Aksel Straume

Magnetic flux density measurements and mobile phone provocation studies

Investigations in the 50 Hz and the mobile phone frequency regions

Thesis for the degree philosophiae doctor

Trondheim, 2007

Norwegian University of Science and Technology
Faculty of Natural Sciences and Technology
Department of Physics

NTNU
Innovation and Creativity

NTNU
Norwegian University of Science and Technology

Thesis for the degree philosophiae doctor

Faculty of Natural Sciences and Technology
Department of Physics

ISBN 978-82-471-2503-8 (printed version)
ISBN 978-82-471-2517-5 (electronic version)
ISSN 1503-8181

Doctoral theses at NTNU, 2007:114

Printed by NTNU-trykk

Acknowledgment

This dissertation is submitted as a partial fulfilment of the requirements for the degree philosophiae doctor, and contains my measurements of ELF magnetic fields as well as mobile phone provocation studies. The work has been performed in the section of Biophysics and Medical Technology at the Department of Physics at The Norwegian University of Science and Technology (NTNU).

First of all, I would like to express my gratitude to my supervisor, Professor Anders Johnsson, for his excellent guidance through out this work. His technical knowledge has been highly appreciated, and his support and enthusiasm have been an important source of inspiration. Our general discussions over several cups of coffee will be fondly remembered. He is a very kind person with whom it has been a pleasure to work.

I also want to thank my co-supervisor Gunnhild Oftedal at the Sør-Trøndelag University College (HiST), Norway. Her guidance and thoroughness have been invaluable, especially in statistical calculations and pedagogical way of making presentations. Her constructive questions have helped making the manuscripts as unambiguous as possible, and the discussions are highly appreciated. It has been a pleasure travelling with her to the BEMS annual meetings and sightseeing with her have resulted in many great experiences.

I am grateful to Professor Kjell Hansson Mild who gave me the opportunity to visit his lab at the National Institute of Working Life in Umeå, Sweden. I also thank PhD Jonna Wilén for co-authorship, collaboration, and constructive discussions.

Further, I would like to thank Professor Lars Jacob Stovner Department of Neurology at St. Olav's Hospital, for co-authorship and for our discussions regarding the headache provocation study.

The technical staffs at our department deserve thanks for their assistance in building the cabinetry for the lab used for the provocation studies and for their help in various parts of the experiments.

I am grateful to my colleagues in biophysics and medical technology for creating such a positive working environment. The discussions during lunch were always interesting breaks! I would also like to thank Professor Thor-Bernt Melø for his help and always taking interest in my work.

A special thanks to my friends with whom I go off piste skiing in the winter season. The trips to the Alps have consisted of many awesome experiences and they have been an important source of motivation as well as reminding me of the world outside the PhD efforts.

Finally, I would like to thank my family for supporting me during all my years of studies. I am especially grateful to Kristin for being patient and supportive in my most frustrating moments.

Aksel Straume.
Trondheim April 16th 2007

The financial support was mainly from a project financed by the Research Council of Norway (NFR) but also from Statnett, Norwegian Post and Telecommunication Authority, Telenor A/S, NetCom, NORTIB (all in Oslo, Norway), Torstein Erbos Gavefond (Trondheim, sponsor of G.O.).
Support from the Department of Physics, NTNU, is likewise acknowledged.

Table of contents

Lists of papers I-IV

I Straume A, Johnsson A, Oftedal G. ELF-magnetic flux densities measured in a city environment in summer and winter time. Submitted to Bioelectromagnetics

II Straume A, Johnsson A, Oftedal G, Wilén J. Frequency spectrum from current- vs. magnetic flux density measurements for mobile phones and other electrical appliances. Accepted to Health Physics Journal.

III Straume A, Oftedal G, Johnsson A. Skin temperature increase caused by a mobile phone: A methodological infrared camera study. Bioelectromagnetics 2005;26:510-519.

IV Oftedal G, Straume A, Johnsson A, Stovner LJ. Mobile phone headache: a double blind, sham-controlled provocation study. Cephalalgia 2007;27(5):447-455. Published article online: 14-Mar-2007 (DOI): http:/www.blackwell-synergy.com/doi/pdf/10.1111/j.1468-2982.2007.01336.x

Abbreviations

DTX	Discontinuous Transmission
EEG	Electroencephalogram
ELF	Extremely Low frequency
EM	Electro Magnetic
EMF	Electro Magnetic Field
ERP	Event–Related Potentials
GSM	Global System for Mobile Communication
ICNIRP	International Commission on Non-Ionizing Radiation Protection
LF	Low frequency
RF	Radio Frequency
RMS	Root Mean Square
SAR	Specific energy Absorption Rate
TETRA	Terrestrial Trunked Radio
TWA	Time Weighted Average
VAS	Visual Analogue Scale
VDU	Visual Display Unit

Summary

The aims of this thesis work were divided into two main areas. The first area was an investigation of the extremely low frequency magnetic fields in urban environment and from electrical devices. The second area was mobile phone provocation studies to investigate skin temperature increase and headaches attributed to mobile phone use.

The magnetic flux density was measured along 17 km of pavement in an urban area of Trondheim. The magnetic flux density in summer was quite small compared to other cities (mean value 0.13 μT). In winter when it snows, the mean value of the magnetic flux density was almost seven times greater (0.90 μT) compared to summer conditions. The two main reason for the increased magnetic flux density in winter are increased power consumption due to electrical indoor heating and electrical heating of the pavement to get rid of snow and ice. The highest recorded measurements above net stations in pavement were higher in Trondheim than in other cites (37 μT). The basic restrictions were not exceeded.

Spectral measurements on electrical devices showed that the spectral distribution of the current drawn to the device does not necessarily reflect the spectral distribution of magnetic flux density around the device. Mapping of the magnetic flux densities around mobile phones was emphasized.

Skin temperature measurements after mobile phone use showed that there was a statistically significant temperature rise on the cheek and on the ear. However, this temperature rise was found to be mainly caused by insulation and impeded convection prevention of convection which the mobile phone device itself causes. There was not a significant additional heating by the RF-radiation emitted.

In a double blind provocation study, all subjects who went through a mobile phone provocation study reported typical headache symptoms at an open selection test for participation in the study. The study consisted of 65 pairs of double blind tests. The result did not give any evidence that RF fields caused any pain or discomfort in the head. Subjects displayed symptoms at both RF-exposure and SHAM-exposure and the result could most likely be explained by negative expectations, i.e. a nocebo effect. There was no statistically significant change in heart rate and/or blood pressure.

1. Introduction to thesis

During the last hundred years, the numbers of electromagnetic devices have increased tremendously in our everyday life. Sources of electromagnetic fields (EMF) and radiation have also increased due to the use of wireless devices, mainly during the last decades. These increases have caused general concern in many countries due to the possibility of adverse health effects of EMFs.

It is well known that ionizing radiation may cause ionization in biological cells, sometimes leading to severe health effects [Hall 2000]. The effects of ionizing radiation have been investigated experimentally predominantly in cancer research. The theories for action mechanisms leading to cell damage and to cancer are fairly well established [Hall 2000]. The ionizing radiation, with its higher energy compared to non-ionizing radiation, is not the topic to be discussed in the present thesis. However, it can sometimes be useful to compare the characteristics and action of the two kinds of radiation and fields.

There is also a general concern that non-ionizing EMFs could have important biological effects. “Strong” EMFs certainly cause biological effects via induced current densities at low frequencies and via heat deposition in tissue at high frequencies [ICNIRP 1998]. Such established *biological* effects might or might not lead to *health* effects. Also, in the case of “weak” EMFs, as encountered in normal (non-occupational) everyday life, there is an increasing discussion on their possible health effects [e.g. Feychting 2005 and Seitz et al. 2005]. This is of great interest, particularly in respect to some forms of cancer [e,g, Ahlbom 2000]. However, the list of discussed symptoms and effects is long. Some users of different electrical devices such as Visual Display Units (VDU) and mobile phones claim to get different symptoms like headaches, concentration difficulties, fatigue, nausea, and dizziness as a result of using the device [Rubin et al. 2005, Oftedal et al. 2000]. There are also relevant questions about any possible reproductive effects on humans [Bergqvist and Vogel 1997].

A meaningful discussion about EMFs and possible health effects must start by a focus on possible biophysical effects that can be ascribed to EMFs in different frequency ranges (see Fig. 1, Table 1). The known biological effects of EMFs are crucially dependent on the frequencies of the fields.

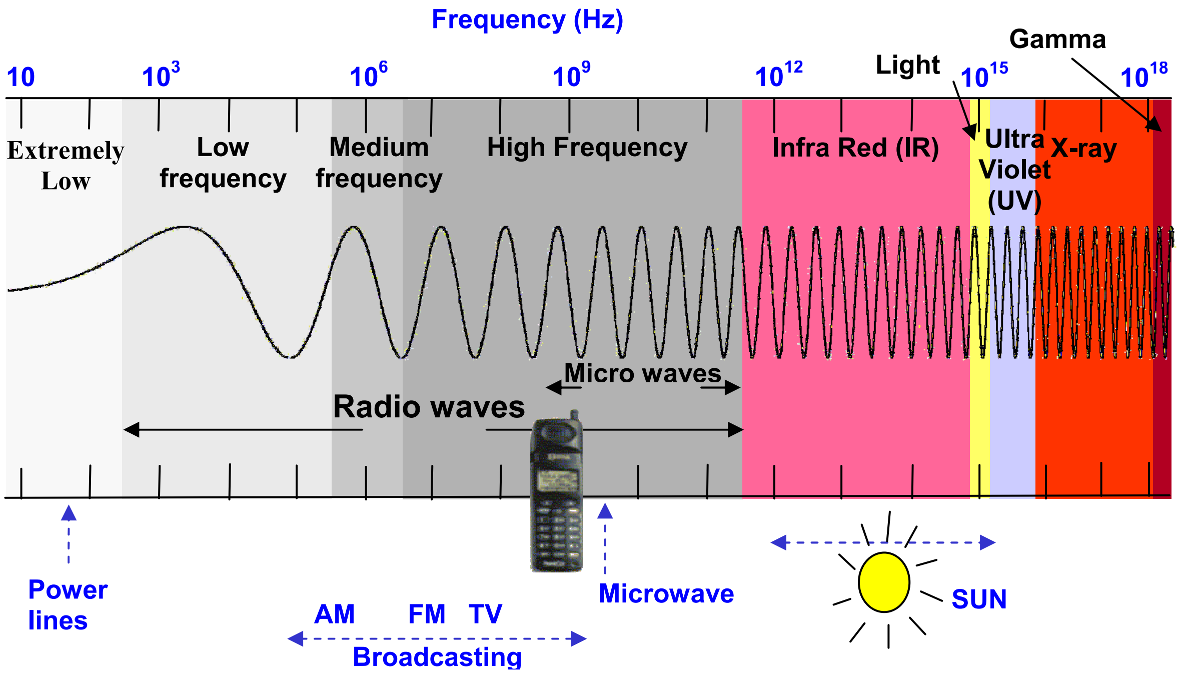

Fig. 1. The electromagnetic spectrum. Frequently used terms are indicated for the different frequency bands and typical user bands are also shown.

The figure shows in a popular form the frequency and wavelength of EMFs, and indicates the ranges where some EMF sources in our surroundings are situated. In this thesis only weak fields are investigated and the frequency ranges studied are presented in bold in Table 1.

Table 1. A possible classification of relevant frequency bands (adapted from textbook by Brune et al. [2001]; page 115).

Terms used for the frequency bands	Frequency band (f)	Wavelength (λ)
Static field	0-3 Hz	-100 000 km
Extremely low frequency (ELF)	3-3000 Hz	100 000- 100 km
Very low frequency (VLF)	3-300 kHz	100- 1 km
Radio frequency (RF)[1]	0.3-300 MHz	1000 – 1 m
Microwaves[1]	0.3-300 GHz	1000 – 1 mm

[1] *Note that in many cases as in Fig. 1. the term microwaves is defined as a specific area within the RF-band. In the thesis 900 MHz fields from mobile phones is indicated as RF-radiation.*

It should again be emphasized that the term “electromagnetic fields” is used as a common description for a broad range of frequencies, but the biological action mechanism is principally different for the various parts of this range. Reactions which are started in biological systems due to, ionizing radiation, high frequency fields or low frequency magnetic fields are by no means identical. The biological action mechanisms for the different frequency bands have to be studied separately (for a general survey see textbook by Brune et al. [2001]. As this thesis has not included work on biological interaction mechanisms, this topic will not be discussed in detail.

Another important point is that the *field strength* involved when biological organisms are exposed to electromagnetic fields must be specified. One must also describe the type of tissue under discussion. Exposure to high intensity fields from parts of the spectrum might cause severe biological effects while very weak fields with the same frequency are without any dangerous effects. For example, the retina is damaged by high intensity light, but not by low intensity light of the same wavelength. Another example is cataract induction in rabbit eye: two to three hours of exposure to high microwave fields (SAR values from 100-140 W/kg) can cause cataracts [Guy et al. 1975] while exposure to low fields do not cause such an effect. Discussion of threshold values in different regions of the electromagnetic spectrum must, therefore, be based on specifications on frequencies and energy involved as well as on description of tissue and organism. This might look trivial, but in many general discussions one does not even try to distinguish between "strong" and "weak" fields.

When it comes to low frequency EMF, one of the controversies focuses on the question whether *weak* fields (fields below the ICNIRP 1998 guideline) cause any biological effects. While there is no doubt about biological effects of *strong* fields, the experimental *weak* field studies have not given any unambiguous answers or clear clues on possible interaction with biological material. Such interaction will not necessarily lead to hazardous health effects. Only some of the many research areas concerning the biological effects of electromagnetic fields will be briefly discussed below.

Electromagnetic fields and cancer risk

One of the first studies to indicate a causal relation between electromagnetic fields and health effects was published by Wertheimer and Leeper in 1979. They reported that children living in residential areas close to high power transmission lines (60 Hz) had a higher incidence of childhood leukemia. Furthermore, the incidence decreased with the distance from the power lines. Even if the increased risk was low, the study triggered further scientific studies as well as public engagement in possible health effects by electromagnetic fields, such as cancer (leukemia, brain tumors and breast cancer), cardiovascular disease, and reproduction effects [see in general [Feychting et al. 2005]. The reader is referred to reviews of this field in ([Feychting et al. 2005] (general), [Naarala et al. 2004] (ELF cellular effects), [Crasson et al. 2003] (ELF effects on cognitive functions). One of the challenges which all these studies share is to define and specify the type and magnitude of electromagnetic fields to which subjects are exposed and which exposure levels may cause health effects.

As mentioned, many of the first epidemiological investigation of ELF exposure were limited by insufficient exposure assessments [as emphasized by for instance Feychting et al. 2005]. Most of the epidemiological investigations have used the exposure in residential areas or at work places for the exposure assessments. There are a limited amount of studies concerning the outdoor exposure of ELF MF [Lindgren et al. 2001 and Paniagua et al. 2004]. The magnetic flux density in a city in Norway has not been mapped.

Some of the most recent findings among large breast cancer studies [Davis et al. 2002, London et al. 2003, and Schoenfeld et al. 2003] failed to demonstrate any association between breast cancer and exposure to ELF EMFs.

Similarly, in individual studies regarding the ELF range, meta and pooled analysis of specific subtypes of leukaemia or brain tumours among adults did not show a consistent exposure-response relationship [Feychting et al. 2005].

Two pooled studies of childhood leukaemia based on studies by Ahlbom et al. [2000] and Greenland et al. [2000] showed an increase in relative risk of 2 for fields above 0.4 μT and 1.7 for fields above 0.3 μT respectively (time weighted average, TWA, magnetic flux densities). Because of these results, ELF magnetic fields have been classified as possibly carcinogenic to humans (Group 2B) by the IARC (International Agency for Research on Cancer) [IARC 2002].

Recently, there have also been many epidemiological studies on the health effects due to RF fields. In particular, the fields from mobile phones have been discussed. Most of the studies found no relationship between brain tumour risk and mobile phone use[Auinen et al. 2002, Christensen et al. 2005, Hepworth et al. 2006, Lönn et al. 2005, Lönn et al. 2006, Muscat et al. 2002, Schoemaker et al. 2005 and Schüz et al. 2005]. Conversely, there are studies showing a statistically significant relationship between mobile phone use and brain tumours, particularly for acoustic neuroma [Hardell et al. 2005] and glioma [Hardell et al. 2006]. The highest correlation was found between use of analogue mobile phones and acoustic neuroma risk [Hardell et al. 2005]. However, it seems fair to state that the overall available data are contradictory and it is difficult at the present stage to draw any definite conclusions [Moulder et al. 2005].

RF-fields and male reproduction effects

There is a limited amount of literature concerning RF-field exposure in relation to *reproductive* outcomes. The topic could be investigated from many different standpoints: epidemiological investigations, animal studies, and investigations concerning semen quality. There are however several difficulties in many of these approaches.

For example, in epidemiological investigations it can be difficult finding proper control groups. In addition, the exposure assessment of electromagnetic field/radiation is often based on subjective reports which may be biased.

There have been studies of semen quality especially among military personnel [Weyandt et al. 1996], and mobile-phone users [Kilgallon and Simmons 2005, Erogul et al. 2006]. One study reported that mobile phones carried close to men's testicles resulted in a significant negative impact on sperm concentration [Kilgallon and

Simmons 2005]. However, when the mobile phone is in standby mode it rarely transmits RF signals and when doing so it is to identify itself to the base stations. An indication that RF signals were of interest here would require that the subjects used handsfree equipment with the mobile phone in the pocket. Otherwise, a confounding factor can be that the tight trousers may reduce the sperm quality and having the phone in a tight pocket may lead to the same effect. Again the exposure assessment is lacking in the reports.

