitors, and medical staff are 21.8-27.9°C, 22.0-27.1°C, and 24.1-25.6°C, respectively [41].

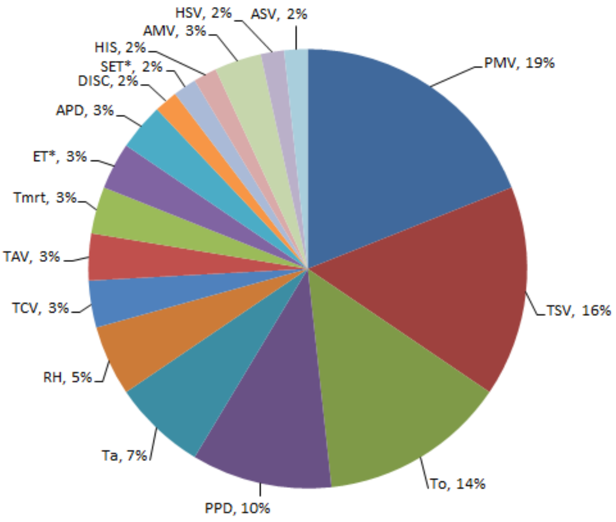
3.2.3 Analysis of the information revealed in field-surveys

Detailed information from the field surveys are shown in Table 2. The monitoring parameters were analyzed. It can be seen that many basic parameters were collected for thermal comfort evaluation. Parameters of IEQ besides thermal comfort have also been evaluated in field surveys. Demographic characteristics were also evaluated, which revealed much useful information.

3.2.3.1 Thermal indices used in field-surveys

According to a study conducted by De Freitas and Grigorieva [52], thermal indices applied in the reviewed publications were summarized. The proportion of these thermal indices is represented in Figure 4. PMV and TSV are the two most commonly used indices with PMV the most widely used. Regarding the selection of values for PMV calculation, in the ORs, due to the variability of different locations in the room, using the average ventilation values (i.e., velocity, temperature, and humidity) to calculate the PMV does not provide a correct and sufficient descriptive evaluation [51].

Fig.4: The frequency of thermal indices applied in the reviewed studies.



Nomenclature

PMV	Predicted Mean Vote
TSV	Thermal Sensation Vote
To	Operative Temperature
PPD	Predicted Percentage of Dissatisfied
Ta	Air Temperature
RH	Relative Humidity
TCV	Thermal Comfort Vote
TAV	Thermal Acceptability Vote
Tmrt	Mean Radiant Temperature
ET*	Effective Temperature
AMV	Actual Mean Vote
APD	Actual Percentage Dissatisfied
DISC	Discomfort Index
SET*	Standard Effective Temperature Index
HIS	Heat Stress Index
HSV	Humidity Sensation Vote
ASV	Actual Thermal Sensation Vote

Though PMV is the most widely used index, some studies have indicated that it is not always the appropriate indicator [33, 46, 53]. One reason pointed out by Li and Lian [53] is that Fanger's work was pioneered using college students in good health and under steady-state conditions. In addition, there is a deviation between PMV and actual thermal sensation. During a survey in four physiotherapy centers, the thermal perception was found to be generally closer to neutrality than predicted by the PMV-PPD model [45]. In hot-humid regions, the neutral operative temperatures based on TSV and PMV regression models are 26.8°C and 25°C, respectively, which deviates from the "neutral" point on the ASHRAE scale by +0.75 [35]. Another study conducted in the same region also suggested that the neutral point shifted to +0.7 on the seven-point ASHRAE scale [36]. A study [46] aimed to confirm if a standard steady-state thermal comfort approach is adequate, especially in hot climates. Since the PMV was not sufficiently accurate, it was supplemented in Malaysia by applying an adaptive comfort model [37] in which the voters' state of mind was considered as a non-negligible parameter [40].

Due to the discrepancy between PMV and TSV, many studies have investigated the neutral temperature. The large range of neutral temperatures not only emphasized the inaccuracy in using PMV, but also the diversity in thermal requirements [46]. Patients have diverse desires in the indoor environment. Therefore, further work classifying patients' diverse desires by illness should be considered. In addition to considering the diverse desires of patients, visitors and staff also have different needs. Staff and patients cannot be treated as one coherent group of users with the same needs and preferences [29, 33]. The thermal sensation, acceptability, and satisfaction of patients, visitors, and staff were different [41]. Special patient groups in the hospital, such as pregnant women, have been studied as subjects. The wide gap between TSV and PMV can be attributed to the fact that the standardized metabolic unit from ISO does not correctly reflect the physiological condition of pregnant women. When investigating thermal comfort, the specific met in the standards needs to be defined for some particular categories (children, the elderly, pregnant women, etc.) [34].

To meet the thermal comfort needs of both the patients and nursing staff, different conditioning set-points for different zones can be the most straightforward solution [42]. Thermal expectations of each group of medical staff were different [39]. Occupant thermal perception was not impacted by the temperature difference of the transition when the air temperature differences were within ±2°[43]. Nevertheless, it is difficult to come up with a general solution because of the current design and state of ventilation systems, as large variations exist between individuals in terms of physical and emotional satisfaction [54].

3.2.3.2 Parameters of IEQ besides thermal comfort evaluated in field-surveys

Some researchers have monitored parameters related to IAQ. A study considered the particulate matter and whether it influenced the judgment of wet sensation [42]. The RH values were within an acceptable range, but there were many responses with complaints about dry air with particulate matter being considered as a possible cause [42]. The CO_2, lighting, and noise levels have also been considered in hospitals. The CO_2 level in the office was higher than the standard range due to the number of occupants. The lighting level was lower than the criteria set by the standards [35]. IAQ, thermal comfort, the lighting and acoustic environment, and other important components of indoor environmental quality (IEQ), can interact with each other.

3.2.3.3 Demographic characteristics analyzed in field-surveys

Gender and age are the most frequently considered demographic characteristics. Differences in the environmental preferences of male and female healthcare providers were found [20], which have been confirmed by other studies from office settings [55-57]. An analysis of data from 30 patients and 19 medical staff suggests that females tend to feel more uncomfortable compared to males when the thermal environment deviates from neutrality. The association between AMV and PMV values is weak among females compared to males. Moreover, it is very weak among subjects over 65 years of age compared to subjects under that age. Hence, gender and age are factors that must be taken into account in the assessment of thermal comfort in hospitals [33]. Height, weight, disease categories, and health conditions are considered in some studies, one of which collected data from 305 patients and concluded that the health conditions of the patients had highly significant effects on their thermal preference, overall comfort, and air quality feeling. However, other characteristics like age, gender, and days hospitalized had no effect on other thermal comfort parameters [38].

In contrast, another study with a large sample size identified gender, age, and health status as parameters affecting the perception of patients. In particular, patients older than 65 years were slightly less satisfied with the temperature, and women expressed a slightly lower TSV as did patients not rating themselves as healthy [45]. In the future, larger samples and longer periods of investigation are needed in order to study the effect of gender, age, health conditions, and other related factors on thermal comfort.

3.3 Measures to improve thermal comfort

3.3.1 *Focus issue* I : Measures to address inadvertent perioperative hypothermia

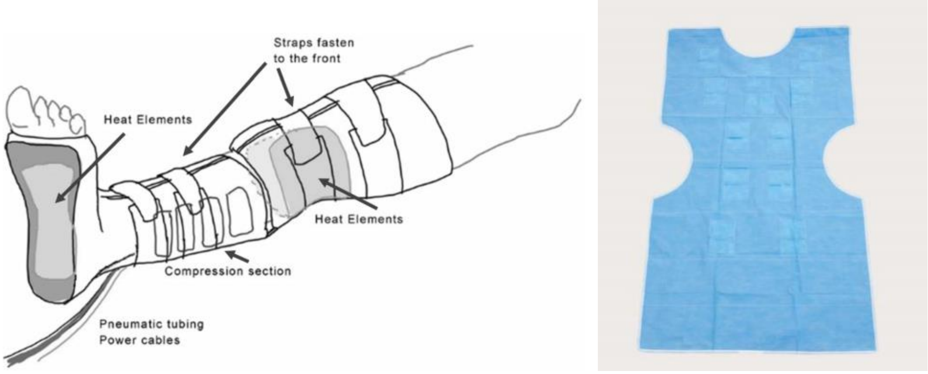
Inadvertent perioperative hypothermia (IPH) is defined as a patient core temperature of less than 36°C [58]. The incidence of postoperative hypothermia in elective surgery is reported to be 26% to 90% [59]. It may negatively impact not only patient outcomes, including patient satisfaction but also total hospital treatment costs [58, 60, 61]. However, IPH is a preventable phenomenon. The solutions for patient warming are summarized as follows: preoperative skin warming, adjusting the ambient temperature in the operating room, intraoperative temperature monitoring, heated and humidified anesthesia circuits, forced-air warming blankets and other devices, warmed intravenous fluids and blood products, postoperative mechanical ventilation, prevention and treatment of postoperative shivering, and the anticipation and treatment of rewarming vasodilatation [62]. Present guidelines advocate "prewarming" for IPH prevention. Environment-induced core body temperature has a negative impact on hypothermic patient risk [63]. Prewarming means preoperative patient skin warming, which minimizes redistribution of hypothermia caused by the induction of anesthesia. Using a real-scale OR model can determine the necessary climatic parameters to avoid the patient's hypothermia and ensure the thermal comfort of the patients and the surgical team [64].