Also in an *in vitro* study [Erogul et al. 2006] it was suggested that electromagnetic fields influence human sperm motility, but the exposure conditions are not given in detail. An ordinary mobile phone was used as EM source and the listed peak output power was 2 W with the sperm container 10 cm from the phone. But the SAR-distribution at the exposed position is not specified. The authors also refer to a third report [Panagopoulos et al. 2004] which used the phone with its antenna pointing downwards towards the specimen. Exposure was carried out by speaking into the phone. This ensures continuous transmission but one does not know the relevant output level of the phone (which is mainly dependent on the distance to the base station used).

The examples given demonstrate incomplete or lacking exposure assessments in the published reports, and the number of studies that seem complete on this point is not high enough to warrant safe conclusions about possible reproduction effects at the present stage.

Electromagnetic fields and possible effects on EEG, blood pressure and reaction times

Several studies have been published on the effects of GSM mobile phone exposure, static, and ELF magnetic fields on electroencephalogram (EEG), cognitive functions (e.g. reaction times), heart rate, and blood pressure [see review by Cook et al. 2006]. Most of the studies reviewed find an effect; either an increased EEG activity [Fuller et al. 2003, Marino et al. 2004, Cook et al. 2004 and Ghione et al. 2005] or decreased EEG activity [Cook et al. 2005] due to exposure to static or an ELF magnetic field. Only one study found no effect [Crasson and Legros 2005].

With regards to ELF modulated RF fields, many studies have found an increased alpha activity (8-14Hz) [Croft et al, 2002, Huber et al. 2002, Huber et al. 2003, D’Costa et al. 2003, Curcio et al. 2005, Huber et al. 2005 and Loughran et al. 2005].

When it comes to possible effects on reaction times, the exposure conditions as well as the methodology vary and the results are at the present stage difficult to evaluate and compare. Koivisto et al. [2000] found that RF exposure slightly improved cognitive processes. This has, however, not been confirmed and other studies [Preece et al. 1999, Croft et al. 2002, Haarala et al. 2003 and Hamblin et al. 2006] have found no effect on reaction times. Hamblin et al. [2006] concluded that there was no clear evidence in support of a mobile phone EMF effect on reaction times.

Wilén et al. [2006] did not see any significant difference in heart rate and local blood flow in relation to RF exposure.

2. Background – electromagnetic theory

The detailed behavior of electric and magnetic fields are described by Maxwell's equations, described in their non-relativistic form already by 1864. Maxwell's equations in integral form can, for our purposes, be written in a simplified form as follows (valid for free space conditions)[see in general references Serway 1992] :

$$\oint \vec{E} \bullet d\vec{A} = \frac{Q}{\varepsilon_0} \qquad (1)$$

$$\oint \vec{B} \bullet d\vec{A} = 0 \qquad (2)$$

$$\oint \vec{E} \bullet d\vec{s} = -\frac{d\Phi_m}{dt} \qquad (3)$$

$$\oint \vec{B} \bullet d\vec{s} = \mu_0 I + \mu_0 \varepsilon_0 \frac{d\Phi_e}{dt} \qquad (4)$$

Where E is the electric field [V/m], B magnetic flux density [T], A [m^2] area of the surface of the object, Q [C] net charge inside the surface of the object, ε_0 [C^2/Nm^2] permittivity of space, μ_0 [N/A^2]permeability of space, Φ_m [Wb] magnetic flux , Φ_e [Vm] electric flux and ds a circumference element of the object.

The magnetic flux density B and magnetic field strength H is related by the permeability μ in a homogenous medium:

$$\vec{H} = \frac{1}{\mu} \vec{B} \qquad (5)$$

In a homogenous medium the propagation velocity v [m/s] of an electromagnetic wave is:

$$v = \frac{1}{\sqrt{\varepsilon \mu}} \qquad (6)$$

and in empty space the velocity equals the speed of light c in free space:

$$c = 1/\sqrt{\varepsilon_0 \mu_0} \qquad (7)$$

The connection between the frequency (*f*) of the fields and their wavelength (λ) in vacuum and their propagation velocity (c) is:

$$c = f \cdot \lambda \qquad (8)$$

Table 1 shows the frequencies and wavelengths for the electromagnetic fields in a vacuum , EMFs that are treated and discussed in the present thesis.

The amount of power per unit area carried by the electromagnetic waves in the direction of propagation (waves travelling in free space and at a certain distance from the source) is described by a vector $\vec{S}$ [W/m^2] called the Poynting vector.

$$\vec{S} \equiv \frac{1}{\mu_0} \vec{E} \times \vec{B} \qquad (9)$$

At a sufficient distance from a source (for example an antenna) the E and B fields are perpendicular to each other, both in turn being perpendicular to the propagation direction.

The above relations between E- and B- fields are generally not valid close to the source, in the so-called “near zone” or the “near field”. In this zone, typically of the order of one wavelength from a dipole antenna, there is no simple connection between the electric and the magnetic fields when it comes to size and directions. In the near zone one can not use the terminology of *electromagnetic waves* or *radiation propagation* according to the equations above. Instead, one specifies the electrical and magnetic fields separately. On the other hand, under “far field” conditions, typically at a distance of one wavelength or more from a dipole antenna, it is proper to talk in terms of electromagnetic waves, electromagnetic radiation and Poynting vector energy flux. The transition between the near field and the far field zones is not well defined but, as mentioned, one often uses one wavelength from the source as a typical measure ($\lambda = c / f$).

3. Biological background. International exposure limits for electro-magnetic fields

Guidelines and restrictions as published by the International Commission on Non-Ionizing Radiation Protection (ICNIRP) [ICNIRP, 1998] are based on *established health effects*. The main biological effects by high level fields up to 10 MHz are stimulation of nerves and muscles, which are indirectly caused by induced currents in the body, as well as shocks and burns caused by touching conducting objects. Above 100 kHz, the main biological effect is increased tissue temperature because of absorption of energy of the EMF’s. Since the biological response depends on the frequency of the EMF’s, the measurements of the frequency content of the exposure is evidently of high importance.

Some aspects of the different health effects at different electromagnetic frequencies will be briefly discussed below.

3.1 Exposure limits for electromagnetic fields due to induced currents in the body

Up to about 100 kHz, magnetic and electric fields normally result in negligible energy absorption by tissue and, therefore, in no substantial or measurable temperature rise in the body [ICNIRP 1998].

The induced current in the body by magnetic fields (principally given by the Maxwell equations) depends on the conductivity of the tissue, the rate of change of the magnetic flux density and also of the radius of the current loops. Often one assumes homogenous tissue for simplicity. The current density, J [A/m^2], could be calculated for sine waveforms by using the following equation (derived from Faraday's law of induction (eq. 3)):

$$J = \pi R f \sigma B \qquad (10)$$

Using a homogeneous conductivity σ of 0.2 Sm^{-1}, a frequency f of 50 Hz, and a radius R of 0.3 m with 100 μT magnetic flux density, B, the formula indicates that the magnetic field would generate a 0.9 mA m^{-2} current density in the peripheral parts of the body. The formula also emphasizes that one magnitude of the magnetic flux density induces different current densities if applied from above, from the front or from the side of the body (since R (radius) can take different values in the different directions).

One of the first known acute effects from (currents induced by) low frequency magnetic fields was trigging of nerves. During volunteer studies of ELF magnetic fields at 3-5 mT [Silny 1986] many of the subjects experienced flickering visual sensations known as magnetic phosphenes. These effects have also been seen when exposing the head to weak electric currents [Lövsund P et al. 1980 and Tenforde 1990]. The threshold for induction of magnetic phosphenes has been estimated to be 10 mA m^{-2} at 20 Hz in the retina [Lövsund P et al. 1980 and Tenforde 1990].

It is stated in ICNIRP [1998] that between 1 Hz and 10 MHz, the basic restrictions are determined so that current densities do not cause effects on nervous system functions. The basic restriction on induced current density is unaltered between 4 Hz to 1 kHz but below 4 Hz and above 1 kHz it increases progressively with the thresholds for nerve stimulations. Therefore, the basic restrictions on induced current density also increase with frequency from 1 kHz to 10 MHz. For occupational exposure, a safety factor of 10 is used and for the general public an additional factor of 5 is applied. The Basic restrictions values are shown in Table 2.

Since the current density is difficult to measure in tissue, a set of reference levels (Table 3 and 4) are obtained by mathematical modeling and extrapolations from laboratory investigations. The reference levels are based on maximum coupling of the field to the exposed individuals and provide, therefore, a worst case approach. As a consequence, if the reference level is exceeded it does not necessarily imply that the basic restriction is exceeded (Eq. 10 could be used as a first approach to calculate the reference level to the corresponding basic restriction).

Table 2. Basic restrictions for time varying induced current density for frequencies up to 10 MHz. (f in Hz). Head and trunk restrictions.

Frequency range	Current density for head and trunk [mA m^{-2}] (rms)	
	Occupational exposure	General public exposure
Up to 1 Hz	40	8
1-4 Hz	40/f	8/f
4 Hz-1 kHz	10	2
1-100 kHz	f/100	f/500
100 kHz-10 MHz	f/100	f/500

Since the present thesis is concentrated on the magnetic fields, the focus is not on the restrictions for electric fields (the reader interested in electric fields is referred to ICNIRP 1998).

Table 3. Reference levels for Occupational exposure to time varying electric and magnetic fields (unperturbed rms values). f is indicated in the frequency column.

Frequency range	Occupational exposure		
	B-field [µT]	H-field [A m^{-1}]	E-field [V m^{-1}]
Up to 1 Hz	$2 * 10^5$	$1.63 * 10^5$	-
1-8 Hz	$2* 10^5/f^2$	$1.63 * 10^5/f^2$	20 000
18-25 Hz	$2.5* 10^4/f$	$2* 10^4/f$	20 000
0.025-0.82 kHz	25/f	20/f	500/f
0.82 -65 kHz	30,7	24.4	610
0.065-1 MHz	2.0/f	1.6/f	610
1-10MHz	2.0/f	1.6/f	610/f

Table 4. Reference levels for General public exposure to time varying electric and magnetic fields (unperturbed rms values). f is indicated in the frequency column.

Frequency range	General public exposure		
	B-field [µT]	H-field [A m^{-1}]	E-field [V m^{-1}]
Up to 1 Hz	$4 * 10^4$	$3.2 * 10^4$	-
1-8 Hz	$4 * 10^4/f^2$	$3.2 * 10^4/f^2$	10 000
8-25 Hz	5 000/f	4 000/f	10 000
0.025-0.8 kHz	5/f	4/f	250/f
0.8 -3 kHz	6.25	5	250/f
3 kHz-150 kHz	6.25	5	87
0.15-1 MHz	0.92/f	0.73/f	87
1-10 MHz	0.92/f	0.73/f	$87/f^{1/2}$

For simultaneous exposure to multiple frequency fields which are additive, the induced current densities should be added according to ICNIRP [1998]:

$$\sum_{i=1Hz}^{10MHz} \frac{J_i}{J_{L,i}} \leq 1 \qquad (12)$$

Where J_i is the current density induced at frequency f, and $J_{L,i}$ the induced current density restriction at frequency i as given in Table 2.

3.2 Exposure limits for electromagnetic fields due to heating of tissue

Exposure to electromagnetic fields at around 100 kHz and above can lead to significant absorption of energy and cause a temperature increase in the tissue [ICNIRP 1998]. Therefore, for electromagnetic fields in the frequency range from about 100 kHz to below 20 MHz, the absorption in the trunk is of most importance. Significant absorption can also occur in the neck and legs. The absorption decreases rapidly with decreasing frequency in this frequency band.

At 10 MHz to 300 GHz, heating is the major effect of absorption of electromagnetic energy. Whole body temperature rises of more than 1-2 °C can cause adverse health effects. From 300 MHz to several GHz there could also be a more non uniform absorption and significant local heating. Above 10 GHz the absorption occurs primarily at the body surface.

Since this energy absorption of RF-fields in tissue is the most important biological effect at these frequencies, one operates with the Specific energy Absorption Rate (SAR) concept. SAR is expressed in W/kg.

$$SAR = \frac{\sigma E_{rms}^2}{\rho} \qquad (13)$$

Here σ is the tissue conductivity, ρ is the mass (tissue) density. The deposited energy leads to temperature increase with time and this is assumed to be proportional to the SAR value [Meier et al. 1995]

$$SAR = k_{thermal} \frac{\partial T}{\partial t} \qquad (14)$$

The proportionality constant $k_{thermal}$ is the specific thermal constant of the tissue at the measurement site. Blood flow influences the temperature increase and the relation between the temperature increases can be complicated and it will be difficult to measure [Meier et al. 1995]. The temperature measurements will have clear limits on maximum sensitivity, and thus, measurements of electric field are desired [Meier et al. 1995].

The basic restrictions with regards to absorption of radiation in tissue are different for whole body exposure and localized absorption in different parts of the body. In general, whole body SAR of 4 W/kg for up to 30 min caused an increase in the body core temperature of less than 1°C [ICNIRP 1998]. For partial-body exposure, significant thermal damage can occur on sensitive tissue such as the testicles and the eyes [ICNIRP 1998]. The limits are shown in Table 5.

Table 5: Basic restrictions for absorption of radiation of time varying electric and magnetic fields.

Frequency range	Occupational exposure			General public exposure		
	Whole-body average SAR (W/kg)	Localized SAR (head and trunk) (W/kg)	Localized SAR (limbs) (W/kg)	Whole-body average SAR (W/kg)	Localized SAR (head and trunk) (W/kg)	Localized SAR (limbs) (W/kg)
100kHz-10 GHz	0.4	10	20	0.08	2	4

All the SAR values are to be averaged over any 6-min period and the localized SAR are to be averaged over any 10 g of contiguous tissue.

SAR values caused by mobile phones are derived by measurements of the electric field inside phantoms filled with a liquid with the same dielectric properties as brain tissue. [Meier et al. 1995.]

In addition to the restrictions mentioned, there is also a recommended restriction to avoid auditory effects called "microwave hearing". It is based on so-called thermoelastic interaction in the auditory cortex of the brain [Frey 1961, Frey 1973 and Lin 1978]. Therefore the specific absorption (SA) should not exceed 10 mJ/kg for occupational workers and 2 mJ/kg for the general public (averaged over 10 g tissue).

For simultaneous exposure to multiple frequency fields with frequencies above 100 kHz, SAR and power density vales should be added as follows [ICNIRP 1998]:

$$\frac{1}{SAR_L}\sum_{i=100kHz}^{10GHz} SAR_i + \frac{1}{S_L}\sum_{i=10GHz}^{300GHz} S_i \leq 1 \qquad (15)$$

Here SAR_i is the SAR caused by the exposure at frequency i, and SAR_L the SAR limit given in Table 5. The basic restrictions for absorption of radiation by exposure at frequency i are given in Table 5. S_i is the power density at frequency i and S_L is the power density limit which is 50 W/m^2 for occupational exposure and 10 W/m^2 for the general public.

4. Aim of thesis

The aims of this thesis were the following:

1. Map the magnetic flux density in an urban area of a city in Norway. Investigate if there are any seasonal changes in the flux density levels. Compare the measured magnetic flux density with existing guidelines and the limited published experimental data available in the literature.

2. Investigate and calculate the magnetic flux density exposure from electrical devices with special emphasis on GSM 900 mobile phones. Evaluate magnetic flux densities found with respect to the ICNIRP guidelines. Investigate procedures to measure frequency content of the magnetic flux density signals.

3. Investigate reported heat effects caused by the use of mobile phones. Use a differential skin temperature measurement, based in infrared (IR) camera imaging, to investigate the origin of temperature increases in the ear regions during mobile phone use.

4. Investigate whether exposure to RF fields from mobile phones may cause headache or discomfort and whether it may influence physiological variables in a group of individuals attributing such symptoms to mobile phone use.

5. Materials and Methods

This section contains a short presentation of some relevant *equipment, software* and *methods* used in the investigations. The “Methods and materials” chapters in the majority of the papers are sufficiently detailed and there is no need to repeat the information. However, aspects and information that could not be included or were only briefly discussed in the papers will be emphasized in this section.

5.1. Instruments, measurements and data processing

The EMDEX II instrument (Paper I & II)

For the ELF magnetic flux density measurements the EMDEX II instrument (Enertech Consultants Cambell, CA, USA) was chosen. This is a standard instrument which is not affected by RF-fields, has a low pass filter and is, therefore, suited for ELF magnetic field measurements on mobile phones as well as on 50 Hz sources. The RMS values of the magnetic flux density in the x, y and z directions are logged via three orthogonal coils. The data processing and logging are built into the instrument. The signal is processed through a “true mean square” (TRMS) circuit before it is stored in the instrument. The biophysics group owns two instruments of this type and they were sent for calibration before the measurements started.

The specified accuracy of the measurements is typically ±3% and the worst case is ±10%. Therefore, the measurement values have been specified with two figures (in some special cases with three). The specified operating temperature of the device is from 0 to 60°C. We tested the instrument by cooling it down to see if the measured magnetic field increased when the temperature increased but could not see any significant difference. To be safe we started each measurement for the cold conditions in Trondheim with a newly charged battery. An indoor pause was embedded in between the measurements series.

The measurements have been processed and plotted using the Matlab software (7.0.0. R14, MathWorks Inc.). Some measurements were related to the geographical position of the measurement site on a Trondheim map by a special Java program. The EMDEX II instruments are equipped with an event button. The Java program allowed the relation of each event marking on the EMDEX II to the geographical position on the background map. This was done continuously for a whole string of data as the instrument was carried along, e.g. the pavement. The Java program produced a matrix of the geographical event positions. The matrices were connected to corresponding measurement file in Matlab to produce contour maps.