Warming methods are divided into active heating and passive heating. There are multiple active body warming devices available [65], including forced-air warming (FAW) and conduction mattress warming (CMW). Active patient warming should be undertaken, especially in patients whose thermoregulating mechanisms may be less effective [66]. The most common and widely used warming approach is FAW, which significantly decreases cutaneous heat loss [67, 68]. Nevertheless, intraoperative core temperature patterns in patients warmed with this method remain poorly characterized. A research study by Sun *et al*. [69] evaluated the core body temperature in adult patients under various surgical procedures, considering hypothermic exposure throughout the surgery. The results indicated that hypothermia is most likely to occur during the first hour of anesthesia, even in actively warmed patients. One study was conducted to identify a superior active body warming device for preventing IPH during elective cesarean section. All participants received in-line intravenous fluid warming and were randomized to three parallel groups: no active body warming, forced-air warming, and conduction mattress warming. The results revealed that online intravenous fluid warming was sufficient to prevent maternal hypothermia and maintain core temperature [70].

Intraoperative FAW does not prevent IPH even with full compliance [71, 72]. A useful perioperative warming device placed in the preoperative period is needed. For this condition, a prototype thermal compression device that can heat the popliteal fossa and soles of the feet with lower leg compression was developed (see Figure 6a). The trial study confirmed that such devices could increase perioperative temperatures and reduce inadvertent perioperative hypothermia. It is more feasible and efficient than forced-air warming [73]. Existing devices depending on external electrical sources are available to actively prewarm surgical patients [74].

In contrast, the new BARRIER EasyWarm blanket is a disposable, self-warming device (see Figure 6b). This new blanket significantly improved perioperative core body temperatures compared with standard hospital blankets [6]. The results from another test focused on the BARRIER EasyWarm blanket showed that this blanket provided more adequate body temperature control and reduced the number of postoperative shivering episodes [75].

Fig.6: New devices for the prevention of inadvertent perioperative hypothermia



a. A prototype thermal compression device [73];   b. BARRIER EasyWarm blanket [76]

However, a comparison of resistive heating-blankets and forced-air warming systems during hip replacement surgery showed that patients ended surgery in mild hypothermia after elective total hip replacement, but without significant differences between these two warming devices [77].

Some passive warming methods have also been proposed to prevent hypothermia. Considering economy and effectiveness, two passive warming techniques (thermal reflective blankets and warmed cotton blankets) were compared. The results showed that there were no significant differences in patient temperature or comfort between groups. It is unnecessary to purchase thermal reflective blankets due to equivalent performance and minimal cost savings [78].

Opposite results were obtained during studies by Bennett *et al*. [79]. An active solution - forced heated air system - was very efficient in providing thermal homeostasis during surgery, while a passive solution - the metalized plastic sheet - insulated the skin only from radiant and convective heat losses while attenuating the reduction in core temperature. On the other hand, forced-air warming systems may cause field contamination, and passive warming may increase the ambient OR temperature [80]. It is preferred to position these active warming devices above the patient to boost efficiency [47].

3.3.2 *Focus issue* II: Proper ventilation systems

It has been demonstrated that a proper ventilation system can improve indoor air quality and potentially increase occupant satisfaction [81-88].

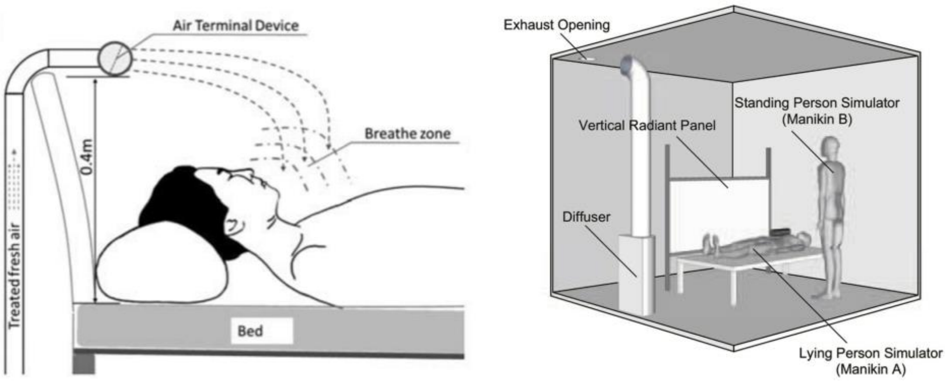
For the OR, designing an appropriate air conditioning system can prevent infections from spreading while offering a comfortable environment for all persons.

There are two standard airflow distribution methods used in OR: Laminar (or unidirectional) airflow and mixing (or conventional ventilation) systems. Recent studies show that the number and location of exhaust diffusers in ORs with mixing ventilation will also affect the air quality close to a surgical patient [89, 90]. Many hospitals use laminar airflow systems (LAF) in their operating rooms to decrease rates of surgical site infections (SSIs). Modern vertical LAF designs have removed the need for panels or curtains to direct the laminar flow with the introduction of exponential laminar flow systems [91]. There are three categories of modern vertical LAF designs: air curtain systems, multi-diffuser arrays, or a single large diffuser [92]. The LAF associated with the air curtain to air conditioning was studied and compared with the system without the air curtain. The results showed that an air curtain having an optimal velocity of the outlet air greatly influences the reduction of air contamination and the desired conditions [93]. Laminar flow ventilation systems reduce OR bacterial counts, but the evidence for these systems is limited or even contradictory [92, 94-96]. The thermal comfort level varies with different ventilation methods, and relevant studies show that ORs with mixing ventilation (MV) might have a higher percentage dissatisfaction with the thermal environment than those with LAF ventilation [97, 98].

Indoor conditions in wardrooms are very different compared with other environments, such as office spaces. Two types of ventilation systems are usually used in hospital wards: the mixing type and displacement type [99]. The analysis in patient rooms by CFD has shown that displacement ventilation was found to make larger bioaerosols (>10μm) suspend in the air for more extended periods. In contrast, smaller particles were able to escape space [100]. Another study conducted experiments in multiple-bed patient rooms. It has been found that the spacing between beds should be greater with the displacement ventilation strategy compared with air-mixing ventilation. During displacement ventilation, the exhaled nuclei droplets from infected patients penetrate for greater distances and take longer to dissipate than in air-mixing ventilation strategies [101]. In individual hospital rooms, swirl ceiling diffusers have the best performance among four different mixing ventilation configurations based on ventilation performance and health workers' exposure to the contaminants released by a confined patient [102]. Fans appear to be a simple retrofit measure compared with an expensive and energy-consuming air-conditioning system [103]. For some special spaces, such as the wards within a hospital tower building, fans can be a good choice for maintaining thermal comfort. Natural ventilation is another method used to provide high airflow rates with low energy consumption, which is particularly encouraged in the UK and commonly practiced in tropical countries [99]. In addition to the characteristics of the ventilation system itself, human behavior can also affect ventilation efficiency. The occupants' window-opening behaviors played a decisive role in natural ventilation performance. Therefore, logistic regression models in different seasons based on the seasonal variation of window-opening behaviors were developed to predict the window opening/closing state. The effect of indoor and outdoor physical variables on window-opening behaviors varies significantly by season. The indoor air temperature or relative humidity is found to be a dominant factor for window-opening behaviors in all seasons [104].

Some new ventilation strategies have been proposed for hospital wards. The bedside PV system shown in Figure 7a was studied and proved to improve the thermal comfort level and subjective sleep quality in experiments with children, adults, and the elderly [105]. The buoyancy-driven personalized ventilation (NPV) system is a feasible low energy innovation that can achieve dedicated personalized ventilation and mixing regimes in occupied spaces. Nevertheless, this system requires integrating the architectural enclosure and bed layout based on the design principles for buoyancy-driven natural ventilation systems. Results achieved in computational fluid dynamics (CFD) simulations showed that an NPV system could deliver fresh air to multiple patients, including those located 10m away from an external wall, and the potential ingress of airborne contaminants into patients' breathing zone and summer overheating was minimized [106]. To solve the serious odor problem in hospital wards, a displacement ventilation system combined with an individually controlled vertical radiant panel was designed (shown in Figure 7b). Experimental results indicated that the location of the vertical radiant panel is important when used as a complementary heating or cooling system with displacement ventilation [107].