In the Matlab program, one could edit the measurement files before linking them to the geographical matrix. This was useful, in cases where one had to stop the sampling of values for any reason. An event marking when stopping the measurements and a new marking when restarting the measurements allowed precise data sequences in the files (one could, e.g., delete measurements taken between two such markings).

Magnetic flux density from each block could be statistically analysed separately as it was done for the different blocks as depicted in paper I. For the statistical calculations, the raw data measured by the instruments were used (all digits included). The interpolated command in Matlab has been used for the visualization of the contour maps of the magnetic fields both around the mobile phones in paper II and in the downtown streets in Trondheim in paper I.

The EMDEX WaveCorder instrument (Paper II)

The Wavecorder (Enertech Consultants Cambell, CA, USA) is a battery-powered instrument which detects the magnetic flux density through three orthogonal coils for the three spatial directions. The instrument measures the magnetic flux density and its frequency content as a function of time. There is a built in Fast Fourier Transform (FFT) function within the instrument. The measured and calculated data can easily be transferred to a PC.

The operating temperature of the Wavecorder is from 0 to 60°C. Measuring the magnetic flux density was not a problem at colder temperatures but the visibility on the LCD-screen was poor after long periods out in the cold. The accuracy was ±2% per

10°C. The temperature of the device itself was never below zero when used for measurements.

For each frequency contained in the signal, the FFT results could be used directly with the absolute value of the magnetic flux density compared with the corresponding reference level and summed up according to the multiple frequency rule [ICNIRP 1998]. Another method is to calculate the percentage of each harmonic compared to the basic frequency and use the relative contributions to see if each harmonic exceed the reference levels (same method as described in paper II below). This could be done to estimate the ratio according to the multiple frequency rule when we only have a rms measurement, for example: the highest recorded magnetic flux density in Trondheim. Then one could use the percentages from the Wavecorder together with the rms value from the EMDEX II to calculate how large each of the frequency components contributes to the total field. This method is explained in paper II where the FFT results from the CA 42 and the current clamp are used together with the EMDEX II.

Chauvin Arnoux C.A 42. (Paper II)

This instrument was used during two visits to Umeå, Sweden, in collaboration with the National Institute of Working Health. The Chauvin Arnoux C.A 42 LF magnetic flux density meter (Chauvin Arnoux, Paris, France) was used with the magnetic probe MF 400 for recording of the wave shape of the magnetic flux density and for the FFT analysis. The MF 400 is an *isotropic* measurement probe with a 5.6 cm radius. The built inn FFT analysis was used for the frequency analysis.

Fluke 80I-1000s (Paper II)

The current clamp Fluke 80I-1000s (Fluke Industrial B.V., Almelo, The Netherlands) was used during the two visits to Umeå, Sweden, in collaboration with the National Institute of Working Health. This instrument, which uses a routine method to record the magnetic field around the current carrying wire, was used to calculate the current in the wire.

Infrared (IR) camera (Paper III)

First used for military proposes, thermal imaging is an excellent tool for measuring surface temperatures. The size of available IR-cameras has decreased but accuracy has increased with time. A ThermaCam PM595 (FLIR Systems Inc., North Billerica, MA, USA) rented from Presisjonsteknikk, Oslo, Norway, was used for IR measurements.

The absolute values of temperatures are difficult to measure accurately since the absolute accuracy is ±2°C and ±2% if all the variables (emissivity, temperature and humidity) are correctly set, but we used relative values (thermal sensitivity ±0.1°C at 30°C ambient temperature). Therefore, we used the differences between the sides of the head from before and after exposure which increased the worst case accuracy from 4°C to 0.4°C. All the IR pictures were converted to Matlab format (mat) and the image analysis was executed in Matlab.

Finapres® (Paper IV)

For the blood pressure and heart rate monitoring, a 2300 Finapres® blood pressure monitor was used. This is a system using a finger cuff to measure the blood pressure and heart rate continuously for several hours if desired (see Fig 4 and 5). The accuracy of the heart rate was ±5 beats per min (bpm) or ±5% of the reading (whichever is greatest) (Finapres® manual 1992). The accuracy is given as +2 mmHg to -4.5 mmHg.

If the cuff control box to the Finapres® was unshielded, it was found that the RF field interfered with the signal from the control box on the forearm of the subjects. The interference was mechanically felt on the cuff finger in preliminary trials and was also noticed on the control screen of the Finapres®. Therefore, the cuff control box was carefully shielded using aluminum foil. We also placed a home made mitten of shielding material around the hand and the cuff control box.

For later analysis of the blood pressure and heart rate, the Finapres® control box was connected to the same pc as a Logitech web-cam which was used for monitoring the subjects. A computer program showed the physiological data on the computer screen and it was possible to mark the data files at "start of the experiment session", "start of exposure", "end of exposure", and "end of experiment session". These events where later used for the analyses of the physiological data.

The mean value of the physiological data every 10 seconds was calculated using a Matlab program. The results were further statistically investigated using SPSS (version 13.0 and 14.0) packages. We measured blood pressure and heart rate in a relative way (see summary of paper IV in section 6.4).

5.2. The laboratory for the provocation study

When choosing exposure equipment for a mobile phone provocation study, there are several choices that have to be made. In this section, I will discuss different possibilities for exposure setup, provide a short explanation of the differences between them, and the reasons for the choices made. I will also briefly go through the technical parts of the exposure setup and explain some of the challenges in our lab.

One option for an exposure setup is to use an ordinary mobile phone as a relevant RF source. This, however, requires a base station to control the output level of the mobile phone. An alternative would be to use a test mobile phone which could be set to transmit at a given level. A study by Barker et al. [2006] has constructed a prototype of a "mobile phone" which could transmit at several different modes. Yet the construction of such a prototype was found to be both time consuming and expensive.

One advantage when using a mobile phone set up is that the exposure situation is very similar to the one experienced in the everyday use of a mobile phone. Relevant RF fields, ELF magnetic fields, and increased skin temperature in the ear region (see Straume et al. 2005) will be present in the exposure situation.

One of the major drawbacks with an ordinary mobile phone as an RF source in exposure experiments is the difference in SAR distribution caused by different models (Wilén et al. 2003). Since one does not know if there is a specific target tissue or organ where RF-fields might interact to induce headaches, it would be difficult to choose a type of mobile phone with relevant SAR distribution. In addition, blinding of the experiment could be a possible problem since the increased temperature of the mobile phone (due to the currents in the electronics) can cause heat sensations, confounding the blinding.

Huber et al. (2003) used base station antennae (dipole antennae) to replace the ordinary mobile phone antenna in human provocation studies. The signal to the base station antennae can be generated in a room outside the exposure room, and sent to the base station by shielded wires. This makes the blinding of the exposure easier than when using an ordinary mobile phone. An additional advantage is that several of the indoor base station antennae usually expose a larger area than a mobile phone, which means that tissues in the head, nerves, or blood vessels that could possibly play a role initiating headaches would be activated.

There are no ELF-currents from the base station antennae because the RF-signal is already generated by a mobile phone in an external room. This is in contrast to a mobile phone where ELF currents from the battery give rise to ELF magnetic fields.

The skin temperature increase due to insulation will also be reduced with external antennae. This is because the antennae could be further away from the subjects head, therefore reducing the insulation.

Arguments against the use of only RF-fields in a provocation test should also be discussed. A reaction to mobile phone exposure could possibly be due to the *combined* effect of the RF and ELF fields as well as the temperature increase. If this were the case, the use of RF-fields alone in a provocation experiment might not reveal the cause for headaches. However, there is no evidence for such reaction mechanisms. Therefore, the argument against using RF-fields alone should be disregarded at least for the time being. In summary, the use of base station antennae results in a more controlled experiment, since only the RF exposure is present. A positive result from the experiment would allow unequivocal evidence that RF-fields may provoke headaches. Based on these conclusions, we chose to use base station antennae.

The exposure system consisted of a GSM 900 test mobile phone which provided the RF signal. From the mobile phone, the desired frequency and output level could be selected. The battery saving function DTX could be turned ON or OFF.

The mobile phone generated a 902.4 MHz signal in pulses with a rate of 217 Hz, a duty factor of 1/8, and a peak power at 23 dBm (~0.2W). It was then attenuated (-30 dB Radial attenuator) before amplification (+50 dB; Ophir 5802064 power amplifier). To monitor the output level during the exposure, a power divider (MCLI CI-20) was used to direct part of the signal to a power meter (HP 437B power meter) and another part to either of the two antennae (RF exposure) or to an ohmic load (Thermaline 8080). This load absorbed the energy of the signal during sham exposures. The load was placed in the control room, a picture of which is shown in Fig. 2.

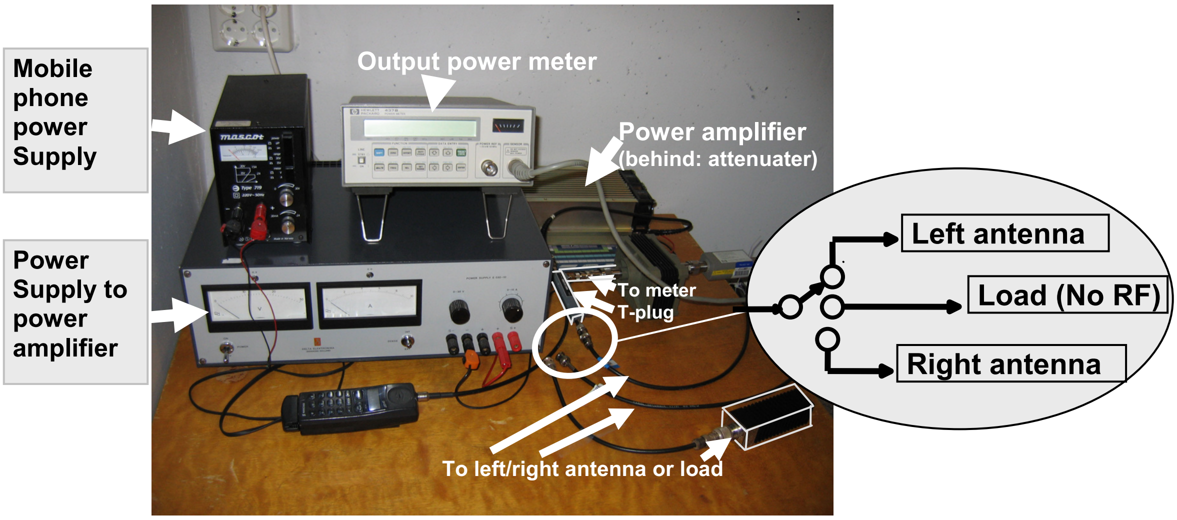

Fig. 2 The electronics in the control room of the exposure laboratory.

Two moveable antennae were positioned on the sides of the subjects' head. The antennae (Indoor Multiband Omni Antenna, Allgon, 800-2100 MHz) were placed 8.5 cm from each side of the head at a specific position. Wooden bars restricted lateral movement of the head. The SAR values from the antennae were relatively uniformly distributed in a large area (see Fig. 3). The spatial peak SAR_{1g} (averaged over 1 g) was 1.0 W/kg and SAR_{10g} was 0.8 W/kg (Wilén et al. 2006).

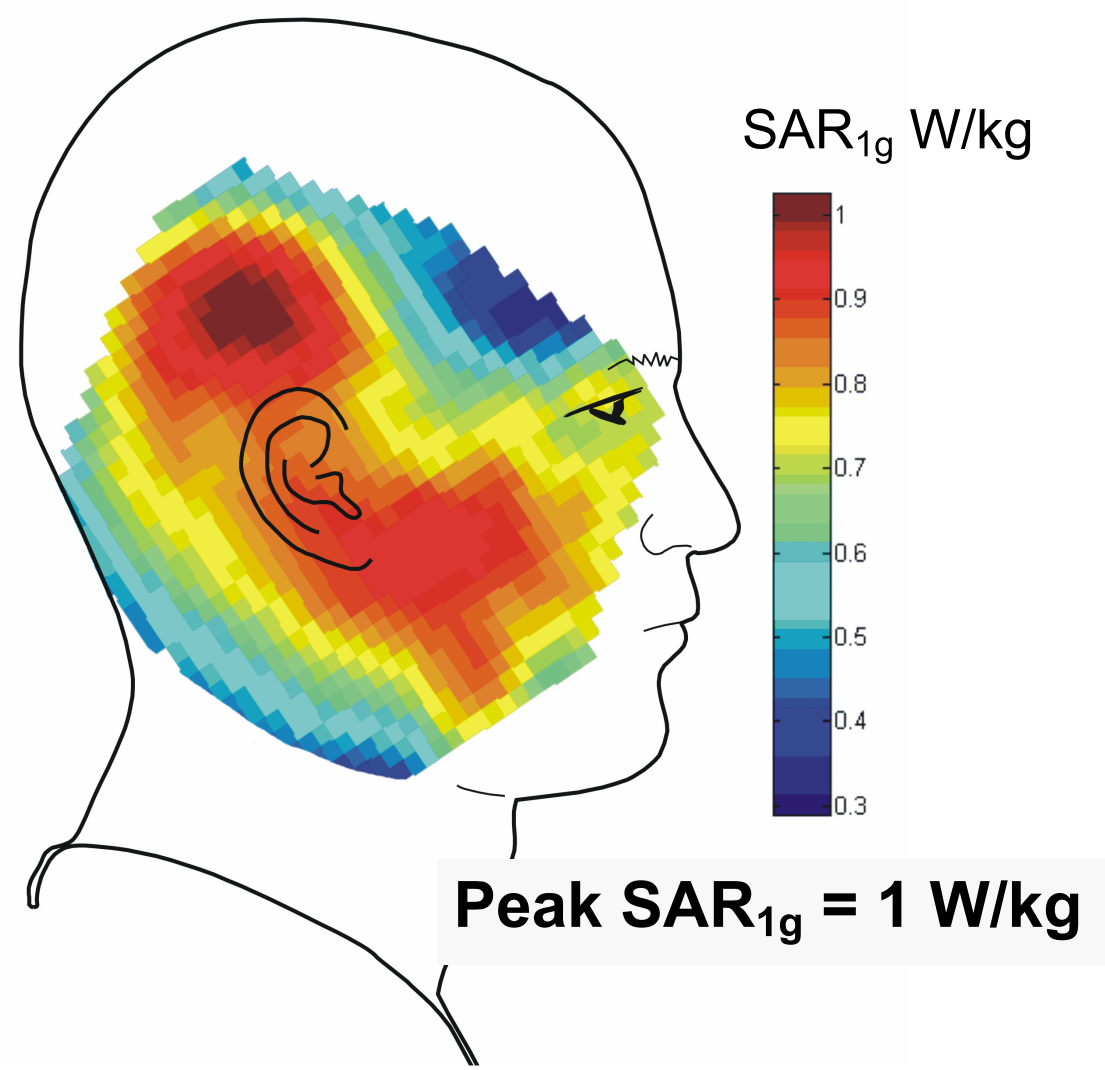

Fig. 3. The SAR distribution (W/kg) from the antenna SAR$_{1g}$=1.0 W/kg, SAR$_{10g}$=0.8 W/kg. ***From: Psychophysiological tests and provocation of subjects with mobile phone related symptoms; Wilén J, Johansson A, Nebojsa K, Lyskov E, Sandström M; Bioelectromagnetics 2006;27:204-214; Reprinted with permission of Wiley-Liss, Inc. a subsidiary of John Wiley & Sons, Inc.***

Subjects should sit comfortably and the arm fixed with the Finapres® should be kept in a stable position. This will reduce movements and thus influences on the recorded blood pressure. To ensure stability, the arm rests of the chair were rebuilt and equipped with foam (see Fig. 4). We attempted to use an analogue video camera connected to a TV to monitor the subjects. However, when the RF-exposure was turned on, disturbances were seen immediately on the TV. The cables and the video camera itself were shielded with aluminum foil but this was not sufficient to get rid of the disturbances. We then tried a Logitech web camera which was connected to a PC. This method worked without disturbances and thus there was no need for shielding.

While seated in the exposure room, the subjects viewed a film on an LCD screen ("The blue planet"). Loudspeakers picked up the RF signals causing a interference noise. This problem was also solved by using many layers of aluminum foil around the loudspeakers and the wire with the sound signal from the PC.

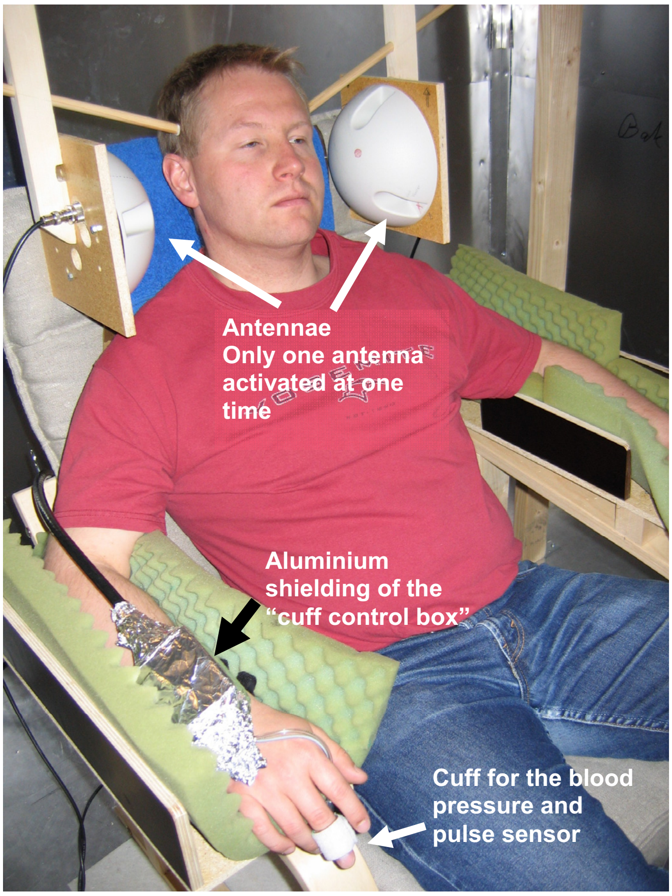

Fig. 4. A person seated in the exposure room

To ensure the experiment was double blinded, two individuals were involved in each session. The session leader was the person in contact with the subject. They monitored the web-cam and the physiological data during the sessions (Fig. 5). The other person was responsible for the exposure. The exposure control room and the subject control room were on opposite sides of the Faraday cage and were also separated by a thick curtain to ensure no visual contact was made between the two individuals.