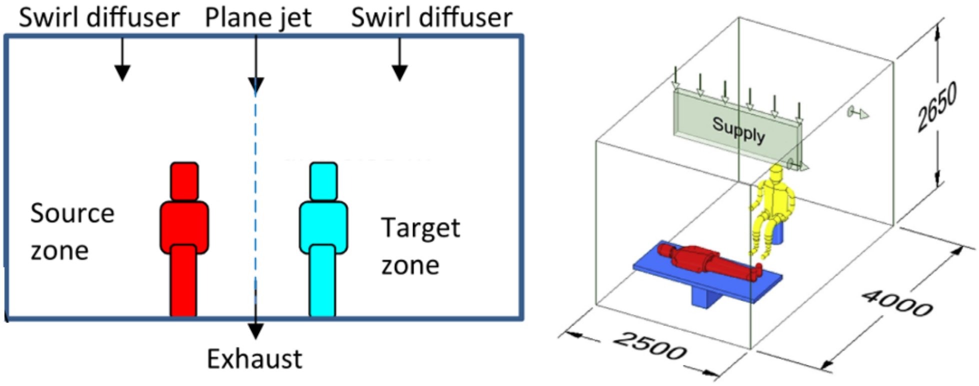
Fig.7: New ventilation systems



a. Bedside PV system [105]; b. displacement ventilation system combined with an individually controlled vertical radiant panel[107].

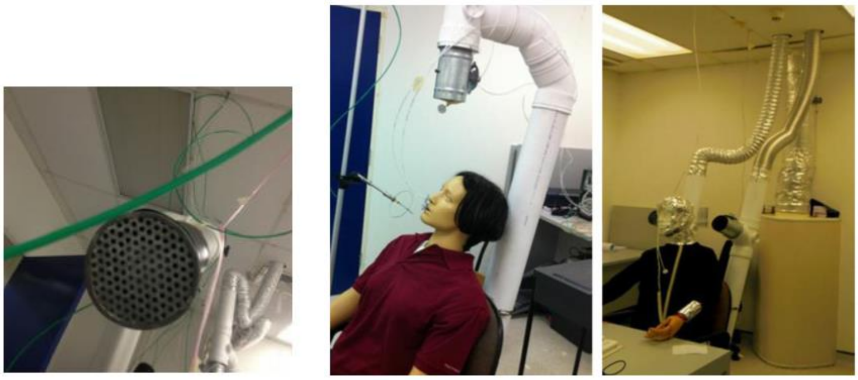
Though PV systems are efficient in reducing contaminants, the necessity for larger equipment and the increased energy consumption due to additional ductwork and pressure loss made the application of PV systems only moderately successful [108]. Therefore, there is an urgent necessity to reconsider the ventilation design of hospital wards. A novel air distribution system has been designed to protect occupants from cross-contamination by separating an internal space into different personal work areas or subzones using downward plane jets (see Figure 8a) [109]. This method, called *protected occupied zone ventilation* (POV), can prevent the transmission of contaminated air from the polluted zone to the protected occupied zone. A study recommended the POV system shown in Figure 8b for a patient ward with a minimal possible draught risk by CFD. The results showed that supply velocities of 1.0, 1.5, and 2.0m/s did not exceed the suggested comfort criterion. Supply velocities of 2.5 and 3.0m/s will cause draught risk at the ankle level of a sitting patient. Another study also shows the ability of downward plane jets to reduce exposure to a high momentum cough jet (discharge velocities of 12.0-16.0m/s) [110]. Considering the protection benefits of the POV system, it can be utilized in isolation wards, where there is a very high risk of airborne infection and where movement between the infected and protected zones is restricted or prohibited [111]. However, these studies have not quantified the impact of different distances between the occupant's position and the supply diffuser regarding draught risk [112].

Fig.8: Protected occupied zone ventilation (POV) system, a) POV with floor level exhaust[109], b) POV with sidewall level exhaust [112]



Most healthcare ventilation system studies focus on specialized areas such as wards, operating rooms, and isolation rooms. A study focused on the regular consultation and simple medical check-up process when the healthcare workers and the infected persons may not be aware of the infection [7]. Among personalized exhaust (PE) devices, Top-PE and Shoulder-PE are likely to perform better [113]. Therefore, the novel combined personalized ventilation (PV) and Top-PE system and the combined PV and Shoulder-PE system are further explored (Shown in Figure 9). The results showed that the Shoulder-PE performs a little better than Top-PE in increasing PV air in inhaled air. Meanwhile, the lowest intake fraction was achieved with the combined PV-PE system for the healthy person (HP). Using the PE system for an infected person alone shows much better performance than using the PV system for the HP alone [7].

Figure 9: A novel PV–PE system[7]



a. Round portable panel PV air terminal device; b. Top- PE; c. shoulder-PE

3.3.3 Other measures

Low carbon adaptive/refurbishment measures can help to improve thermal comfort in hospital buildings [114, 115]. Light-touch low-carbon strategies, including reducing internal gains, horizontal shading above the windows, and user-controlled fans, could positively impact indoor comfort conditions in hospital wards in the UK Midlands [116]. Similar light-touch measures were proposed for Nightingale wards in Bradford [115].

An innovative low-exergy (LowEx) system was designed and tested for the integral control of physical hazards. The LowEx system creates optimal conditions for burn patients by enabling individual control of thermal comfort parameters to meet the needs of individual users in the same room. For the LowEx system, the measured energy use was 11-27% lower for heating and 32-73% lower for cooling than for a conventional system [8].

Self-protection and high-quality healthcare delivery are very necessary for hospital staff. A new optimized working gown for dentists was proposed. The new design was highly appreciated through fitting tests [117]. The appropriate personal protective equipment should be chosen to mitigate infectious germs from patients' saliva and blood. Encouraging a culture of noise reduction as an integral part of high-quality healthcare delivery is very important [118]. The nurse-led interventions were found to improve the patient experience and outcomes [119].

3.4 Energy saving based on thermal comfort

Hospital buildings are highly energy-intensive because of the required level of hygiene control, high air change rate, and the strict set points currently required for temperature and relative humidity. At the same time, from a legislation standpoint, national authorities struggle to impose high requirements for these special units of hospitals through national regulations and standards regarding asepsis, air purity, thermal comfort, etc. These special requirements lead to the HVAC systems dedicated to operating rooms using particularly large air volumes, which can consume over 35% of the total energy used by an entire hospital building [120].

According to the EIA [121], healthcare buildings are the second largest energy users per unit floor area of all building types because of their continuous (24-hour) operation and a large number of users (employees, patients, and visitors), while most of the energy is used by the HVAC systems for the special units (ORs, intensive care, neonatal, isolation, etc.) [122, 123]. Indeed, extremely energy-intensive airflow systems are used in these spaces, with air change rates usually 20-40 times higher than in typical building spaces [124]. Meanwhile, all modern healthcare facilities have the utilities needed to provide the good IEQ required by standards, while the older ones need to update their buildings with systems required to obtain this. Due to these needs, the energy demand is continually growing. The capacity of the HVAC system must be consistent with the occupancy level of the facility. It not only guarantees smooth operation but also ensures occupants' health and comfort to the maximum extent [125]. Once HVAC systems are appropriately chosen and operated, energy savings of up to 30% might be obtained whilst still maintaining an acceptable level of thermal comfort [126].

Today’s clean energy challenges, as well as the emergent awareness concerning environmental issues, can be a burden for those states required to reduce their greenhouse gas emissions by at least 40% while achieving at least 27% improvement in energy efficiency by 2030 [127]. This leads to a real dilemma for the engineers of special building systems and services, including healthcare facilities, who are faced with keeping up with indoor environmental standards and reducing energy consumption. In addition, many energy-intensive activities occur in these buildings: laundry, medical and lab equipment use, sterilization, catering services, refrigeration, etc. A recent study published by the World Bank Group estimates that the health sector alone generates 5% of global CO_2 emissions [128].

Energy-efficient hospitals often result in deteriorated indoor environmental quality and adverse comfort outcomes. The major issue for energy and comfort management in hospital automation is to balance the conflict between the users' comfort and the total energy consumption [129]. It has been suggested that there is a relationship between achieving energy efficiency in buildings and IEQ performance. IEQ performance in buildings, which have thermal comfort and lighting comfort as part of their assessment parameters, contributes to greater building energy consumption [130]. An advanced approach to designing a hospital environment based on a stimulative healing paradigm has been proposed to achieve healthy and comfortable conditions. The interventions presented are guidelines for future extensive hospital renovations and construction [131].