The timing of the sessions was synchronized by using stop watches.

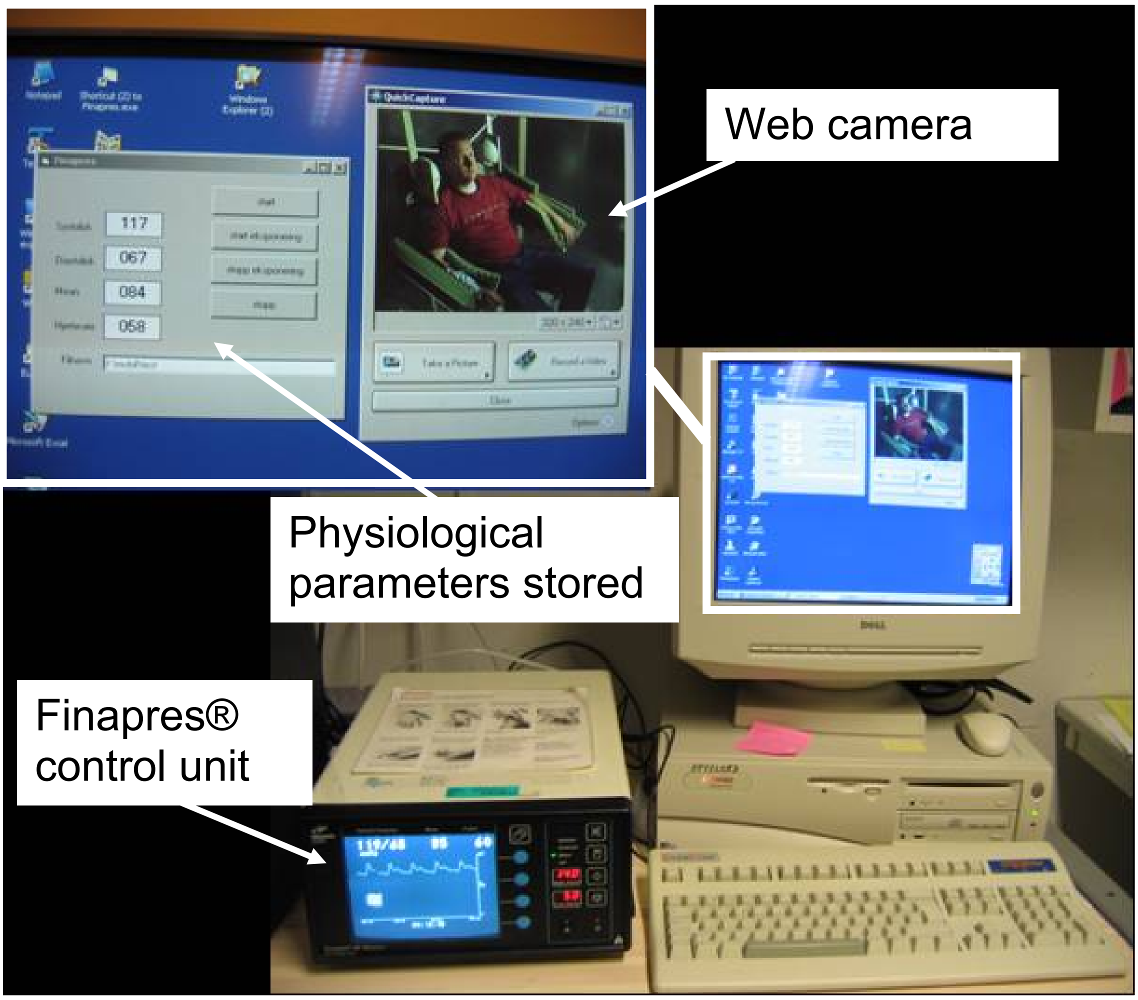

Fig. 5. The view as seen by the assisting person who was in contact with the subjects during the exposure experiment.

The exposure equipment used for our headache provocation study was borrowed from Arbetslivsinstitutet in Umeå, Sweden. They had used the equipment in a similar study (Wilén et al. 2006).

6. Summary of papers

6.1 Paper I

Straume A, Johnsson A, Oftedal G. ELF-magnetic flux densities measured in a city environment in summer and winter time. Submitted to Bioelectromagnetics

Epidemiological studies have indicated a connection between exposure to extremely low frequency fields and a prevalence of childhood leukaemia as mentioned in section 1. Mapping of magnetic flux density levels under different conditions are, therefore, important. One parameter of interest in this connection is the time of the year; there are large seasonal variations in power consumption in Norway and the magnetic flux density levels can therefore vary substantially, both indoor and outdoor. One special feature of outdoor exposure in city environments may be the electrical heating of pavement on snowy days (in order to remove snow and ice) .This can add to the general magnetic flux density levels.

The outdoor ELF magnetic flux density was studied in an urban area of Trondheim (63.42° N), recorded one meter above the pavement. Flux densities were measured along 17 km of pavement under three different conditions: summer 15 -20°C, winter while snowing (-5 - 0°C), and cold winter days (not snowing, $T < -9$°C).

There were large magnetic flux density differences between summer and winter conditions. In the summer, the mean magnetic flux density was 0.13 μT while in “winter, cold” and “winter, snowy” conditions, the values increased to 0.85 and 0.90 μT respectively.

In winter, the power consumption for indoor heating was larger and the magnetic field above net stations (transformers) was therefore correspondingly higher. The use of heating cables in the ground also raised the magnetic field significantly. This is probably caused by single wire heating cables. In earlier times, such heating cables were also used indoor but they are now replaced by twin cables.

The percentage of flux density data above 0.4 μT (level chosen to represent the time weighted average that is associated with childhood leukaemia [Ahlbom 2000]) was 3.6% in summer. The numbers increased substantially and were about 29% and 34% on cold and on snowy winter days, respectively. The highest recorded magnetic field 1 m above the pavement was 37 μT.

Spot measurements in the city showed some time variations but the recordings of the spectral flux density components above net stations and heating cables demonstrated that the amount of harmonics was very low. Consequently, the 50 Hz rms values could be directly compared with the ICNIRP reference levels [ICNIRP 1998] for 50 Hz, i.e. 100 μT. Any weighting of the content of harmonic components did not contribute significantly in the calculations of the exposure levels. The only exception was one pavement measurement at ground level just above a net station for which the ICNIRP reference level was not exceeded.

The measurements also demonstrate that the levels of the magnetic fields in outdoor urban areas could be of the same magnitude as those recorded quite close to a high power transmission line [Vistnes et al. 1997]. Therefore, outdoor conditions should also be taken into account when epidemiological investigations and exposure estimates are carried out.

6.2 Paper II

Straume A, Johnsson A, Oftedal G and Wilén J. Frequency spectrum from current- vs. magnetic flux density measurements for mobile phones and other electrical appliances. Accepted to Health Physics Journal.

Investigations and calculations of the magnetic flux density exposure from electrical devices in accordance with the ICNIRP guidelines [ICNIRP 1998] could be a complicated task if the magnetic fields contain harmonics. The reference level of exposure from magnetic fields (ICNIRP guidelines) decreases with increasing frequency in the range 1 – 800 Hz reflecting the fact (see section 3.1) that the body is more sensitive to the higher frequencies in this frequency band. The amplitude of the different harmonics can be important for the overall exposure. According to the so-called multiple frequency rule [ICNIRP 1998], a ratio between the observed amplitude of a certain frequency component and the exposure limit (ICNIRP guidelines reference values) for the same frequency should be calculated. The sum of the ratios for all frequencies present in the signal should not exceed 1.

The spectral content of the exposure has been measured by direct magnetic field measurements at the device or by estimates based on measurements of the frequency spectrum of the current.

In this paper, we wanted to test if the frequency spectrum of the current drawn to an electric device was representative for the frequency spectrum of the magnetic field from the device, constituting the real exposure. Spectral studies were carried out on one GSM 900 mobile phone, on a drilling machine, a hairdryer, and a desk lamp. The magnetic flux density variations around three GSM mobile phones were studied in detail.

From the contour maps of the magnetic flux density around the mobile phones, it was quite clear that the magnetic flux density varies strongly with the direction relative to the phone (directional dependence). The spatial differences were also large and a spot measurement is not necessarily representative for other positions above the device. The frequency spectra using the two methods mentioned above produced different results. We concluded that spectral measurements of the current drawn to the device could deviate from the spectral content of the magnetic flux density. As a consequence, the frequency spectrum of the current in the wires does not necessarily reflect the magnetic field frequency spectrum around a mobile phone. The same conclusion could be drawn for other electric devices.

6.3 Paper III

Straume A, Oftedal G and Johnsson J: Skin temperature increase caused by a mobile phone: A methodological infrared camera study. Bioelectromagnetics 2005; 26:510-519

Many mobile phone users complain about warmth sensation on the ear and behind the ear. In a Norwegian-Swedish epidemiological study [Oftedal et al. 2000 and Sandström et al. 2001], 31% of the Norwegian and 13% of the Swedish mobile phone users reported some symptoms associated with the use of mobile phones. Warmth sensation on/around the ear was the dominating symptom.

In a cand. scient. thesis [Straume 2002], a statistically significant temperature increase of the skin was demonstrated when the phone was transmitting at the highest output power (as compared to the temperature when the mobile phone was switched off). There was also a trend of increasing skin temperature rise with increasing output power developed by the phone. However, that study did not measure any possible contribution of the RF to the increased temperature.

In a follow-up study, we also wanted to investigate whether the RF exposure would give rise to a statistically significant increase in temperature beyond the two obvious heating sources when a mobile phone is used, viz. the heating due to the power developed in the phone and its insulation effect in prevention of heat loss from the ear region to the surroundings.

A differential measurement method was chosen to increase the precision. The temperature differences between the skin at the telephone side of the head and the other side was calculated. An infrared camera was used to measure the skin surface temperature.

In the exposure situation, a digital GSM 900 test mobile phone, transmitting at 902.4 MHz, was used. The phone could transmit at an adjustable fixed power level. Three different average output levels were chosen: 0.21 W, 0.002W and 0 W (OFF). To eliminate the RF exposure a 50 Ω resistance (LOAD condition) was connected to the antenna output via a cable. For each power level, the mobile phone was used with a transmitting antenna (without the resistance), and with the resistance to eliminate the RF exposure. The battery saving function, DTX (Discontinuous transmission) was inactive during the experiments.

One healthy male subject was selected for the study, designed as a double blind experiment. The experiment was administered to compensate for skin temperature variations throughout the day and thus, exposure sessions were distributed throughout the day. The subject held the mobile phone in the normal position for 30 min in each session. Pictures of the exposed skin area and of the non-exposed area on the opposite side of the head were taken at 0, 15 and 30 min of the exposure. To get a better resolution of the ear region, the exposed area was divided into two sub areas (denoted EAR and CHEEK). The temperature differences between the pictures of the exposed and the non-exposed skin areas were studied.

In general, the temperature of the EAR region increased more than that of the CHEEK region. Within the EAR, the pinna was most heated and a temperature increase from exposure start to 15 and 30 min was statistically significant for all exposure conditions. For the EAR region, there was also a statistically significant difference between recordings taken at MIN and MAX output power.

The temperature increases were slightly higher when using RF-exposure compared to similar LOAD condition but were only statistically significant for the EAR after 30 min of exposure with MIN power. The difference between RF-exposure and RF LOAD was then 0.3°C. This is probably a coincidence since the MIN output level is approximately 1% of the MAX output level.The results showed that the heat insulation of the mobile phone was the main contribution to the increase in skin temperature. One reason for a higher increase in the EAR region as compared to the CHEEK region may be the initially lower temperature of the EAR region and especially the pinna. This is in accordance with a theoretical model study by Bernardi et al. [2001] who predicted that a temperature increase was primarily due to the insulation. The electrical power dissipation and increased mobile phone temperature lead to increased skin temperature, while the RF exposure did not.

6.4. Paper IV

Oftedal G, Straume A, Johnsson A and Stovner LJ. Mobile phone headache: a double blind, sham-controlled provocation study. Cephalalgia 2007;27(5):447-455.

A Norwegian-Swedish epidemiological investigation [Oftedal et al. 2000] found that *headache* was the most frequently occurring symptom attributed to the use of the mobile phone (except for warmth sensation). Most of the people reporting symptoms from mobile phone use do not report symptoms in connection with work at data terminals (VDT's). This suggests that people reporting headaches due to mobile phone use are not "hypersensitive to electricity" in general. For a general reference on electric hypersensitivity see [Rubin et al. 2005 and Seitz et al. 2005].

The present study was designed to investigate whether RF-fields (900 MHz) from mobile phones could provoke headaches in subjects who themselves attributed the symptoms to mobile phone use. We designed a double blind study with highly selected users (see below) and carried out a provocation study in cooperation with a headache specialist from the university hospital. The exposure was controlled from a control room by a person who was neither in contact with the subjects nor with the person who took care of the subjects. We also investigated if RF-fields influenced blood-pressure and heart-rate.

Announcements for subjects who attributed their headaches to mobile phone use were done mainly in local newspapers, but TV and posters were also used. Individuals responding were interviewed by telephone and a questionnaire was mailed to them. The selection process was designed to identify subjects with symptoms in close connection to mobile phone use and not “hypersensitive to electricity” in general. Individuals who fulfilled the requirements participated in an open provocation test with RF-fields. Study subjects who got the same symptoms in the open test as they usually attributed to mobile phone use were invited to the double blind test.

Of 42 individuals who responded to the questionnaire, 38 were eligible for the open provocation test. Seventeen subjects (5 females and 12 males) participated in the double blind study. These individuals took part in sixty-five pairs of RF mobile phone and sham exposure sessions, i.e. 130 exposure sessions in total.

The exposure equipment consisted of two antennae (Indoor Multiband Omni Antenna, Allgon, 800-2100 MHz) symmetrically mounted on the sides of the head. A GSM 900 mobile phone transmitting at 902.4 MHz (pulses rate of 217 Hz and with duty factor of 1/8) was used as the signal generator (the battery saving function was OFF).

The antennae was at a fixed at position relative to the head of the subject. The highest measured spatial SAR_{1g} (averaged over 1 g) and SAR_{10g} were recorded by Wilén et al. (2006) at 1.0 W/kg and 0.8 W/kg respectively. The exposure covered a relatively large area of the head compared to the one covered by ordinary mobile phone exposure. This was done in order to expose potential target organs or tissues which could cause headaches. During dummy exposure, the signal from the amplifier was absorbed by a load in the exposure control room.

Because the RF-signal was generated in the exposure control room, there was no exposure to low frequency magnetic fields from these antennae. This is the main difference between the real exposure from GSM mobile phones and the exposure used in this study.

The subjects were exposed for 30 min on only one side of the head; the same side as they usually used the mobile phone. If the subject used both sides, the side of exposure was drawn by chance. Neither the subject nor the person taking care of the subject knew if the subject was RF or sham exposed. The whole experiment, as well as the analyses, was carried out using double blind methodology.

The seriousness of symptoms was registered on two 100 mm visual analogue scales (VAS) in a questionnaire before and at various times after the exposure. The scales were anchored to “no pain or discomfort” and “unbearable pain”. The subjects were also asked to specify “other symptoms”. The diastolic and systolic blood pressure and the pulse rate were continuously registered before, during, and after the exposure with a

2300 Finapres Blood Pressure Monitor. The output to the computer was a running average over four heart beats.

The primary effect variable defined *a priori* was the maximum change in "pain/discomfort" during exposure and until one hour after exposure. This was calculated relative to the degree of symptoms before the start of exposure. In 68 % of the trials, the subjects experienced an increase in pain and discomfort during both RF and sham exposure, but the symptoms registered were generally relatively low. The increase in pain and discomfort in the head (VAS) in RF sessions was 10.1 and in sham session 12.6 (p=0.30). Evidently, the subjects experienced more pain or discomfort at sham exposure compared to RF in these exposure experiments, although the difference was not significant.

For the analysis of physiological variables, the mean of the data 5 min before the exposure was used as a baseline and compared to data from each 5 min period during the exposure. The last 5 min of the exposure was also compared to the 5 min immediately after exposure. There were no statistical significant changes in any of the physiological parameters.

This study has shown that RF fields from GSM 900 mobile phones did not cause pain or discomfort in the head or other symptoms, even in a highly selected group of users.

7. General Discussion

This discussion will extend the ones in the individual papers and will also be of a more general nature. Some of the more significant aspects may, however, be mentioned here as well as in the papers. The main concentration will be on two broad areas: the basic question of exposure assessment and mobile phone provocation studies.

7.1 Exposure assessments and risk evaluation of ELF-magnetic fields

Pooled analyses of epidemiological investigations [Ahlbom et al. 2000 and Greenland et al. 2000] have shown an increased relative risk of 2 and 1.7 for childhood leukemia from exposure to magnetic fields above 0.4 and 0.3 µT, respectively. Using the available data for this type of 50 Hz magnetic field exposure, the Norwegian Radiation Protection Authority (NRPA) calculated the increase in cases of childhood leukaemia in Norway assuming a relative risk of 2 for children living with a time average flux density above 0.4 µT [Saxebøl 2005]. The result was one case every 7 years and one death every 70 years.

The data thus point at a fairly low risk. These values of magnetic flux densities are based on time weighted averages (TWA) for a 24 hour period. The two environments in which people spend the majority of time during a 24 hour period are the home environment and the work environment (school in the case of children of relevant age). Therefore, these locations have been regarded as providing the most important contributions to the TWA. In our study, we investigated the magnetic flux densities in an "outdoor" public city environment. The magnetic flux density in summer was quite low with a mean value of 0.13 µT, and the 75th and 95th percentiles were 0.06 µT and 0.23 µT, respectively. In winter on snowy days, the mean value rose to 0.90 µT and the 75th and 95th percentile to 1.4 µT and 3.5 µT respectively. Thus there is a large seasonal difference.

One hour exposure in downtown Trondheim during snowy weather would contribute 0.038 µT (0.90 µT/24 h) to the TWA. Twelve hours at home at 0.4 µT would result in a 0.20 µT TWA contribution (0.4 x 12/24). Eight hours at work at 1.0 µT would result in a 0.33 µT contribution. Compared with these values, the outdoor exposure seems to contribute only little to the TWA.

The importance of the different outdoor exposures of magnetic fields is difficult to evaluate because of a general problem, viz. the lack of relevant dose response curves. The numbers above indicate a fairly low contribution to the TWA even in winter. However, at certain spots, the flux densities are higher. Above net-stations and activated heating wires in the ground, most of the recorded values were above 2 µT. Therefore, it is relevant to raise the question whether time averaging really produces a biologically interesting exposure measure (a dose). In other words, does a one hour exposure to 2 µT produce the same biological effects as four hours at 0.5 µT?

In epidemiological studies, the time averaging of the magnetic density fluxes has generally been used as the most relevant and feasible method for large studies (and thus, assuming that the answer to the above question is 'yes'). In the present study, high peak magnetic flux densities have been measured above net stations which can be compared to the magnetic flux densities below high voltage power lines [Vistnes et al. 1997].

If a biological response is non-linearly related to the strength of the magnetic field the conventional dose concept is no longer valid (see for example [Valberg et al. 1995 Repacholi 1997, Vescovic et al. 2002]). Apparently, such possibilities need to be further explored. For example, threshold effects might play a role for the overall exposure and high magnetic flux densities for short periods of time might be more important in exposure assessments etc. A walk downtown in winter may then play a more important role in the exposure assessment than revealed in the TWA calculations which "average out" the high peaks. This picture emphasizes the need for a better understanding of exposure assessment, not only in the working life (where high field levels can be encountered quite often) but also in everyday life situations.

If the TWA over a longer period of time is the major contributory factor, the outdoor exposure investigated here will not be of great importance for the exposed person, especially since the magnetic flux density is quite low in months without snow. However, these measurements are from just one city in Norway and measurements from other cities might be of interest for comparison. Another factor in the complicated overall risk assessment is, of course, the *positive* effects of heating of pavements and its handy removal of snow and ice. This undoubtedly leads to less people sliding and falling on the ice with increased risk of injuries.

The magnetic flux density values around electrical appliances are in some cases very high, at least close to the device or close to the transformer of the device. The values achieved at spot measurements close to a device, e.g., an electrical drill, can exceed the ICNIRP [1998] reference level. However, the magnetic field decreases rapidly with increased distance to the device and the whole body exposure will in general be low, not exceeding the basic restriction. In the last few decades, there has been an increased use of pot lights and light bulbs (using for example 12 V), transformers for general electric devices, and charging batteries in homes. Electrical toys, computers, and other digital electrical devices may have contributed to higher magnetic fields and especially peak magnetic fields which are higher in homes today compared to previously. The question of the relative importance of high peak fields is something that should be under continuous observation and studied in the future.

To compare fields from electrical appliances with the ICNIRP reference levels, the frequency contents of the magnetic fields have to be recorded. Paper II of the present thesis showed that measurements of the frequency content of the current drawn to the electrical device does not necessarily reflect the frequency content of the magnetic field from the device. In our studies, we have used the multiple frequency rule to calculate if the ICNIRP reference level is exceeded [ICNIRP 1998]. This implies an over estimate of the magnetic flux density level since the phase differences between frequency components are not taken into account. Another way to measure the most relevant biological parameter is to measure the changes of the magnetic field with respect to time, dB/dt, directly. The reason for our choice of method was due to the restriction imposed by instrumentation available (size, logging facilities, costs) and the fact that most measurements in the literature were carried out in a comparable manner [Lindgren et al. 2001, Paniagua et al. 2004].

This section thus emphasizes the importance of the measurement procedures when mapping the fields with the frequency contents, high peaks values, and spot distributions. Furthermore, the problem of the assessment of health risk is intimately coupled to the question of whether the biological response is linear with respect to the field strength. Finally, we have to consider the fact that a biological response in itself might not implicate a health hazard.

7.2. Mobile phone use and subjective symptoms and physiological responses

An epidemiological investigation by Oftedal et al. [2000], revealed that many mobile phone users report symptoms like dizziness, discomfort, concentration losses, memory loss, fatigue, *headaches* and *warmth sensation* which they attributed to their mobile phone use. More than 20% of the users in Norway complained about warmth sensation behind and on the ear and 10% complained about headaches; these symptoms being the most frequently reported. An early study on objective performance reported effects on reaction times [Koivisto et al. 2000], but these findings have not been possible to replicate [Preece et al. 1999, Croft et al. 2002, Haarala et al. 2003 and Hamblin et al. 2006].

Our present provocation study (paper III) showed a significant skin temperature rise due to mobile phone use. The temperature rose 5 °C on some parts of the pinna. Such a temperature rise is certainly sensed and it is understandable that many people will be concerned and feel discomfort because of it. However, this temperature rise was found to be mainly caused by insulation and impeded convection prevention of convection which the mobile phone device itself causes. Additional skin heating by the RF-field emitted was not significant. A temperature rise of a couple of degrees is itself not harmful to the skin. A recent article by Anderson and Rowley [2007] confirmed our findings with different types of analogue and GSM mobile phones.

An interesting future study, based on our results from the IR provocation study (paper III), would be to investigate the effect on skin temperature by replacing the mobile phone with antennae (as used in the provocation study in paper IV) which are placed further away from the skin. This would allow recordings at different distances between the antennae and the skin. Since the heat insulation would then be absent (no mobile phone close to the ear region), one could investigate the RF-induced heating of the skin as a function of the antenna distance and there would be no masking effect as a result of the insulation. The additional RF-induced heating has been simulated by Bernardi et al. [2001] and Gandhi et al. [2001]. They calculated an additional temperature rise of 0.037 and 0.005 °C respectively compared to a phone switched on without RF exposure. When using RF fields as the only source, excluding insulation, the temperature increase was estimated by Bernardi et al. [2001] and Gandhi et al. [2001] to be 0.136 °C and 0.203 °C, respectively. Blood flow may also change due to the heating and Monfrecola et al. [2003] showed that the ear skin blood flow was increased when the skin was heated by the phone (both when off and on). The increased blood flow caused by prior heating was also shown to reduce the additional heating by the RFE [Walters et al. 2004].

Most people do not complain about effects from EMF. To see if there is any connection between, for example, EMFs from mobile phones and any subjective symptoms it will be difficult to find it among the general public. Therefore, it seems reasonable that studies selecting the subjects with complaints have a higher possibility to find any connection, if it exists. This was the reason for our choice to study people attributing headaches to mobile phone use. All of the subjects who went through the double blind tests reported the same symptoms at the open provocation test as they previously had attributed to mobile phone use. In the double blind test they reported more severe symptoms during and after sham exposure than during or after RF-exposure, although the difference was not statistical significant. An expectation effect; the nocebo effect, is a possible explanation of this result.

We did not see any statistically significant effects on changes in heart rate and/or blood pressure which are in agreement with the findings of Wilén et al. [2006]. However, the latter study did find a difference between the cases and the controls regarding heart rate variability as measured in frequency. Barker et al. [2006] who used only normal volunteers did not find any effect of GSM and TETRA (Terrestrial Trunked Radio) signals on blood pressure and related physiological parameters. Rubin et al. [2006] did not find any evidence that persons with self reported sensitivity to mobile phone signals could sense the signals or that they react to the signals with increased symptom severity.

The main results from our study are therefore in line with several of the most recent studies that have concluded the RF-fields do not cause the reported subjective and physiological health effects. The picture is, therefore, consistent. Parenthetically, it can be mentioned that also ELF provocation studies on electromagnetic hypersensitive persons have shown negative results [Rubin et al. 2005].

The subjects in our study were interviewed by medical experts in our team. We plan to give a short report on possible findings and subject profiles in relation to the headache symptoms. It might also be of interest to discuss them in relation to the suggested nocebo explanation proposed in paper IV.

Precise measurements and careful experimental designs are necessary in the experiments to reveal any adverse health effects of mobile phones. Lack of or improper measurements of the relevant fields, influences of movements of mobile phones or subjects, improper electric shielding etc., have been mentioned in this thesis as relevant sources of error. Precise information on these points is not always adequately reported in many published papers. This makes it difficult to judge the quality of the results achieved and is an added difficulty when performing meta-studies or epidemiological studies. Critical evaluation of the measuring procedures is an essential point in these studies, and in general, for studies on exposure and risk analysis due to electromagnetic fields.

Finally, a general aspect on the technological development deserves to be mentioned. The rapidly changing of wireless communication systems can make the investigations in the field rapidly outdated. Not only does the output power of the terminal change, the frequency bands and the body parts primarily exposed are changing and so the exposure situations are by no means easy to map. Possible health effects are, therefore, difficult to relate to the precise exposure situation and exposure history. This is especially true if possible long term effects of the RF-fields are considered. Even if this is outside the scope of the present studies it should be mentioned, e.g., in the case of possible brain cancers initiated by mobile phone use. Here the reports are contradictory and the situation unclear.

8. References

Ahlbom A, Day N, Feychting M, Roman E, Skinner J, Dockerty J, Linet M, McBride M, Michaelis J, Olsen JH, Tynes T, Verkasalo PK. 2000. Pooled analysis of magnetic fields and childhood leukaemia. British J of Cancer, 83 (5):692-698.

Anderson V, Rowley J. 2007. Measurements of skin surface temperature during mobile phone use. Bioelectromagnetics 28 (2):159-162.

Auvinen A, Hietanen M, Luukkonen R, et al. 2002. Brain tumors and salivary gland cancers among cellular telephone users. Epidemiology 13:356-359.

Barker AT, Jackson PR, Coulton LA, Cook GG, Parry H. 2006. The Sheffield mobile phone blood pressure/cardiovascular study. 28th Annual Meeting of the Bioelectromagnetics Society, Cancun, Mexico, Abstract Book p. 546-549.

Bergqvist U and Vogel E. 1997. Possible health implications of subjective symptoms and electromagnetic field. A report prepared by a European group of experts for the European Commission, DGV. Arbete och Hälsa, 1997:19. Swedish National Institute for Working Life, Stockholm, Sweden. ISBN 91-7045-438-8.

Bernardi P, Cavagnaro M, Pisa S, Piuzzi E. 2001. Power Absorption and Temperature Elevations Induced in the Human Head by a Dual-Band Monopole-Helix Antenna Phone. IEEE Transductions on microwave theory and techniques 49(12):2539-2546.

Brune D, Helleborg R, Persson BRR, Pääkkönen R. 2001. Radiation at home, outdoors and in the workplace. Scandinavian Science Publisher, Oslo, Norway.

Christensen HC, Schuz J, Kosteljanetz M, et al. 2005. Cellular telephones and risk for brain tumors - A population-based, incident case-control study. Neurology 64:1189-1195.

Cook CM, Thomas AW, Prato FS. 2004. Resting EEG is affected by exposure to a pulsed ELF magnetic field. Bioelectromagnetics 25:196-203.

Cook CM, Thomas AW, Keenliside L, Prato FS. 2005. Resting EEG effects during exposure to a pulsed ELF magnetic field. Bioelectromagnetics 26:367-376

Cook CM, Saucier DM, Thomas AW, prato FS. 2006. Exposure to ELF magnetic and ELF-modulated radiofrequency fields: The time course of physiological

and cognitive effects observed in recent studies (2001-2005). Bioelectromagnetics 27 (8):613-627

Crasson, M. 2003. 50-60 Hz electric and magnetic field effects on cognitive function in humans: A review. Radiat. Prot. Dosim. 106 (4):333-340.

Crasson M, Legros JJ. 2005. Absence of daytime 50 Hz, 100 mu T-rms magnetic field or bright light exposure effect on human performance and psychophysiological parameters. Bioelectromagnetics 26 :225-233

Croft RJ, Chandler JS, Burgess AP, Barry RJ, Williams JD, Clarke AR 2002. Acute mobile phone operation affects neural function in humans. Clinical Neurophysiology 113:1623-1632.

Curcio G, Ferrara M, De Gennaro L, Cristiani R, D'Inzeo G, Bertini M. 2004. Time-course of electromagnetic field effects on human performance and tympanic temperature. Neuroreport 15:161-164.

Davis S, Mirick DK, Stevens RG. 2002. Residential magnetic fields and the risk of breast cancer. Am. J. Epidemiol 155(5):446-454.

D'Costa H, Trueman G, Tang L, Abdel-rahman U, Abdel-rahmanW, Ong K, Cosic I. 2003. Human brain wave activity during exposure to radiofrequency field emissions from mobile phones. Austr Phys Eng Sci Med 26:162-167.

Erogul O, Oztas E, Yildirim I, Kir T, Aydur E, Komesli G, Irkilata HC, Irmak MK, Peker AF. 2006. Effects of electromagnetic radiation from a cellular phone on human sperm motility: An in vitro study. Archives of medical research, 37 (7): 840-843.

Feychting M, Ahlbom A, Kheifets L. 2005. EMF and health. Annu. Rev. Public Health, 26:165-89.

Finapres® manual 1992. 2300 Finapres® blood pressure monitor. Operation and maintenance manual. BOC Health care Inc.

Frey AH. 1961. Auditory system response to radio frequency energy – Technical note. Aerospace Med. 32:1140-1142.

Frey AH. 1973. Human perception of illumination with pulsed ultrahigh-frequency electromagnetic energy. Science 181:356-358.

Fuller M, Wilson CL, Velasco AL, Dunn JR, Dunn JR, Zoeger J. 2003. On the confirmation of an effect of magnetic fields: Evocation of epileptiform activity. Brain Res Bull 15:43-52.

Gandhi OP, Li QX, Kang G. 2001. Temperature rise for the human head for cellular telephones and for peak SARs prescribed in safety guidelines. IEEE Transactions on Microwave Theory and Techniques 49(9):1607-1613.

Ghione S, Del Seppia C, Mezzasalma L, Bonfiglio L. 2005. Effects of 50 Hz electromagnetic fields on electroencephalographic alpha activity, dental pain threshold and cardiovascular parameters in humans. Neuroscience letters 382:112-117.

Greenland S, Sheppard AR, Kaune WT, Poole C, Kelsh MA. 2000. A pooled analysis of magnetic fields, wire codes, and childhood leukemia. Childhood leukemia-EMF study group. Am. J. Epidemiol. 158:534-42.

Guy A, Lin JC, Kramar PO, Emery A. 1975. Effect of 2450-MHz radiation on the rabbit eye. IEEE Transactions on Microwave Theory Technique 23:492-498.

Hall EJ. 2000. Radiobiology for the radiologist, 5th ed. Lippincott Williams & Wilkins, PA, USA.

Hamblin DL, Croft RJ, Wood AW, Stough C, Spong J. 2006. The sensitivity of human event-related potentials and reaction time to mobile phone emitted electromagnetic fields. Bioelectromagnetics 27 (4): 265-273.

Haarala C, Bjornberg L, Ek M, Laine M, Revonsuo A, Koivisto M, Hamalainen H. 2003. Effect of a 902 MHz electromagnetic field emitted by mobile phones on human cognitive function: A replication study. Bioelectromagnetics 24:283-288.

Hardell L, Carlberg M, Mild KH. 2005. Case-control study on cellular and cordless telephones and the risk for acoustic neuroma or meningioma in patients diagnosed 2000-2003. Neuroepidemiology 25:120-128

Hardell L, Carlberg M, Mild KH. 2006. Pooled analysis of two case-control studies on use of cellular and cordless telephones and the risk for malignant brain tumours diagnosed in 1997-2003. Int Arch Environ Health 79:630-639).

Hepworth SJ, Schoemaker MJ, Muir KR, Swerdlow AJ, van Tongeren MJA, McKinney PA. 2006. Mobile phone use and risk of glioma in adults: case-control study BMJ 332:883-886.

Huber R, Treyer V, Borbély AA, Schuderer J, Gottselig JM, Landolt H-P et al. 2002. Electromagnetic fields, such as those from mobile phones, alter regional cerebral blood flow and sleep and waking EEG. J Sleep Res 11:289-295.

Huber R, Schuderer J, Graf T, Jutz K, Borbely AA, Kuster N, Achermann P. 2003. Radio frequency electromagnetic field exposure in humans: Estimation

of SAR distribution in the brain, effects on sleep and heart rate. Bioelectromagnetics ;24:262-276.