3.4.1 Energy consumption

Considering the energy consumption, hospitals have a high demand for heating and electricity. They require a large amount of energy for transport, lighting, ventilation, air conditioning, and electric/electronic equipment. The literature indicates high differences in energy consumption of healthcare facilities, depending on different factors, like occupancy scenarios, imposed indoor parameters, heating/cooling needs, or thermal preferences. Indeed, more than 43% of the energy use in hospitals is dedicated to heating load [132]. Giving this heterogeneity of energy use, no matter the country, there is an important potential for energy efficiency improvements while at the same time meeting the required IEQ standards. However, there is a significant lack of energy consumption data analysis and benchmarking for different types of healthcare units, correlated or not with IEQ requirements. It is difficult to identify the energy efficiency potential of facilities in this critical type of building.

The reduction of hospital energy consumption may be obtained at different building levels, such as ward/room and a complete hospital building [132]. Thus, local ventilation strategies relying on transport principles or local thermal comfort solutions like active or passive warming techniques (e.g., warming blankets) could lead to significant reductions in energy consumption.

For a hospital patient ward, an approach of combining thermodynamics, computational fluid dynamics, and thermal comfort level models have been developed to effectively analyze and compare the thermal comfort impact of alternative low-energy building retrofit concepts. Using this method, passive solutions to ventilation were used effectively for a patient ward in a tropical warm climate hospital [133]. An innovative retrofitting strategy for the methodological approach based on a parametric evaluation was also explored. It started from the typical unit room and scaled to the whole building, reducing the time and resources required to support the decision-making and design phases [134]. New services and equipment combined with roof insulation, façade insulation, and window replacement have been used in a typical hospital room and found to reduce the energy performance index by 75% [134]. It is evident that savings in energy need to be cross-referenced with equivalent performance in delivering adequate airflow rates and acceptable thermal comfort [135].

Energy consumption in ORs is much higher than in other rooms due to the high air cleanliness requirements. The air exchange rate may vary from 18 changes per hour (ACH^{-1}) to $300ACH^{-1}$, making ORs the most energy-intensive hospital units [136]. A recent study by Fan *et al.* shows that the energy consumption in ORs may reach $3.96kWh/m^2/day$ (mixing ventilation) and $7.17kWh/m^2/day$ (laminar airflow). The microclimate design in ORs or other unit types is a complex task mainly due to the requirements for stable air temperature, relative humidity, pressure scheme mean velocities, and air quality [137]. The challenge is mainly caused on the one hand by the complex indoor airflow, clean airflow distribution, and the interaction with the thermal plumes from occupants and the medical equipment, and on the other hand, the thermal comfort requirements**.** Due to the 24hour function and the high IEQ requirements, ORs are the most energy-consuming units in healthcare facilities, requiring both energy efficiency and compliance with strict IEQ requirements. However, the energy-saving potential is great by varying the ventilation strategies, especially during inactive periods. Considering this situation, it is necessary to develop a dynamic energy model of a surgical suite to simulate its yearly energy performance under different ventilation scenarios. Results indicated that the maximum savings obtained are around 70% of the energy demand without compromising the safety and health of patients and medical staff during off-use hours [138]. One study presented an original and straightforward methodology for the energy optimization of an OR. The methodology proposed is fast and useful, and its applicability is broad as it can be transferred entirely to any other cleanroom in the hospital. Energy savings could be up to 51% through reducing ventilation by 50% while complying with airborne particulate standards [139].

Considering the air distribution strategies, there are only a few studies on new ventilation solutions in operating rooms to reduce patients' exposure to various airborne pollutants while maintaining high staff comfort levels. Moreover, studies showed that when increasing the number of air changes per hour (ACH), the most energy-consuming processes for an HVAC system will be heating (re-heating), air circulation (fans), and cooling [140], and the increase of energy consumption is directly correlated with the increase of ACH. Also, there is a lack of studies regarding the time needed for the ORs to become functional when using specific ventilation systems, which is an important real-world issue for the end-users (patients and medical staff). Moreover**,** no study has simultaneously addressed both energy efficiency and better IEQ.

Moreover, the air distribution system also needs to comply with the requirements for thermal comfort of the surgical team and for the patient in order to prevent hypothermia. Considering all these, the strict healthcare IEQ requirements should meet the demanding energy efficiency constraints for the benefit of all involved actors: patients, medical staff, visitors, engineers, healthcare facility administrators, etc.

3.4.2 Energy efficiency

A significant amount of energy usage is due to the inefficiencies of the building envelope and the HVAC system [141]. According to [142], technologies embracing the development of insulation materials and maintaining the envelope system are demand-side energy efficiency technologies.

The refurbishment of the building envelope requires consideration of multiple points of view such as energy savings, improved indoor microclimates, reduction of polluting emissions, and technical and economic feasibility. With reference to primary energy demand for air-conditioning, a building envelope refurbishment is frequently a good idea since energy requests can be reduced by 16%~50% through different refurbishment solutions [143]. Some results show that using a thermal insulation envelope in hospitals was one of the solutions that allowed a reduction in the energy consumption for cooling and heating while increasing the thermal comfort within the hospital [144]. With the use of a passive design strategy, the annual mean thermal performance of hospitals is predicted to increase to 184% by 2060, while 40% of the cost of cooling energy will be saved. Another investigation highlighted that the adoption of wider windows with appropriate glazing and a daylight-linked, lighting-dimming control strategy might lower the primary energy demand by up to 17% [145]. According to the quality-price balance, the "Smart Windows" solution incorporating a "deep-coating" deposition technique is the most suitable solution for the comfort problems in hospitals [146].

4 Future perspectives

Many factors, some of which are correlated, influence thermal comfort and indoor environmental quality in hospital buildings. Further clarification of the correlations is important for the design and operation of premises within hospitals. In addition to the known factors, some other factors also affect thermal comfort and indoor environmental quality, such as the overcrowding in Chinese hospitals. Future research can add some other influencing factors, such as lighting factors. The lighting factors and indoor air quality can be considered variables to study the influence of these additional factors on patient satisfaction [25].

In thermal comfort surveys, it is found that different types of employees and functional areas have different thermal comfort requirements. Most of the attention is focused on ward rooms and ORs, and further studies in other functional areas are urgently needed. Strategic decisions during the design, operation, and maintenance may need to be tailored to the workforce’s needs and priorities. Individual differences in thermal comfort widely exist and should be carefully considered in the design and operation of built environments. Gender and age are considered as two primary sources for individual differences [147]. Limited attention is still paid to specific conditions such as differences in gender, age range, and health status that may alter the conventional perception of comfort [34, 148]. Larger samples and longer periods of investigation are required to study the effect of these various factors on thermal comfort in the future.

In the hospital environment, the type of personnel is also a factor to consider. In addressing individual differences, a Personal Comfort System (PCS) can be a good solution. There are some studies about PCS, such as innovative low exergy (LowEx) systems and novel PV-PE systems [7, 8]. Further research in this area needs to be considered. Met values for different populations also need to be considered when considering their comfort level. For pregnant women in a typical sedentary state when hosted in the inpatient room, the met value corresponds to 2.17. Further consideration needs to be made for specific populations, such as children, the elderly, etc. [34]. It is necessary to define standards for these patients for different types of environments [149].

PMV is the most widely used indicator, which is suitable for a well-controlled environment. The OR is a special place where different people have different thermal sensations whilst their thermal adaptation is constrained, which makes PMV a better index for the evaluation of thermal comfort. It is necessary for surgeons and nurses alike to have adequate clothing insulation, which provides them with a neutral thermal sensation zone according to their met values [51]. However, it has been found that PMV is not an appropriate indicator for evaluation in some practical situations where there can be a deviation between PMV and actual thermal sensation. Due to adaptation, hospital staff in Malaysia prefer a warmer indoor environment, and an adaptive model has been established [37]. The thermal sensations and preferences for older and younger subjects were different in some conditions [148]. One study revealed that patients' physical strength significantly affected their thermal requirements [150]. It is worth investigating whether it is possible to provide different hospital environment designs adapted to individual differences.

With the development of new treatments for diseases, the survival period of very ill patients is much longer than before. At the same time, they also require prolonged hospitalization. Some studies have pointed out that hospitalization represents a period of significant psychological duress and physiological stress that may present unique risks for patients [151, 152]. Due to living in the hospital for an extended period, they have some adaptations to the hospital environment. People use various adaptive mechanisms to regulate their thermal environment, which supports the adaptive model in residential buildings [153]. Whether human adaptations can exist in hospital buildings as well as in residential buildings is worth considering. Whether the PMV model or adaptive model that has been proposed is appropriate or not for long-stay patients also deserves careful consideration, as is the need to improve the existing models based on psychological and health status or some other considerations.

There are many new technologies and measures to improve thermal comfort. The measures for perioperative hypothermia and the use of ventilation systems are the two main aspects. Unfortunately, the influence on the thermal comfort of the staff caused by using heating systems for preventing hypothermia was not analyzed. Future research should be done to evaluate this influence [154]. Some other measures can be used to improve thermal comfort, including integral control of physical hazards [8], new optimized working gowns [117], and high-quality healthcare delivery by hospital staff [118].