Huber R, Treyer V, Schuderer J, Berthold T, Buck A, Kuster N, Landolt HP, Achermann P. 2005. Exposure to pulse-modulated radio frequency electromagnetic fields affects regional cerebral blood flow. Eur J OF Neurosci 21:1000-1006.

IARC. 2002. Non-ionizing radiation, part 1: Static and extremely low-frequency electric and magnetic fields, International Agency for Research on Cancer (IARC) monograph (vol. 80).

ICNIRP 1998. Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). Health Phys. Apr;74(4):494-522

Kilgallon SJ, Simmons LW. 2005. Image content influences men's semen quality Biology letters 1 (3) : 253-255.

Koivisto M, Revonsuo A, Krause C, Haarala C, Sillanmaki L, Laine M, Hamalainen H. 2000. Effects of 902 MHz electromagnetic field emitted by cellular telephones on response times in humans. NEUROREPORT 11(2): 413-415.

Lin JC. 1978. Microwave auditory effects and applications. Springfield, IL, Charles C. Thomas.

Lindgren M, Gustavsson M, Hamnerius Y, Galt S. 2001. ELF magnetic fields in a city environment. Bioelectromagnetics 22:87-90.

London SJ, Pogoda JM, Hwang KL, Langholz B, Monroe KR, Kolonel LN, Kaune WT, Peters JM, Henderson BE. 2003. Residential magnetic field exposure and breast cancer risk: A nested case-control study from a multiethnic cohort in Los Angeles County, California. Am. J. Epidemiol. 158(10):969-980

Lönn S, Ahlbom A, Hall P, Feychting M. 2005. Long-term mobile phone use and brain tumor risk Am J Epidemiol 161:526-535.

Lönn S, Ahlbom A, Christensen HC, Johansen C, Schuz J, Edstrom S, Henriksson G, Lundgren J, Wennerberg J, Feychting M. 2006. Mobile phone use and risk of parotid gland tumor. Am J Epidemiol. 164:637-643.

Loughran SP, Wood AW, Barton JM, Croft RJ, Thompson B, Stough C. 2005. The effect of electromagnetic fields emitted by mobile phones on human sleep Neuroreport 16:1973-1976.

Lövsund P, Oberg PA, Nilsson SEG. 1980. Magnetosphenes and electrophosphenes - a comparative-study medical & biological engineering & computing. 18: 758-764.

Marino AA, Nilsen E, Chesson AL, Frilot C. 2004. Effect of low-frequency magnetic fields on brain electrical activity in human subjects. Clin. Neurophysiology 115:1195-1201.

Meier K, Egger O, Schmid T, Kuster N. 1995. Dosimetric laboratory for mobile communications. Electromagnetic compatibility 1995. 11TH P S Electromagnetic compatibility ZURI:297-300.

Monfrecola G, Moffa G, Procaccini EM. 2003. Non-ionizing electromagnetic radiations, emitted by a cellular phone, modify cutaneous blood flow. Dermatology 207(1):10-14.

Moulder JE, Foster KR, Erdreich LS, McNamee JP. 2005. Mobile phones, mobile phone base stations and cancer: a review. Int J Radiat Biol 81(3):189-203.

Muscat JE, Malkin MG, Shore RE, Thompson S, Neugut AI, Stellman SD, Bruce J. 2002. Handheld cellular telephones and risk of acoustic neuroma. Neurology 58:1304-1306.

Naarala, J, Hoyto, A, Markkanen, A. 2004. Cellular effects of electromagnetic fields. Atla-Altern Lab Anim. 32(4):355-360.

Oftedal G, Wilen J, Sandström M, Hansson Mild K. 2000. Symptoms experienced in connection with mobile phone use. Occup Med 50(4):237-245.

Panagopoulos DJ, Karabarbounis A, Margaritis LH. 2004. Effect of GSM 900-MHz mobile phone radiation on the reproductive capacity of Drosophila melanogaster. Electromagn Biol Med 23**: pp. 29–43.**

Paniagua JM, Jimenez A, Rufo M, Antolin A. 2004. Exposure assessment of ELF magnetic fields in urban environments in Extremadura (Spain). Bioelectromagnetics 25:58-62.

Preece AW, Iwi G, Davies-Smith A, Wesnes K, Butler S, Lim E, Varey A.1999. Effect of a 915-MHz simulated mobile phone signal on cognitive function in man. Int. J of Rradiation Biology 75:447-456.

Repacholi, MH. 1997. Low-level exposure to radiofrequency fields: Health effects and research needed. Bioelectromagnetics 19:1–19.

Rubin GJ, Munshi JD, Wessely S. 2005. Electromagnetic Hypersensitivity: systematic review of provocation studies. Psychsomatic Medicine 67:224-232.

Rubin GJ, Hahn G, Everitt BS, Cleare AJ, Wessely S. 2006. Are some people sensitive to mobile phone signals? Within participants double blind randomised provocation study. BMJ 332:886-889.

Sandström M, Wilen J, Oftedal G, Hansson Mild K. 2001. Mobile phone use and subjective symptoms. Comparison of symptoms experienced by users of analogue and digital mobile phones. Occup Med 51(1):25-35.

Saxebøl G (Chairman). 2005. Management strategy about magnetic fields and health related to power lines. Norwegian Radiation Protection Authority, Østerås. Strålevern Rapport 2005:8. Language: Norwegian.

Schoemaker MJ, Swerdlow AJ, Ahlbom A, Auvinen A, Blaasaas KG, Cardis E, Christensen HC, Feychting M, Hepworth SJ, Johansen C, Klaeboe L, Lonn S, McKinney PA, Muir K, Raitanen J, Salminen T, Thomsen J, Tynes T. 2005. Mobile phone use and risk of acoustic neuroma: results of the Interphone case-control study in five North European countries. British J Cancer 93:842-848.

Schoenfeld ER, O'Leary ES, Henderson K, Grimson R, Kabat GC, Ahnn S, Kaune WT, Gammon MD, Leske MC. 2003. Electromagnetic fields and breast cancer on Long Island: A case-control study. Am. J. Epidemiol. 158(1):47-58

Schuz J, Bohler E, Berg G, Schlehofer B, Hettinger I, Schlaefer K, Wahrendorf J, Kunna-Grass K, Blettner M. 2006. Cellular phones, cordless phones, and the risks of glioma and meningioma (Interphone Study Group, Germany). Am J Epidemiol 163:512-520.

Seitz H, Stinner D, Eikmann T, Herr C, Roosli M. 2005. Electromagnetic hypersensitivity (EHS) and subjective health complaints. Science of the Total Environment 349:45-55.

Serway RA. 1992: Physics for scientists & engineers with modern physics, 3rd edition, Saunders Golden Sunburst Series, USA.

Silny J. 1986. The influence threshold of a time varying magnetic field in the human organism. In: Bernhardt, HH. Ed. Biological effects of static and extremely-low-frequency magnetic fields. Munich: MMV Medizin Verlag:105-112.

Straume A, Oftedal G, Johnsson A. 2005. Skin temperature increase caused by a mobile phone: A methodological infrared camera study. Bioelectromagnetics 26:510-519

Straume A. 2002. An investigation of skin temperature changes by use of mobile phones, and measurements of ELF magnetic fields close to a mobile phone.

Norwegian University of Science and Technology, Trondheim, Norway. Cand. Scient. Thesis.

Tenforde TS. 1990. Biological interactions and human health effects of extremely-low-frequency magnetic fields. In Anderson Le, Stevens RG, Wilson BW. Eds. Extremely low frequency electromagnetic fields: the question of cancer. Columbia, OH: Battelle Press; 291- 315.

Valberg PA, Kaune WT, Wilson BW. 1995. Designing EMF experiments: what is required to chcracterize (exposure)? Bioelectromagnetics 16:396–406.

Veskovic M, Mattsson M-O, Hansson Mild, K. 2002: Dose and Exposure in Mobile Phone Research. – Arbetslivsrapport, 2002:4 National Institute for Working Life, Umeå, Sweden. ISSN 1400 -8211).

Vistnes AI, Ramberg GB, Bjørnevik LR, Tynes T, Haldorsen T. 1997. Exposure of children to residential magnetic fields in Norway: is proximity to power lines an adequate predictor of exposure? Bioelectromagnetics 18:47-57.

Walters TJ, Ryan KL, Nelson DA, Blick DW, Mason PA. 2004. Effects of blood flow on skin heating induced by millimeter wave irradiation in humans. Health Physics 86(2):115-120.

Wertheimer N, Leeper E. 1979. Electric wiring configuration and childhood cancer. Am J Epidemiol 109:273-384.

Weyandt TB, Schrader SM, Turner TW, Simon SD. 1996, Semen analysis of military personnel associated with military duty assignments. Reproductive Toxicology, 10(6): 521-528.

Wilén J, Johansson A, Nebojsa K, Lyskov E, Sandström M. 2006. Psychophysiological tests and provocation of subjects with mobile phone related symptoms. Bioelectromagnetics 27:204-214.

Wilén J, Sandström M, Hansson Mild K. 2003. Subjective Symptoms Among Mobile Phone Users-A Consequence of Absorption of Radiofrequency Fields? Bioelectromagnetics 24:152-159.

Paper I

ELF-magnetic flux densities measured in a city environment in summer and winter

Aksel Straume[1], Anders Johnsson[1*], Gunnhild Oftedal[2]

[1]Dept. of Physics, Norwegian University of Science and Technology (NTNU), N - 7491 Trondheim, Norway. [2]Sør-Trøndelag University College (HiST), N - 7004 Trondheim, Norway.

Abstract

Epidemiological studies have indicated a connection between extremely low frequency magnetic flux densities above 0.4 µT (time weighted average) and childhood leukaemia risks. This conclusion is based mainly on indoor exposure measurements. We therefore regarded it important to map outdoor magnetic flux densities in public areas in Trondheim, Norway. Because of seasonal power consumption variations, the fields were measured both during summer and winter. Magnetic flux density was mapped 1.0 m above the ground along 17 km of pavements downtown Trondheim. The spectrum was measured at some spots and the magnetic flux density emanated mainly from the power frequency of 50 Hz. In summer less than 4% of the streets showed values exceeding 0.4 µT, increasing to 29% and 34% on cold and on snowy winter days, respectively. The average levels were 0.13 µT (summer), 0.85 µT (winter, cold) and 0.90 µT (winter, snow), with the highest recorded value of 37 µT. High spot measurements were usually encountered above underground transformer substations. In winter also electric heating of pavements gave rise to relatively high flux densities. There was no indication that the ICNIRP basic restriction was exceeded. It would be of interest to map the flux density situation in other cities and towns with cold climate.

Keywords: outdoor exposure assessment, seasonal variations, spectral analysis, magnetic fields, ICNIRP guidelines

Submitted to Bioelectromagnetics.

Grant sponsors: The Research Council of Norway, Statnett, Norwegian Post and Telecommunication Authority, Telenor A/S, NetCom, NORTIB (all in Oslo, Norway), Torstein Erbos Gavefond (Trondheim, sponsor of G.O.) .

*Correspondence to: Anders Johnsson, Dept. of Physics, Norwegian University of Science and Technology (NTNU), N - 7491 TRONDHEIM, Norway
E-mail: anders.johnsson@ntnu.no. Telephone: +47 73 59 18 54. Fax: +47 73 59 77 10

INTRODUCTION

A causal connection between exposure to weak 50 Hz electromagnetic fields and health problems has been claimed and is an important epidemiological issue. It is mainly the incidence of childhood leukaemia and certain forms of cancer that constitute the concern. Some authors [e.g. Wertheimer and Leeper, 1979; Feychting and Ahlbom, 1993; Ahlbom et al., 2000] have supported such an effect, while others [e.g. Coleman and Beral, 1989; Rao et al., 2002] were unable to find statistically significant correlations. The different opinions have led to a public concern about possible health effects of electromagnetic fields and this is an impetus for precise measurements of the fields in different environments and under different conditions.

With this background, the levels of the electromagnetic fields in public areas are important to map but measurements are also of great interest in discussions of city planning, in for instance positioning high voltage transmission lines. However, in order to relate the levels to the exposure guidelines (as published e.g. by ICNIRP [1998]) or guidance to standards [ICNIRP 2003], detailed mapping of the fields in public areas is necessary, including the frequency content of the signals. The distribution net often involves transformer stations (transformer substations), which can be placed in public areas, under pavements and in houses. Other sources of electromagnetic fields; e.g. trams, electric buses, can contribute to a complicated electromagnetic field picture.

Exposure assessments of extremely low frequency electromagnetic fields in public areas have been performed [Lindgren et al., 2001; Paniagua et al., 2004]. The studies have focussed on city environments (Göteborg, Sweden, and the four cities in Extremadura, Spain), and results confirmed the presence of 50 Hz fields as well as higher frequencies. In large street areas (Göteborg) levels above 0.4 µT were recorded for approximately 30% of the measurement positions. This level is associated with increased risks of childhood leukaemia in epidemiological studies [Ahlbom et al., 2000]. Also in the cities in Extremadura the level exceeded 0.4 µT but for fewer positions than in Göteborg. None of these investigations exceeded the INCIRP reference values. The measured values were in general higher than those reported for residential areas [Mild et al., 1996] and for office environments [Sandström et al., 1993].

The electric distribution nets and patterns vary from country to country and certain features in the consumer patterns can also vary considerably. In Norway the need for increased house heating in winter time as compared to summer time has, traditionally, been solved in urban areas by the use of 50 Hz electric power. An additional electric power demand in winter comes from electric heating cables that are often used in street pavements to get rid of the snow and ice.

The ELF magnetic fields in a city environment in Norway have not been mapped earlier. The objective of the present study was to map and statistically analyse the ELF magnetic flux density distributions in city environments under three different conditions: in summer and under two different winter conditions. This will provide new information about the magnetic flux density levels for cities and towns with a relatively cold climate.

The normal temperature in Trondheim (63.42° N) in summer (June-August) is 13.5° C and in winter (December- March) -1.1°C (averaged for the period from 1961 to 1990; station number 68150 [Meteorologisk institutt, Oslo, Norway, 2007]).

MATERIALS & METHODS

A three-axis EMDEX II magnetic flux density meter (Enertech Consultants Cambell, CA, USA) was chosen for the magnetic field measurements. The true RMS values of the magnetic fields can be measured in two different frequency bands, *broadband* (40-800 Hz) and *harmonic* (100-800 Hz). The EMDEX II measures magnetic flux densities in the range from 0.01 to 300 μT. The typical accuracy is ± 3%, and the worst case is ± 10%, whereas the sampling intervals can be varied from 1.5 to 300 seconds.

For the magnetic field waveform measurements an EMDEX WaveCorder (Enertech Consultants Cambell, CA, USA) was used. The measurement range was 0.01 μT - 1.5 mT (accuracy 2%) from 10 Hz to 1 kHz and 0.01 μT - 0.7 mT (accuracy 2%) from 1 kHz to 3 kHz. The frequency bandwidth used was 10 Hz - 3 kHz.

Mapping of magnetic flux densities along pavements

The magnetic flux density was recorded under three different conditions: *summer*, *winter while snowing* (-5-0 °C) and *on cold winter days* (*not snowing,* T<-9 °C). All measurements were done during ordinary business hours between 10.00 and 16.00 h.

The magnetic fields were measured while walking along pavements with an EMDEX II held 1.0 m above the ground. Both broadband and harmonics were measured and the sampling interval was 3 s. In summer the walking speed used resulted in approximately one measurement every 3 m. A test was done at twice the original speed and gave the same result with respect to the flux density. Therefore a higher walking speed was used in winter resulting in one measurement approximately every 5 m. Each city block was measured continuously with marks set on the data file at each street corner of the block. The summer recordings consisted of 5583 measurements, the winter snow files of 3224 measurements and winter cold files of 3241 measurements. The distance covered along pavements under each condition was approximately 17 km. To plot the data, plots denoted 2-D plots, along the pavements, the Matlab interpolation command "*interp*" was used to generate magnetic flux density values between the measurement points and to place the measurement points with equal spacing along the pavement between the two corners as marked in the data file. The magnetic flux densities were interpolated linearly between the measurement points.

Spot measurements and spectral measurements

Under summer and winter conditions the magnetic flux density was recorded for 5-min periods with a sampling interval of 3 s using the EMDEX II at six random places within the city centre. The reference levels for exposure to magnetic fields (ICNIRP guidelines) decrease with increasing frequency in the range 1 – 800 Hz and therefore the harmonics could be important for the overall exposure. Therefore, we measured the frequency spectra at the same positions with the WaveCorder. According to the multiple frequency rule [ICNIRP 1998], the ratio between the observed amplitude of a component and the exposure limit (ICNIRP guidelines reference values) for the same frequency was calculated. The sum of the ratios for all components should not exceed 1.

At two locations, both close to the pavement inside shops, 24-h measurements were done with a sampling interval of 15 s by using the EMDEX II. This was done in the summer.

The height dependency of the flux density above two net-stations and above two pavements with activated heating cables was mapped in winter when snowing. Also the spectral densities at different distances above the ground were measured. The height dependency was estimated by using the "*power trendline*" function in Excel applied to the measurements from 0.25 m to 1.5 m.

RESULTS

Mapping of magnetic flux densities above pavements

Figure 1-3 show the magnetic flux densities downtown Trondheim in summer (15-20 °C), on winter days with falling snow (-5-0 °C) and on cold winter days (T<-9 °C) without falling snow.

To facilitate the visualization of the differences achieved under the different conditions, the ranges of the 2-D plot scales in the figures are identical and with 5.0 µT as the maximum level (all the values above 5.0 µT are dark red). In summer (Fig. 1.) the magnetic flux density was below 0.2 µT in most places. There are some spots with higher values, usually emanating from power transformer substations where the power is in most cases transformed from 11.4 kV to 400 V or 230 V and distributed to the surrounding buildings.

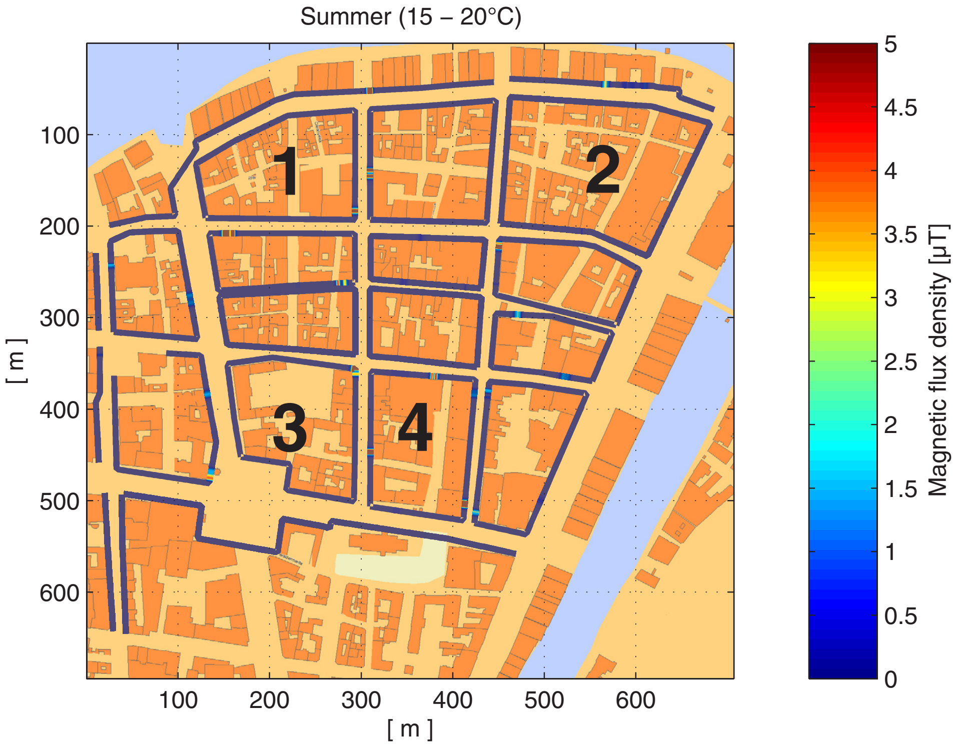

Fig. 1. 2-D plot of the interpolated magnetic flux density downtown Trondheim in summer (temperature 15-20 °C). Results from blocks 1-4 shown in Table 1.

When comparing the summer conditions and the winter conditions when it was snowing, (Fig. 2) the difference in magnetic flux density becomes evident: many of the pavements in winter had magnetic flux densities above 1.0 µT.

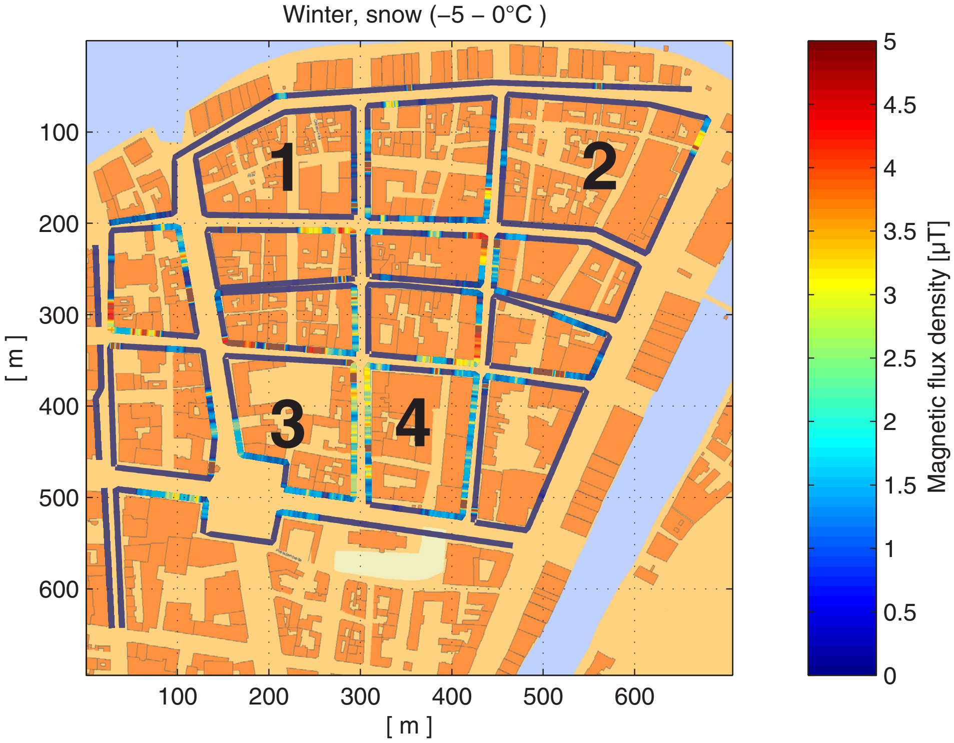

Fig. 2. 2-D plot of the interpolated magnetic flux density downtown Trondheim in winter when snowing (temperature -5 – 0 °C).

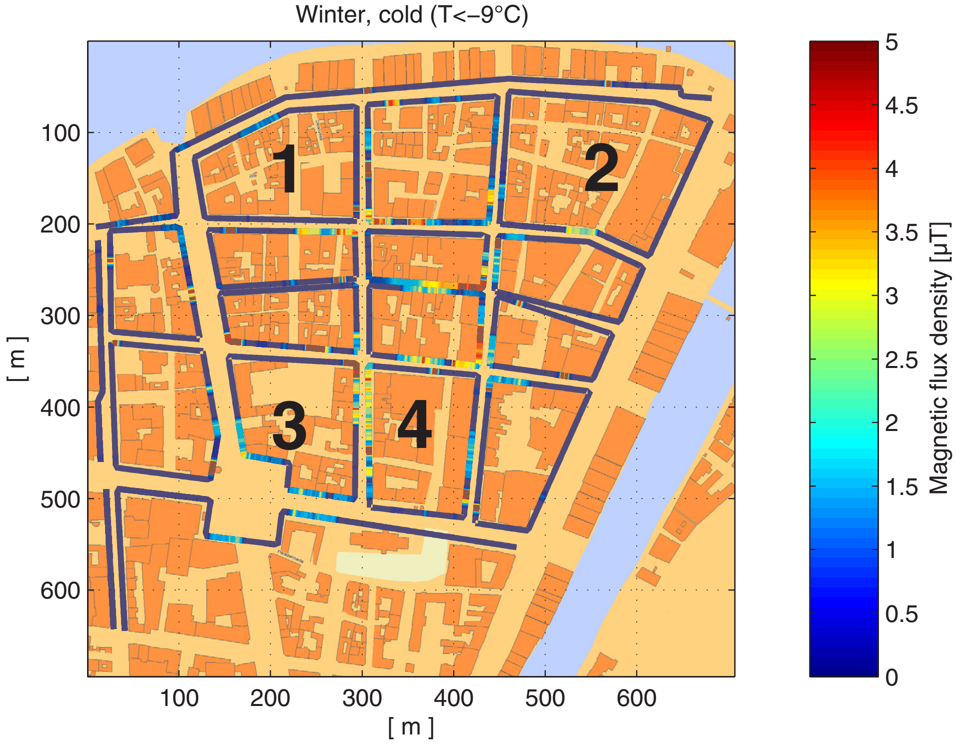

Fig. 3. 2-D plot of the interpolated magnetic flux density downtown Trondheim in winter when *not snowing* (temperature < -9 °C).

The maps of “winter snow” (Fig. 2) and “winter cold” (Fig. 3) are quite similar, but with lower levels during the cold days in some areas. Similar differences between the three conditions can be seen from Table 1, showing maximum magnetic flux densities, mean values and percentiles for four blocks (identified in Fig. 1) and for the mapped area as a whole.

TABLE 1. The maximum (MAX), mean, the 25 percentile (P25), the median, the 75 percentile (P75) and the 95 percentile (P95) of the magnetic flux densities for 4 blocks and for the whole area for the three different conditions (n denotes the sample size).

Block	Condition	MAX [µT]	MEAN [µT]	P25 [µT]	MEDIAN [µT]	P75 [µT]	P95 [µT]
1	Summer (n=367)	6.6	0.09	0.01	0.01	0.05	0.12
	Winter snow (n=207)	13	0.17	0.01	0.03	0.09	0.49
	Winter cold (n=199)	14	0.30	0.03	0.06	0.17	1.4
2	Summer (n=521)	0.48	0.04	0.01	0.03	0.05	0.10
	Winter snow (n=271)	5.5	0.26	0.03	0.05	0.10	1.8
	Winter cold (n=255)	3.4	0.23	0.03	0.04	0.09	1.7
3	Summer (n=334)	14	0.15	0.01	0.01	0.03	0.12
	Winter snow (n=227)	18	1.4	0.03	1.3	2.2	3.1
	Winter cold (n=255)	35	1.4	0.03	0.08	1.9	5.0
4	Summer (n=342)	15	0.41	0.03	0.06	0.21	1.4
	Winter snow (n=225)	21	2.1	1.2	1.9	2.6	3.5
	Winter cold (n=235)	37	1.8	0.11	0.56	2.5	3.9
Whole AREA	Summer (n=5583)	16	0.13	0.01	0.03	0.06	0.23
	Winter snow (n=3224)	29	0.90	0.03	0.08	1.4	3.5
	Winter cold (n=3241)	37	0.85	0.03	0.07	0.76	3.5

The percentage of measurement points with flux densities exceeding a given value is given in Fig. 4. Specifically, the percentage of data above 0.4 µT is 3.6% in summer, and about 29 and 34% on cold and on snowy winter days, respectively.

Previous articles [Lindgren et al., 2001; Paniagua et al., 2004] have used the definitions of “low fields”: < 0.2 µT, “medium fields”: 0,2 - 1.0 µT and “high field”: > 1.0 µT. In summer, 94% of the magnetic flux densities values were below 0.20 µT (derived from Fig. 4). In winter about 23 and 30 % (cold days and snowy days, respectively) of the measurements exceeded 1.0 µT. Also the percentages of values falling in the medium field range were higher under the winter conditions than in the summer. Many areas categorized as “low fields” in the summer were “high fields” in the winter. The percentage of values between 0.2 - 1.0 µT increased from 4% in summer to 8% on snowy days and to 10% on cold days.

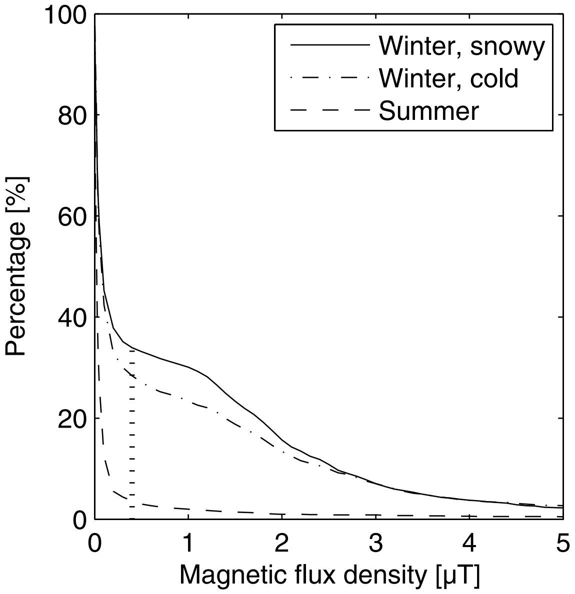

Fig. 4. The percentage of measurements along pavements exceeding the magnetic field densities at the horizontal axis. The value of 0.4 µT is indicated.

Spot measurements and spectral measurements

For all of the 5-min measurement periods in the summer the maximum magnetic field was 0.15 µT. The difference between the highest and the lowest values during any of the 5-min periods was less than 0.03 µT. In winter the maximum value of four of the six spot measurements exceeded 0.19 µT. These measurements (spots denoted A, B, C and D) are exemplified in Fig. 5.

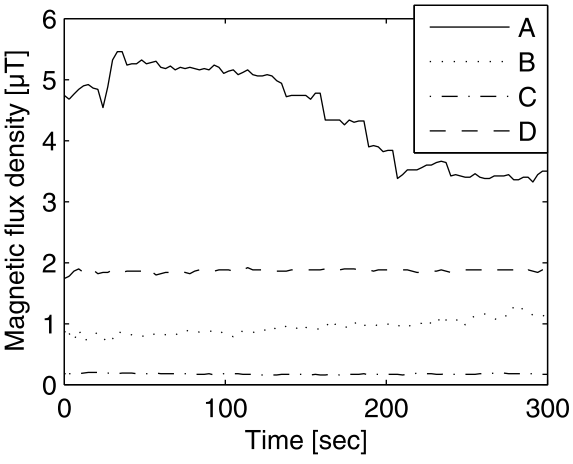

Fig. 5: Temporal variations of the magnetic flux densities at four different positions downtown Trondheim in winter.

Using the 24-hour measurements (summer) the mean value for a 2-h period during business hours was 1.9 µT and the mean value for 2 h during the night was 0.88 µT. The standard deviation in both cases was 0.13 µT. The lowest and the highest values during business hours were 1.6 µT and 2.4 µT, respectively. During the night the corresponding values were 0.63 µT and 1.2 µT.

The waveform and the frequency spectrum for the three randomly chosen sites are shown in Fig. 6 and 7 respectively. The amplitudes of the three directional components differed at the three measurement positions. In position A the waveforms of the magnetic flux densities in the x-, y-, and z directions were approximately sinusoidal, which is indicated by low values of the harmonics (150 Hz amplitudes are less than 2.5% of the 50 Hz amplitudes). The deviations from sinusoidal waveform were small also for the z-direction in position B and the y- and z-directions in position C (150 Hz amplitudes less than 3 % of the 50 Hz amplitudes). The most obvious deviation from a sinusoidal form is seen for the x-direction in position B where the curve form approached a trapeze. In this case the amplitude of the harmonics in the x-direction was 22% of the basic frequency. We estimated the exposure in a worst case situation by using the highest magnetic flux density measured when walking along the pavements (37 μT) and the amplitude spectra with the highest content of harmonic components, including harmonics up to 3.0 kHz (position B, X-axis Fig.7). The ratio for the ICNIRP reference level calculated according to the multiple frequency rule [ICNIRP 1998] was 1.1, i.e. slightly exceeding the upper limit of 1.0.

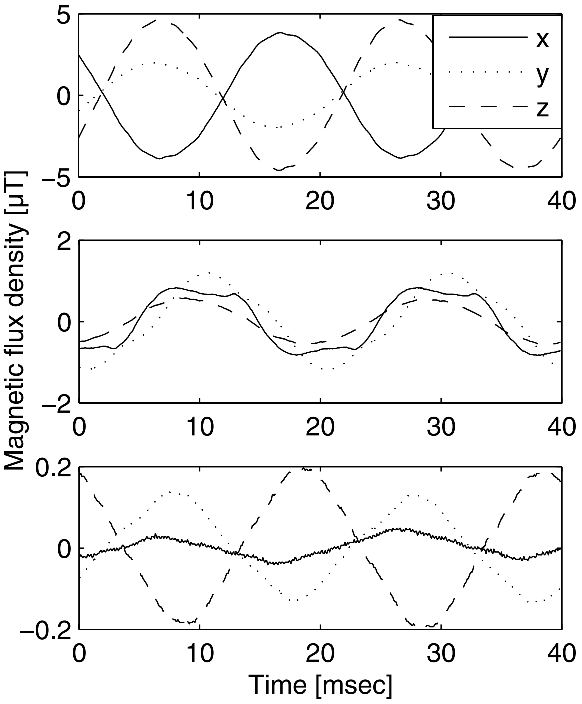

Fig. 6. The waveform of the magnetic flux density at positions A, B and C (from top to bottom).

The height dependency of the flux density above two ground transformer substations and above pavements with heating cables are shown in Fig. 8. Close to the ground above one of the transformer substations the magnetic flux density (1.1×10^2 μT) exceeded the ICNIRP reference level. The magnetic flux density decreased rapidly with distance to the ground (distance dependence from $1/d^{0.6}$ to $1/d^{1.0}$ calculated from 0.25 m to 1.5 m). The spectral distribution at all the distances above the pavements showed that the harmonics were below 2% of the basic frequency. Therefore, it is sufficient to include only the basic frequency to calculate the exposure according to ICNIRP reference levels.

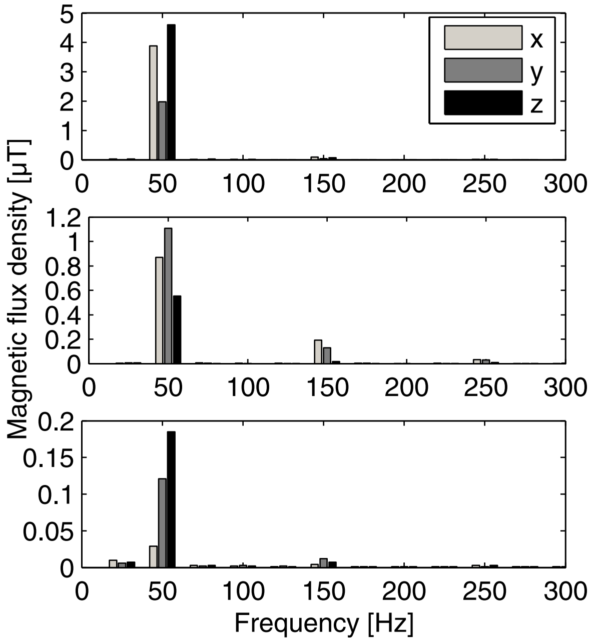

Fig. 7. The frequency spectrum at position A, B and C (from top to bottom).The three orthogonal directional components are shown as X, Y, Z.