Hospitals account for approximately 6% of total energy consumption in the tertiary buildings sector [155], and the high energy-intensive healthcare sector will come under increasing pressure to adopt lower-carbon solutions. For example, the electrical energy consumption per bed varies from 5.1MWh (Italy) to 28.1MWh (Australia), with an average consumption of 16.1MWh [156, 157]. Thermal energy consumption is more homogenous, fluctuating between 23.3MWh (Italy) and 42.8MWh (Canada), with an average of 33.9MWh. What is most visible is the large variation in electricity consumption. Australian hospitals consume about six times more electricity than hospitals in Italy [158]. In Europe, the energy efficiency constraints are usually set out in national regulations, with values almost two to three times higher than those imposed on residential buildings [156, 159].

Energy consumption needs to consider indoor environmental quality for all involved actors, both staff and patients. This problem can be viewed in terms of reducing energy consumption and increasing energy efficiency. The measures currently mentioned to minimize energy consumption mainly focus on improving the performance of the envelope structure and establishing a useful model.

However, there is a lack of energy consumption data analysis and benchmarking for different healthcare unit types, correlated or not with IEQ requirements, and it is difficult to identify the energy efficiency potential of these critical types of facility in the building sector with strict regulations for temperature, humidity, quality, and cleanliness. This increases the need for proper heating, cooling, and fresh air intake.

Further detailed research is needed in the future on how to optimize the physical environment for different employee characteristics and work types. Many studies in this literature review were undertaken in a single hospital for each case study and generally for one occupant type. For making general conclusions, the results achieved from just one case study are considered insufficient. Further field investigations at different hospitals are needed to make the results more widely applicable and improve standards and guidelines.

5 Conclusions

This literature review summarizes the factors that affect thermal comfort and indoor environmental quality based on the comprehensive analysis of the existing studies on the topic of hospital thermal comfort and the improvement measures for thermal comfort and energy consumption. Based on the overview of reviewed publications, the findings, and the future research direction are as follows:

(1) It is important to identify the factors that affect thermal comfort inside and outside the buildings. The layout of the various functional areas, including the hospital street, contributes to the overall thermal comfort in hospital buildings. A properly designed layout can improve a hospital's operational efficiency and staff and patient satisfaction. Gender, age, health conditions, and other related factors may have an impact on thermal comfort. In the future, larger samples and longer investigation periods are required to study the effect of these factors on thermal comfort.

(2) Thermal comfort, as one of the important components of IEQ, is often influenced by other related IEQ factors. A comprehensive assessment considering the interactive impact of factors such as the thermal, lighting, and acoustic environments in a hospital is encouraged.

(3) PMV and TSV are the two most commonly used indices in field studies. There are significant (or slight) discrepancies between PMV and TSV. Using PMV for hospital rooms cannot give a reasonable reflection of patients' diverse requirements. The accurate evaluation of the thermal comfort of the patients and surgical staff will be an important requirement. Individualized thermal comfort provision for different types of personnel is also important. Classifying patients by illness and giving proper temperature set-points is needed. Zonal indoor environment solutions and personalized microenvironment control with personalized IEQ control may be a future research direction. New research focusing on an individual's thermal sensation in different function areas, like

different zones in ORs, should be encouraged.

(4) The self-warming blankets, prototype thermal compression devices, and in-line intravenous fluid warming are effective measures to provide satisfactory body temperature control and reduce discomfort for perioperative patients.

(5) A proper ventilation system can improve indoor air quality and potentially increase occupant satisfaction. A personalized ventilation system could deliver fresh air to multiple patients and minimize airborne contaminants. However, the improvement of thermal comfort must also be accompanied by energy considerations.

(6) Energy-efficient design, especially for operation rooms, is an important research topic. The retrofitting of windows and walls and the adjustment of ventilation strategies are significant for the energy efficiency of hospital buildings. Beyond the thermal comfort topic, the elimination of infection transmission is paramount.

Acknowledgement

The work is supported by the Natural Science Foundation funded by Chongqing Government CQYC20200101120 and The International Key Collaborative R&D Program of China 'Research and Integrated Demonstration on Suitable Technology of Net Zero Energy Building' [2019YFE0100300].

References

1. ASHRAE, *ANSI/ASHRAE Standard 55-2013 Thermal Environmental Conditions for Human Occupancy.* 2013: Atlanta.
2. ASHRAE, *ASHRAE Handbook-HVAC applications (SI).* 2019: Atlanta.
3. Singer, B.C., *Hospital Energy Benchmarking Guidance-Version 1.0.* 2009, Lawrence Berkeley National Lab.(LBNL), Berkeley, CA (United States).
4. Liao, J.-z. and J. Wu, *Development Path and Urgency of further Strengthening Construction of Public Hospitals Based on Novel Coronavirus Pneumonia Treatment.* Current Medical Science, 2020: p. 1-5.
5. Andersen, B.M., *Hospital Buildings—Construction Projects*, in *Prevention and Control of Infections in Hospitals: Practice and Theory*. 2019, Springer International Publishing: Cham. p. 987-994.
6. Torossian, A., et al., *Active perioperative patient warming using a self-warming blanket (BARRIER EasyWarm) is superior to passive thermal insulation: a multinational, multicenter, randomized trial.* Journal of Clinical Anesthesia, 2016. **34**: p. 547-554.
7. Yang, J., et al., *Performance evaluation of a novel personalized ventilation-personalized exhaust system for airborne infection control.* Indoor Air, 2014.
8. Dovjak, M., et al., *Integral Control of Health Hazards in Hospital Environment.* Indoor Built Environment, 2013. **22**(5): p. 776-795.
9. Dovjak, M., M. Shukuya, and A. Krainer, *Individualisation of personal space in hospital environment.* International Journal of Exergy, 2014. **14**(2): p. 125-155.
10. Chen, C., *Science mapping: a systematic review of the literature.* Journal of Data Information Science, 2017. **2**(2): p. 1-40.
11. Börner, K., C. Chen, and K.W. Boyack, *Visualizing knowledge domains.* Annual review of information science technology, 2003. **37**(1): p. 179-255.
12. Houghten, F. and W. Cook, *Cooling requirements of operating room and recovery ward.* Trans. Am. Soc. Heat. Vent. Engrs, 1939. **45**: p. 161.
13. Nimlyat, P.S. and M.Z. Kandar, *Appraisal of indoor environmental quality (IEQ) in healthcare facilities: A literature review.* Sustainable Cities Society, 2015. **17**: p. 61-68.
14. Alzoubi, H. and R.F. Bataineh, *Pre-versus post-occupancy evaluation of daylight quality in hospitals.* Building and Environment, 2010. **45**(12): p. 2652-2665.
15. Tiffanie, R., et al., *Spatial and Temporal Variations in Indoor Environmental Conditions, Human Occupancy, and Operational Characteristics in a New Hospital Building.* Plos One, 2015. **10**(3): p. e0118207.
16. Tinner, M., P. Crovella, and P.F. Rosenbaum, *Perceived Importance of Wellness Features at a Cancer Center: Patient and Staff Perspectives.* HERD, 2018. **11**(3): p. 193758671875844.
17. Mourshed, M. and Y. Zhao, *Healthcare providers' perception of design factors related to physical environments in hospitals.* Journal of Environmental Psychology, 2012. **32**(4): p. 362-370.
18. Alfa, M. and A. Öztürk, *Perceived indoor environmental quality of hospital wards and patients' outcomes: A study of a general hospital, Minna, Nigeria.* Appl. Ecol. Environ. Res, 2019. **17**: p. 8235-8259.
19. Shajahan, A., C.H. Culp, and B. Williamson, *Effects of indoor environmental parameters related to building heating, ventilation, and air conditioning systems on patients' medical outcomes: A review of scientific research on hospital buildings.* Indoor air, 2019. **29**(2): p. 161-176.
20. Zadeh, et al., *The Importance of Specific Workplace Environment Characteristics for Maximum Health and Performance Healthcare Workers' Perspective.* Journal of Occupational

Environmental Medicine, 2018.

21. Jankowski, T. and M. Młynarczyk, *An impact of the efficient functioning of the ventilation and air-conditioning system on thermal comfort of the medical staff in the operating room.* Journal of Ecological Engineering, 2016. **17**(5).
22. Chaudhury, H., A. Mahmood, and M. Valente, *The Effect of Environmental Design on Reducing Nursing Errors and Increasing Efficiency in Acute Care Settings.* Environment and Behavior, 2009. **22 suppl 1**(6): p. 755-786.
23. Lai, A.C.K., et al., *An evaluation model for indoor environmental quality (IEQ) acceptance in residential buildings.* Energy & Buildings, 2009. **41**(9): p. 930-936.
24. Karmann, C., et al., *Cooling capacity and acoustic performance of radiant slab systems with free-hanging acoustical clouds.* Energy and Buildings, 2017. **138**: p. 676-686.
25. Wu, Y., et al., *Interaction between Sound and Thermal Influences on Patient Comfort in the Hospitals of China's Northern Heating Region.* Applied Sciences, 2019. **9**(24): p. 5551.
26. Liu, Y., et al., *Investigation on the Indoor Environment Quality of health care facilities in China.* Building and Environment, 2018. **141**: p. 273-287.
27. Mccunn, L.J. and R. Gifford, *Environmental Design in Acute Care Settings: A Case Study of a Neurological Rehabilitation Unit.* Herd Health Environments Research Design Journal, 2013. **7**(1): p. 102-113.
28. Tang, H., J. Ding, and Z. Lin, *On-site measurement of indoor environment quality in a Chinese healthcare facility with a semi-closed hospital street.* Building and Environment, 2020. **173**: p. 106637.
29. Skoog, J., N. Fransson, and L. Jagemar, *Thermal environment in Swedish hospitals: Summer and winter measurements.* Energy and Buildings, 2005. **37**(8): p. 872-877.
30. Hashiguchi, N., et al., *Thermal environment and subjective responses of patients and staff in a hospital during winter.* Journal of physiological anthropology and Applied Human Science, 2005. **24**(1): p. 111-115.
31. Hashiguchi, N., et al., *Effects of setting up of humidifiers on thermal conditions and subjective responses of patients and staff in a hospital during winter.* Applied ergonomics, 2008. **39**(2): p. 158-165.
32. De Giuli, V., et al., *Measured and perceived indoor environmental quality: Padua Hospital case study.* Building and Environment, 2013. **59**: p. 211-226.
33. Del Ferraro, S., et al., *A field study on thermal comfort in an Italian hospital considering differences in gender and age.* Applied Ergonomics, 2015. **50**: p. 177-184.
34. Fabbri, K., J. Gaspari, and L. Vandi, *Indoor Thermal Comfort of Pregnant Women in Hospital: A Case Study Evidence.* Sustainability, 2019. **11**(23): p. 6664.
35. Azizpour, F., et al., *A thermal comfort investigation of a facility department of a hospital in hot-humid climate: correlation between objective and subjective measurements.* Indoor Built Environment, 2013. **22**(5): p. 836-845.
36. Azizpour, F., et al., *Thermal comfort assessment of large-scale hospitals in tropical climates: A case study of University Kebangsaan Malaysia Medical Centre (UKMMC).* Energy and Buildings, 2013. **64**: p. 317-322.
37. Yau, Y. and B. Chew, *Adaptive thermal comfort model for air-conditioned hospitals in Malaysia.* Building Services Engineering Research Technology, 2014. **35**(2): p. 117-138.
38. Khalid, W., et al., *Investigation of comfort temperature and thermal adaptation for patients and visitors in Malaysian hospitals.* Energy and Buildings, 2019. **183**: p. 484-499.
39. Uścinowicz, P., M. Chludzińska, and A. Bogdan, *Thermal environment conditions in Polish operating rooms.* Building and Environment, 2015. **94**: p. 296-304.
40. Nematchoua, M.K., et al., *Thermal comfort and comparison of some parameters coming from hospitals and shopping centers under natural ventilation: The case of Madagascar Island.* Journal of Building Engineering, 2017. **13**: p. 196-206.
41. Sattayakorn, S., M. Ichinose, and R. Sasaki, *Clarifying thermal comfort of healthcare occupants in tropical region: A case of indoor environment in Thai hospitals.* Energy and Buildings, 2017. **149**: p. 45-57.
42. Derks, M., et al., *Understanding thermal comfort perception of nurses in a hospital ward work environment.* Building and Environment, 2018. **140**: p. 119-127.
43. Loomans, M., et al., *Occupant response to transitions across indoor thermal environments in two different workspaces.* Building and Environment, 2018. **144**: p. 402-411.
44. Gough, H., et al., *Assessment of overheating risk in gynaecology scanning rooms during near-*

heatwave conditions: a case study of the Royal Berkshire Hospital in the UK. International Journal of Environmental Research Public Health, 2019. **16**(18): p. 3347.

45. Zaniboni, L., et al., *Subjective and objective assessment of thermal comfort in physiotherapy centers.* Building and Environment, 2020: p. 106808.
46. Alotaibi, B.S., et al., *Evaluating the suitability of standard thermal comfort approaches for hospital patients in air-conditioned environments in hot climates.* Building and Environment 2020. **169**(Feb.): p. 106561.1-106561.13.
47. Khodakarami, J. and N. Nasrollahi, *Thermal comfort in hospitals–A literature review.* Renewable and Sustainable Energy Reviews, 2012. **16**(6): p. 4071-4077.
48. Pourshaghaghy, A. and M. Omidvari, *Examination of thermal comfort in a hospital using PMV–PPD model.* Applied ergonomics, 2012. **43**(6): p. 1089-1095.
49. Dascalaki, E.G., et al., *Indoor environmental quality in Hellenic hospital operating rooms.* Energy and Buildings, 2009. **41**(5): p. 551-560.
50. Verheyen, J., et al., *Thermal comfort of patients: Objective and subjective measurements in patient rooms of a Belgian healthcare facility.* Building and Environment, 2011. **46**(5): p. 1195-1204.
51. Rodrigues, N.J., et al., *Thermal comfort assessment of a surgical room through computational fluid dynamics using local PMV index.* Work, 2015. **51**(3): p. 445-456.
52. De Freitas, C.R. and E.A. Grigorieva, *A comparison and appraisal of a comprehensive range of human thermal climate indices.* International Journal of Biometeorology, 2017. **61**(3): p. 487-512.
53. Lan, L. and Z. Lian, *Ten questions concerning thermal environment and sleep quality.* Building and Environment, 2016. **99**: p. 252-259.
54. Sadrizadeh, S. and M. Loomans. *Thermal comfort in hospital and healthcare facilities: a literature review*. in *IAQVAC 2016, the 9th International Conference on Indoor Air Quality Ventilation & Energy Conservation in Buildings, 23-26 October 2016, Seoul, South Korea*. 2016.
55. Bakke, J.V., et al., *Gender and the physical and psychosocial work environments are related to indoor air symptoms.* Journal of occupational environmental medicine, 2007. **49**(6): p. 641-650.
56. Kim, J., et al., *Gender differences in office occupant perception of indoor environmental quality (IEQ).* Building and environment 2013. **70**: p. 245-256.
57. Karjalainen, S., *Thermal comfort and gender: a literature review.* Indoor air, 2012. **22**(2): p. 96-109.
58. NICE, *Inadvertent Perioperative Hypothermia: The Management of Inadvertent Perioperative Hypothermia in Adults.* 2008.
59. Moola, S. and C. Lockwood, *Effectiveness of strategies for the management and/or prevention of hypothermia within the adult perioperative environment.* International Journal of Evidence - Based Healthcare, 2011. **9**(4): p. 337-345.
60. Fleisher, L.A., et al., *Perioperative cost-finding analysis of the routine use of intraoperative forced-air warming during general anesthesia.* Anesthesiology: The Journal of the American Society of Anesthesiologists, 1998. **88**(5): p. 1357-1364.
61. Alexander, T., et al., *Preventing Inadvertent Perioperative Hypothermia.* Deutsches Aerzteblatt Online, 2015.
62. Young, C.C. and R.N. Sladen, *Hypothermia*, in *Complications in Anesthesia*. 2007, Elsevier. p. 419-422.
63. Goodhew, S., et al., *Hospital ward temperatures related to hypothermic risk in orthopaedic patients.* Building Research Information, 2020. **48**(3): p. 286-300.
64. Cannistraro, G. and M. Cannistraro, *Hypothermia risk, monitoring and environment control in operating rooms.* Intl J Heat Technol, 2016. **34**(2): p. 165-171.
65. Madrid, E., et al., *Active body surface warming systems for preventing complications caused by inadvertent perioperative hypothermia in adults.* Cochrane Database of Systematic Reviews, 2016(4).
66. Benson, E.E., D.E. McMillan, and B. Ong, *The effects of active warming on patient temperature and pain after total knee arthroplasty.* AJN The American Journal of Nursing, 2012. **112**(5): p. 26-33.
67. Sessler, D.I. and A. Moayeri, *Skin-Surface WarmingHeat Flux and Central Temperature.* Anesthesiology: The Journal of the American Society of Anesthesiologists, 1990. **73**(2): p. 218-224.
68. Giesbrecht, G.G., M.B. Ducharme, and J.P. McGuire, *Comparison of forced-air patient*

warming systems for perioperative use. Anesthesiology: The Journal of the American Society of Anesthesiologists, 1994. **80**(3): p. 671-679.

69. Sun, Z., et al., *Intraoperative core temperature patterns, transfusion requirement, and hospital duration in patients warmed with forced air.* Anesthesiology: The Journal of the American Society of Anesthesiologists, 2015. **122**(2): p. 276-285.
70. Chebbout, R., et al., *Does the addition of active body warming to in-line intravenous fluid warming prevent maternal hypothermia during elective caesarean section? A randomised controlled trial.* International Journal of Obstetric Anesthesia, 2017. **31**: p. 37-44.
71. de Brito Poveda, V., A.M. Clark, and C.M. Galvão, *A systematic review on the effectiveness of prewarming to prevent perioperative hypothermia.* Journal of Clinical Nursing, 2013. **22**(7-8): p. 906-918.
72. Hynson, J.M., et al., *The effects of preinduction warming on temperature and blood pressure during propofol/nitrous oxide anesthesia.* Anesthesiology: The Journal of the American Society of Anesthesiologists, 1993. **79**(2): p. 219-228.
73. Santa Maria, P.L., et al., *A novel thermal compression device for perioperative warming: a randomized trial for feasibility and efficacy.* BMC anesthesiology, 2017. **17**(1): p. 102.
74. De Witte, J.L., C. Demeyer, and E. Vandemaele, *Resistive-heating or forced-air warming for the prevention of redistribution hypothermia.* Anesthesia & Analgesia, 2010. **110**(3): p. 829-833.
75. Dostálová, V., et al., *Thermal management in patients undergoing elective spinal surgery in prone position: a prospective randomized trial.* Česká a slovenská neurologie a neurochirurgie, 2017. **80**(5).
76. Mölnlycke. *BARRIER EasyWarm*. Available from: https://www.molnlycke.com/products-solutions/barrier-easywarm/.
77. Fanelli, A., et al., *The efficacy of a resistive heating under-patient blanket versus a forced-air warming system: a randomized controlled trial.* Anesthesia & Analgesia, 2009. **108**(1): p. 199-201.
78. Kurnat-Thoma, E.L., M.M. Roberts, and E.B. Corcoran, *Perioperative Heat Loss Prevention—A Feasibility Trial.* AORN journal, 2016. **104**(4): p. 307-319.
79. Bennett, J., et al., *Prevention of hypothermia during hip surgery: effect of passive compared with active skin surface warming.* British Journal of Anaesthesia, 1994. **73**(2): p. 180-183.
80. Weirich, T.L., *Hypothermia/warming protocols: why are they not widely used in the OR?* AORN journal, 2008. **87**(2): p. 333-344.
81. Gong, N., et al., *The acceptable air velocity range for local air movement in the tropics.* Hvac&r Research, 2006. **12**(4): p. 1065-1076.
82. Kaczmarczyk, J., et al. *Thermal sensation and comfort with five different air terminal devices for personalized ventilation*. in *Manuel Carlos Gameiro da Silva Roomvent2004*. 2004.
83. Li, R., S. Sekhar, and A.K. Melikov, *Thermal comfort and indoor air quality in rooms with integrated personalized ventilation and under-floor air distribution systems.* Hvac&r Research, 2011. **17**(5): p. 829-846.
84. Melikov, A.K., R. Cermak, and M. Majer, *Personalized ventilation: evaluation of different air terminal devices.* Energy and buildings, 2002. **34**(8): p. 829-836.
85. Sekhar, S., et al., *Findings of personalized ventilation studies in a hot and humid climate.* HVAC&R Research, 2005. **11**(4): p. 603-620.
86. Tian, L., Z. Lin, and Q. Wang, *Comparison of gaseous contaminant diffusion under stratum ventilation and under displacement ventilation.* Building and Environment, 2010. **45**(9): p. 2035-2046.
87. Tian, L., et al., *Numerical investigation of indoor aerosol particle dispersion under stratum ventilation and under displacement ventilation.* Indoor Built Environment, 2009. **18**(4): p. 360-375.
88. Yang, B., S. Sekhar, and A.K. Melikov, *Ceiling‐mounted personalized ventilation system integrated with a secondary air distribution system‐a human response study in hot and humid climate.* Indoor Air, 2010. **20**(4): p. 309-319.
89. Xue, K., et al., *Experimental study on the effect of exhaust airflows on the surgical environment in an operating room with mixing ventilation.* Journal of Building Engineering, 2020. **32**: p. 101837.
90. Zhang, Y., et al., *The impact of air change rate on the air quality of surgical microenvironment in an operating room with mixing ventilation.* Journal of Building Engineering, 2020. **32**: p. 101770.

91. Evans, R.P., *Current Concepts for Clean Air and Total Joint Arthroplasty: Laminar Airflow and Ultraviolet Radiation: A Systematic Review.* Clinical Orthopaedics & Related Research, 2011. **469**(4): p. 945-953.
92. Weiser, M.C. and C.S. Moucha, *Operating-Room Airflow Technology and Infection Prevention.* The Journal of Bone and Joint Surgery, 2018. **100**(9): p. 795-804.
93. Bahador, M. and M.M. Keshtkar, *Reviewing and modeling the optimal output velocity of slot linear diffusers to reduce air contamination in the surgical site of operating rooms.* INTERNATIONAL JOURNAL OF COMPUTER SCIENCE NETWORK SECURITY, 2017. **17**(8): p. 82-89.
94. Bischoff, P., et al., *Effect of laminar airflow ventilation on surgical site infections: a systematic review and meta-analysis.* Lancet Infectious Diseases, 2017. **17**(5): p. 553.
95. Gastmeier, P., A.C. Breier, and C. Brandt, *Influence of laminar airflow on prosthetic joint infections: a systematic review.* Journal of Hospital Infection, 2012. **81**(2): p. 73-78.
96. Ss, A., et al., *A Systematic Review of Operating Room Ventilation.* Journal of Building Engineering, 2021. **40**(Suppl 1): p. 102693.
97. Kuivjõgi, H., et al., *Field investigation of thermal comfort level of patients and surgical staff in operating rooms at St. Olavs hospital.* Surgeon, 2019. **1**(5): p. 10.
98. Kuivjõgi, H., *Field investigation of thermal comfort level of patients and surgical staff in operating rooms at St Olavs hospital*. 2019, NTNU.
99. Yau, Y.H., D. Chandrasegaran, and A. Badarudin, *The ventilation of multiple-bed hospital wards in the tropics: A review.* Building Environment, 2011. **46**(5): p. 1125-1132.
100. Zhao, B., et al., *Comparison of indoor aerosol particle concentration and deposition in different ventilated rooms by numerical method.* Building & Environment, 2004. **39**(1): p. 1-8.
101. Qian, H., et al., *Dispersion of exhaled droplet nuclei in a two-bed hospital ward with three different ventilation systems.* Indoor Air, 2010. **16**(2): p. 111-128.
102. Berlanga, F., et al., *Experimental assessment of different mixing air ventilation systems on ventilation performance and exposure to exhaled contaminants in hospital rooms.* Energy and Buildings, 2018. **177**: p. 207-219.
103. Lomas, K.J. and R. Giridharan, *Thermal comfort standards, measured internal temperatures and thermal resilience to climate change of free-running buildings: A case-study of hospital wards.* Building and Environment, 2012. **55**: p. 57-72.
104. Shi, Z., et al., *Seasonal variation of window opening behaviors in two naturally ventilated hospital wards.* Building and Environment 2018. **130**: p. 85-93.
105. Zhou, X., Z. Lian, and L. Lan, *Experimental study on a bedside personalized ventilation system for improving sleep comfort and quality.* Indoor Built Environment, 2014. **23**(2): p. 313-323.
106. Adamu, Z.A. and A. Price, *The design and simulation of natural personalised ventilation (NPV) system for multi-bed hospital wards.* Buildings, 2015. **5**(2): p. 381-404.
107. Choi, N., et al., *Displacement ventilation with radiant panel for hospital wards: Measurement and prediction of the temperature and contaminant concentration profiles.* Building and Environment 2019. **160**: p. 106197.
108. Melikov, A.K., *Advanced air distribution: improving health and comfort while reducing energy use.* Indoor air, 2016. **26**(1): p. 112-124.
109. Cao, G., et al., *Protected zone ventilation and reduced personal exposure to airborne cross - infection.* Indoor Air, 2015. **25**(3): p. 307-319.
110. Cao, G., et al., *Dynamic interaction of a downward plane jet and a cough jet with respect to particle transmission: An analytical and experimental study.* Journal of occupational environmental hygiene, 2017. **14**(8): p. 618-631.
111. Aganovic, A. and G. Cao, *Evaluation of airborne contaminant exposure in a single-bed isolation ward equipped with a protected occupied zone ventilation system.* Indoor and built environment, 2019. **28**(8): p. 1092-1103.
112. Aganovic, A., M. Steffensen, and G. Cao, *CFD study of the air distribution and occupant draught sensation in a patient ward equipped with protected zone ventilation.* Building and Environment, 2019. **162**: p. 106279.
113. Yang, J., et al., *Computational fluid dynamics study and evaluation of different personalized exhaust devices.* HVAC & R Research, 2013. **19**(8): p. 934-946.
114. Short, C.A., et al., *Building resilience to overheating into 1960's UK hospital buildings within the constraint of the national carbon reduction target: Adaptive strategies.* Building Environment, 2012. **55**: p. 73-95.

115. Lomas, K.J., et al., *Resilience of 'Nightingale'hospital wards in a changing climate.* Building Services Engineering Research Technology, 2012. **33**(1): p. 81-103.
116. Giridharan, R., et al., *Performance of hospital spaces in summer: A case study of a 'Nucleus'-type hospital in the UK Midlands.* Energy and Buildings, 2013. **66**: p. 315-328.
117. Tran, T.A.D., et al., *Development of personal protection equipment for medical staff: case of dental surgeon.* AUTEX Research Journal, 2015. **15**(4): p. 280-287.
118. Xyrichis, A., et al., *Noise pollution in hospitals*. 2018, British Medical Journal Publishing Group.
119. Sawyer, L., et al., *Noisy and Restless: 24 hours in an NHS community hospital ward, a qualitative and quantitative Analysis of the patient environment.* Building and Environment, 2020: p. 106795.
120. Sheppy, M., S. Pless, and F. Kung, *Healthcare Energy End-Use Monitoring*. 2014, National Renewable Energy Laboratory.
121. Administration, E.I., *Consumption and Efficiency - Energy sources and end uses*, C.S. Data, Editor. 2012 U.S. Energy Information Administration.
122. Bonnema, E., et al., *Large Hospital 50% Energy Savings: Technical Support Document*, D.o. Energy, Editor. 2010.
123. Committee, A.T., *HVAC Design Manual for Hospitals and Clinics, Second Edition*. 2013.
124. Memarzadeh, F.a.M., A., *Comparison of Operating Room Ventilation Systems in the Protection of the Surgical Site.* ASHRAE Transactions, 2002.
125. Moscato, U., A. Borghini, and A.A. Teleman, *HVAC management in health facilities*, in *Indoor Air Quality in Healthcare Facilities*. 2017, Springer. p. 95-106.
126. Fasiuddin, M. and I. Budaiwi, *HVAC system strategies for energy conservation in commercial buildings in Saudi Arabia.* Energy and Buildings, 2011. **43**(12): p. 3457-3466.
127. Diapouli, E., et al., *Evolution of air pollution source contributions over one decade, derived by PM10 and PM2.5 source apportionment in two metropolitan urban areas in Greece.* Atmospheric Environment, 2017. **164**(Supplement C): p. 416-430.
128. Bouley, T., S. Roschnik, and J. Karliner, *Climate-smart healthcare: low-carbon and resilience strategies for the health sector. World Bank; January 1, 2017*. 2017.
129. Gatea, A., M.F.M. Batcha, and J. Taweekun, *Energy Efficiency and Thermal Comfort in Hospital Buildings: A Review.* International Journal of Integrated Engineering, 2020. **12**(3): p. 33-41.
130. Nimlyat, P.S., M.Z. Kandar, and E. Sediadi, *Empirical investigation of Indoor Environmental Quality (IEQ) performance in hospital buildings in Nigeria.* Jurnal Teknologi, 2015. **77**(14).
131. Dovjak, M., M. Shukuya, and A. Krainer, *User-centred healing-oriented conditions in the design of hospital environments.* International journal of environmental research public health, 2018. **15**(10): p. 2140.
132. Čongradac, V., et al., *Assessing the energy consumption for heating and cooling in hospitals.* Energy & Buildings, 2012. **48**: p. 146-154.
133. Lan, L., et al., *Thermal comfort improvement of naturally ventilated patient wards in Singapore.* Energy and Buildings, 2017. **154**: p. 499-512.
134. Gaspari, J., K. Fabbri, and L. Gabrielli, *A study on parametric design application to hospital retrofitting for improving energy savings and comfort conditions.* Buildings, 2019. **9**(10): p. 220.
135. Adamu, Z.A., A.D. Price, and M.J. Cook, *Performance evaluation of natural ventilation strategies for hospital wards–A case study of Great Ormond Street Hospital.* Building Environment, 2012. **56**: p. 211-222.
136. Fan, M., et al., *Suitability evaluation on laminar airflow and mixing airflow distribution strategies in operating rooms: A case study at St. Olavs Hospital.* Building and Environment, 2021: p. 107677.
137. Cao, G., et al., *Do surgeons and surgical facilities disturb the clean air distribution close to a surgical patient in an orthopedic operating room with laminar airflow?* American Journal of Infection Control, 2018. **46**(10): p. 1115-1122.
138. Cacabelos-Reyes, A., et al., *Assessing the Energy Demand Reduction in a Surgical Suite by Optimizing the HVAC Operation During Off-Use Periods.* Applied Sciences, 2020. **10**(7): p. 2233.
139. Febrero-Garrido, L., et al., *Development of a calibrated simulation method for airborne particles to optimize energy consumption in operating rooms.* Energies, 2019. **12**(12): p. 2433.
140. English, T.R., *A simultaneous consideration of energy and ventilation in health care.* ASHRAE Transactions, 2014. **120**(2).

141. Buonomano, A., et al., *Dynamic energy performance analysis: Case study for energy efficiency retrofits of hospital buildings.* Energy, 2014. **78**: p. 555-572.
142. Martínez-Molina, A., et al., *Energy efficiency and thermal comfort in historic buildings: A review.* Renewable Sustainable Energy Reviews, 2016. **61**: p. 70-85.
143. Ascione, F., et al., *Rehabilitation of the building envelope of hospitals: Achievable energy savings and microclimatic control on varying the HVAC systems in Mediterranean climates.* Energy and Buildings, 2013. **60**: p. 125-138.
144. Nematchoua, M.K., et al., *Impact of climate change on demands for heating and cooling energy in hospitals: An in-depth case study of six islands located in the Indian Ocean region.* Sustainable Cities and Society, 2019. **44**: p. 629-645.
145. Cesari, S., et al., *The Energy Saving Potential of Wide Windows in Hospital Patient Rooms, Optimizing the Type of Glazing and Lighting Control Strategy under Different Climatic Conditions.* Energies, 2020. **13**(8): p. 2116.
146. Cannistraro, M. and E. Bernardo, *Monitoring of the indoor microclimate in hospital environments a case study the Papardo hospital in Messina.* International journal of heat and technology, 2017. **35**(1): p. S456-S465.
147. Wang, Z., et al., *Individual difference in thermal comfort: A literature review.* Building and Environment, 2018. **138**: p. 181-193.
148. Soebarto, V., H. Zhang, and S. Schiavon, *A thermal comfort environmental chamber study of older and younger people.* Building and Environment 2019. **155**: p. 1-14.
149. Pereira, P.F.d.C., E.E. Broday, and A.A.d.P. Xavier, *Thermal Comfort Applied in Hospital Environments: A Literature Review.* Applied Sciences, 2020. **10**(20): p. 7030.
150. Hwang, R.-L., et al., *Patient thermal comfort requirement for hospital environments in Taiwan.* Building and environment, 2007. **42**(8): p. 2980-2987.
151. Chang, B.P., *Can hospitalization be hazardous to your health? A nosocomial based stress model for hospitalization.* General hospital psychiatry, 2019. **60**: p. 83-89.
152. Dischinger, M., L. Lange, and S. Vehling, *Loss of resources and demoralization in the chronically ill.* General hospital psychiatry, 2019. **61**: p. 10-15.
153. Rijal, H., M. Humphreys, and J. Nicol, *Adaptive model and the adaptive mechanisms for thermal comfort in Japanese dwellings.* Energy and Buildings, 2019. **202**: p. 109371.
154. Melhado, M.A., J. Hensen, and M. Loomans. *Literature review of staff thermal comfort and patient thermal risks in operating rooms*. in *8th International healthy buildings conference*. 2006.
155. Teke, A. and O. Timur, *Assessing the energy efficiency improvement potentials of HVAC systems considering economic and environmental aspects at the hospitals.* Renewable and Sustainable Energy Reviews, 2014. **33**: p. 224-235.
156. Justo García-Sanz-Calcedo, Alfonso G. González, and David R. Salgado, *Assessment of Energy Consumption in Spanish Hospitals*. 2018: Springer, Cham.
157. González, A.G., J. Sanz-Calcedo, and D. Rodríguez Salgado, *Evaluation of Energy Consumption in German Hospitals: Benchmarking in the Public Sector*. Vol. 11. 2018. 2279.
158. Brochure, M., *Saving energy with Energy Efficiency in Hospitals.* Center for the, 1997.
159. Norwegian building regulation, *Regulations on Technical Requirements for Construction (Building Technology Regulations - TEK17)*. 2017.