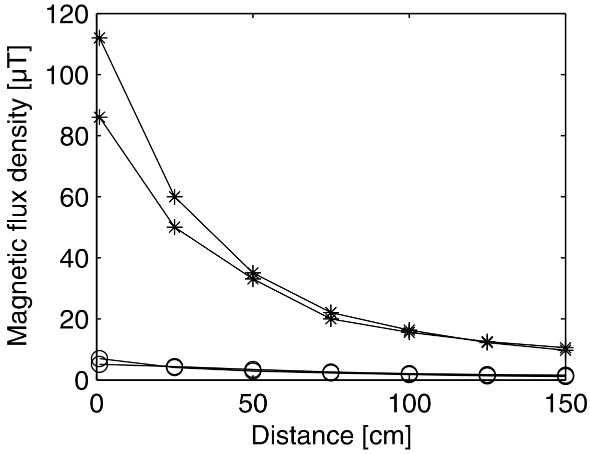

Fig. 8. Magnetic flux density from two transformer substations (*) and above two positions with heating cables under the pavements (o) as a function of distance above the ground.

DISCUSSION

In the present study we found large differences between the summer and the winter measurements of the magnetic flux densities in Trondheim, both with respect to mean values and the amount of “high” magnetic flux densities. In general, these differences can be explained by the use of electric energy for indoor heating during the cold season. On *snowy* winter days electric heating is also used to melt snow and ice on some pavements and walking streets. This is reflected by higher flux densities in certain areas on snowy days than on even colder winter days with no falling snow. For city block 4 (see Fig. 2.) with heating cables around almost the entire block, the 25th percentile rose from 0.03 µT in summer to 0.11 µT on a cold winter day and further to 1.2 µT on a day with falling snow.

In the summer the mean value of the magnetic flux densities recorded in the centre of Trondheim was 0.13 µT while 95 % of the measurements were below 0.23 µT. In the Swedish study cited above [Lindgren et al., 2001], the arithmetic average was 0.34 µT and the 95 percentile 1.08 µT. When comparing the percentage of data exceeding 0.4 µT, the value assumed to be associated with increased risk for childhood leukaemia [Ahlbom et al., 2000], the Swedish result (about 30 % of measurements) is similar to the percentages obtained for winter conditions in Trondheim, while in summer less than 4% of the data exceeded this value. In Trondheim the distribution of the magnetic flux density measurements do not decline in the same manner in summer and winter. In winter there are few measurements between 0.4 µT and 1.0 µT especially when snowing. The percentage above 0.4 µT in winter is similar to that in Sweden despite the fact that the Swedish mapping was done in September and the first half of October [Yngve Hamnerius, personal communication] and the air temperatures were most likely more similar to those in summer than in winter in Trondheim. However, most of the data are in fact above 1.0 µT in our winter measurements and will not necessarily produce the same biological effects. Lindgren et al. [2001] explained the high values with stray currents, i.e. return currents flowing via the local protective earth cables and metallic objects back to the transformers rather than flowing back via the neutral conductors. The stray currents in Göteborg were demonstrated by rapid fluctuations in the magnetic flux densities. They were not present in the spot measurements in Trondheim. In Norway different power supply systems are often used that give rise to significantly less stray currents than the system used in Sweden. This as well as the use of buried cables with small distances between the phases explains the low magnetic flux densities in almost the whole area in summer. In Spain most of the distribution lines are airborne and recordings in cities in Extremadura indicate stray currents [Paniagua et al., 2004]. Approximately 10% of the Spanish data exceeded 0.4 µT, the mean value for all cities was 0.20 µT and the 95 percentile 0.76 µT, i.e. exceeding the corresponding values from Trondheim (summer). In Spain the fields were measured both in summer and winter [Jesús M. Paniagua, personal communication], but the results from both seasons are combined and there is no information about the seasonal variation.

Although the mean magnetic flux density was lower in Trondheim in summer than in the Spanish and Swedish cities, the maximum recorded value in summer (16 µT) was higher than in Göteborg (9.70 µT) and Cáceres (7.04 µT). The high values in Trondheim were recorded above transformer substations.

In several places downtown Trondheim the magnetic flux densities also exceeded the highest values measured in apartments above transformer stations in Hungary (26 µT; [Szabó et al., 2007]). The mean values in winter (0.90 µT (snowy) and 0.85 µT (cold days)) are considerably higher than those reported for homes in Sweden (0.040 µT) and Norway (0.013µT) [Mild et al., 1996]. The arithmetic mean values downtown Trondheim in winter are even higher than in houses closer than 50 m to power lines [Vistnes et al., 1997]. The highest magnetic field recorded when a child passed under a power line has been reported to be less than 20 µT [Fig 1.Vistnes et al., 1997], which can be compared with the highest recorded magnetic field in winter in Trondheim, i.e. 37 µT.

All the measurements done when walking along pavements in the present study were taken 1.0 m above the ground. For children walking or sitting in strollers, the relevant magnetic flux densities will be higher than the values given. Since the magnetic field in areas with activated heating cables exceeded 1.0 µT at 1.0 m above ground level, the whole body exposure for small children will be classified as "high field". One reason why the magnetic flux density is fairly high in these areas could be the use of heating cable with "single wire" configuration. Some years ago this type of heating cables was also used for indoor purposes but they are now substituted with two conductor cables to reduce the magnetic fields. The use of two conductor cable for new installations in pavements would reduce the magnetic flux densities significantly.

We would like to emphasize that although the ICNIRP reference level was slightly exceeded in one measurement at ground level in winter, there is no reason to assume that the basic restrictions for the whole body would be exceeded since the flux density decreased rapidly with increasing distance above the ground. Spectral measurements above two transformer substations also showed that the amount of harmonics was very low and the calculated ratio of 1.1 is an overestimation. Furthermore, the peak spot was restricted to a very small area and the exposure would therefore normally be of short duration, as people are walking by. Our calculations are worst case calculations when comparing the exposure with the ICNIRP reference levels. The exposure in urban street environments should be considered when discussing magnetic flux density exposure over time. This is particularly true if short duration high peak magnetic fields will turn out to be of importance. Therefore, further counter measures against magnetic fields around transformer substations are worth discussing.

When discussing the risk, the exposure duration has to be considered. On warm summer days people spend more time out in the streets, but also in the winter season people are walking around in Norwegian cities, and in particular young people may spend time outdoors in the city or in town centres. Therefore, it would be of interest to get a general overview and mapping of the flux density situation in cities and towns in cold climate regions, with an even colder climate than Trondheim. A collaborative international effort would here be relevant e.g. in the artic regions.

CONCLUSION

The magnetic field exposure downtown Trondheim depends strongly on the season. In summer the magnetic fields are very low except for a few spots above underground transformer substations. In general the exposure is considerably higher in winter than in summer due to higher power consumption. This is also reflected in the peak magnetic flux densities above transformer substations in winter. The use of electric heating cables in the ground (activated especially on snowy winter days) also strongly contributes to higher magnetic flux densities in winter. Although the ICNIRP exposure reference level is violated at ground level, there is no reason to believe that the basic restrictions are exceeded.

ACKNOWLEDGMENTS

The authors would like to thank Thomas Lauf (Max-Planck-Institute for extraterrestrial physics, Garching, Germany) for his help with executing the Matlab programming for visualization of the magnetic flux densities.

REFERENCES

Ahlbom A, Day N, Feychting M, Roman E, Skinner J, Dockerty J, Linet M, McBride M, Michaelis J, Olsen JH, Tynes T, Verkasalo PK. 2000. Pooled analysis of magnetic fields and childhood leukaemia. British J of Cancer, 83 (5):692-698.

Coleman M, Beral VA. 1989. A review of epidemiological studies on health effects of living near or working with electricity generation and transmission equipment. Int J Epidemiol Rev 11:599-678.

Feychting M, Ahlbom A.1993. Magnetic-fields and cancer in children residing near Swedish high-voltage power lines. Am.J Epidemiol 138:467-481.

ICNIRP. 1998. International commission on Non-Ionizing Radiation Protection. Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). Health Phys. 74:494-522.

ICNIRP. 2003. International commission on Non-Ionizing Radiation Protection. Guidance on determining compliance of exposure to pulsed and complex non-sinusoidal waveforms below 100 kHz with ICNIRP guidelines. Health Phys. 84:383-387.

Lindgren M, Gustavsson M, Hamnerius Y, Galt S. 2001. ELF magnetic fields in a city environment. Bioelectromagnetics 22:87-90.

Meteorologisk institutt. [12th of Feb. 2007]. Normal temperatures in Trondheim in the period from 1961 to1990. Available from: http://met.no/observasjoner/sortrondelag/normaler_for_kommune_1601.html?kommuner [last updated 2nd of Jan 2007].

Mild KH, Sanström M, Johnsson A. 1996. Measured 50 Hz electric and magnetic fields in Swedish and Norwegian residental buildings. IEEE Transactions on instrumentation and measurement. 45(3):710-714.

Paniagua JM, Jimenez A, Rufo M, Antolin A. 2004. Exposure assessment of ELF magnetic fields in urban environments in Extremadura (Spain). Bioelectromagnetics 25:58-62.

Rao RR, Halper J, Kisaalita WS. 2002. Effects of 60 Hz electromagnetic field exposure on APP695 transcription levels in differentiating human nevroblastoma cells. Bioelectrochemistry 57(1):9-15.

Sandstöm M, Mild KH, Stenberg B, Wall S. 1993. A survey of electric and magnetic-fields among VDT operators in offices. IEEE Transactions on electromagnetic compatibility 35:394-397.

Szabó J, Jánossy G, Thuróczy G. 2007. Survey of residential 50 Hz EMF exposure from transformer stations. Bioelectromagnetics 28:48-52.

Vistnes AI, Ramberg GB, Bjørnevik LR, Tynes T, Haldorsen T. 1997. Exposure of children to residential magnetic fields in Norway: is proximity to power lines an adequate predictor of exposure? Bioelectromagnetics 18:47-57.

Wertheimer N, Leeper E. 1979. Electric wiring configuration and childhood cancer. Am J Epidemiol 109:273-384.

Paper II

Frequency spectra from current- vs. magnetic flux density measurements for mobile phones and other electrical appliances

Aksel Straume[1]*, Anders Johnsson[1], Gunnhild Oftedal[2], Jonna Wilén[3]

[1]Dept. of Physics, Norwegian University of Science and Technology (NTNU), 7491 Trondheim, Norway. [2]Sør-Trøndelag University College (HiST), 7004 Trondheim, Norway. [3]National Institute for Working Life, Umeå, Sweden, Department of Radiation Sciences, Umeå University, Sweden.

Abstract

The frequency spectra of electromagnetic fields have to be determined to evaluate the human exposure in accordance to ICNIRP guidelines. In the literature, comparisons with magnetic field guidelines have been performed by using the frequency distribution of the current drawn from the battery. In the present study we compared the frequency spectrum in the range 217 Hz to 2.4 kHz of the magnetic flux density measured near the surface of a mobile phone with the frequency spectrum of the supply current. By using the multiple frequency rule, recommended in the ICNIRP guidelines, we estimated the magnetic field exposure in the two cases. Similar measurements and estimations were done for an electric drill, a hair dryer and a fluorescence desk lamp. All the devices have basic frequency 50 Hz and the frequency spectra were evaluated up to 550 Hz. We also mapped the magnetic field in 3D around three mobile phones. The frequency distributions obtained from the two measurement methods are not equal. The frequency content of the current leads to an overestimation of the magnetic field exposure with a factor up to 2.2 for the mobile phone. For the drill, the hair dryer and the fluorescence lamp the supply current signal underestimated the exposure with a factor up to 2.3. In conclusion, an accurate exposure evaluation requires the magnetic flux density spectrum of the device to be measured directly. There was no indication that the devices studied would exceed the reference levels at the working distances normally used.

Key words: electromagnetic fields, induced currents, safety standards.

Accepted to Health Physics Journal.

Grant sponsors: The Research Council of Norway, Statnett, Norwegian Post and Telecommunication Authority, Telenor A/S, NetCom, NORTIB.

*Correspondence to: Aksel Straume, Dept. of Physics, Norwegian University of Science and Technology (NTNU), 7491 TRONDHEIM, Norway
E-mail: aksel.straume@ntnu.no. Telephone: +47 73 59 18 62. Fax: +47 73 59 77 10

INTRODUCTION

The International Commission on Non-Ionizing Radiation Protection – ICNIRP – provides guidelines concerning human exposure to electromagnetic fields (ICNIRP 1998). The guidelines, comprising ‘basic restrictions’ as well as ‘reference levels’, especially consider the *frequency* content of the fields to which the human body is exposed. Pulsed fields and fields with non-sinusoidal waveforms contain high frequency components and the treatment of such exposure signals is not straightforward (Jokela 1997). On the other hand they are important since they induce comparatively larger currents in the body.

The exposure to complex signals is handled according to the *multiple frequency rule* (ICNIRP 1998) or by the so-called *weighted peak* approach (Jokela 2000 and ICNIRP 2003). Somewhat simplified the multiple frequency rule states that the sum of the ratios between the field amplitude at a certain frequency and the corresponding limit at that frequency should not exceed unity when summed over all frequencies encountered.

In the present paper we concentrate on measurements of the extremely low frequency (ELF) magnetic flux density spectra. We demonstrate that there are differences in the waveform and frequency distribution as determined from the supply current and from the device itself. We use the multiple frequency rule to demonstrate that such differences influence comparisons with established basic restrictions and guidelines. Corresponding calculations could have been performed for the weighted peak approach (ICNIRP 2003) but was superfluous for our purposes. In both methods it is of importance to measure the true signal and/or the frequency spectrum of the signal. Also for strict comparison with ICNIRP guidelines, spatially averages over the head and trunk should be calculated.

The GSM 900 mobile phone system transmits one RF-pulse with 0.577 ms duration every 4.6 ms, which gives rise to a pulse repetition frequency of 217 Hz. In the literature the ELF electromagnetic fields around mobile phones have only to a certain extent been measured and discussed (Andersen and Pedersen 1997, Pedersen 1997, Linde and Hansson Mild 1997, Jokela et al. 2004, Ilvonen et al. 2005). Comparisons with guidelines, using the multiple frequency rule have only been approached by Jokela et al. (2004) and Ilvonen et al. (2005). Estimates were based on considerations of the *currents* drawn by the devices (see below). However, spectral measurements of the current drawn by electric devices might not reflect the spectra of magnetic flux density signals generated in or around the devices.

In this work we have focused on mobile phones and compared two methods of frequency analyses; the frequency spectrum of the current drawn by the devices and of the actual magnetic flux density close to the device. To generalize to other electrical appliances we have also compared this for an electrical drill, hair dryer and a fluorescence desk lamp.

We have also mapped the magnetic flux densities in three directions around three mobile phone devices since the previously reported studies have not taken the spatial variation and direction of the magnetic flux densities into account. The complicated frequency spectrum as well as the detailed gradients of the flux density close to the phones makes relevant measurements and flux density mapping difficult and time consuming.

MATERIAL AND METHODS

Sources investigated

Detailed measurements were carried out on a GSM 900 test phone with a helix antenna on top of the mobile phone chassis (denoted mobile phone I) with adjustable frequency and power level. A 6V NiMH battery was used with the device. Also two ordinary GSM 900 phones with built in antennas (denoted mobile phone II and III, respectively) with 3.7 V Li-ion batteries was used. A base station (Rohde & Scwartz CTS –30) controlled these phones. During all measurements the frequency of the RF signal was 902.4 MHz and the highest output power level (nominally 33 dBm, corresponding to 2.0 W (peak value)) was chosen. The phones were transmitting and the battery saving function mode (DTx) mode was off. The phone batteries were always charged to saturation before a measurement session started.

A comparison of the frequency spectrum of the current drawn by the device with the magnetic flux density close to the device was also carried out for a drilling machine (AEG SB 2E-680), a hair dryer (ARIK HT-1800 D; used with two fan levels and three heat levels) and a fluorescence desk lamp with an internal transformer.

Measurements of the frequency spectra of the magnetic flux density

Chauvin Arnoux C.A 42 LF field meter (Chauvin Arnoux, Paris, France) was used with the magnetic probe MF 400 for recording of the wave shape of the magnetic flux density and for the Fast Fourier Transform (FFT) analysis. The instrument covers the frequency range from DC to 400 kHz (working range: 10 nT-20 mT). There was no interference with radio frequency fields and the measurement probe.

The field meter was also used to determine the spectral content of the *magnetic flux density* near the middle of one of the 1.0 m extension cables between the battery and the mobile test phone. The same equipments and procedure were used to determine the magnetic flux density spectral components 0 cm from three specified positions of the mobile test phone. (The radius of the probe was 5.6 cm and the surface of the probe was in contact with the device investigated). These positions were above the microphone, the middle of the mobile phone and above the loudspeaker. The X-, Y- and Z-components (X parallel to bottom and top of the mobile phone, Y-parallel to the sides of the mobile phone and Z perpendicular to the surface of the mobile phone) of the flux density were investigated both with respect to the waveform and the FFT spectral distribution. The magnetic flux densities were evaluated from 217 Hz to 2.4 kHz. Measurements were first taken with the mobile phone still coupled to the battery via the extension cables. Then FFT measurements were done with the battery inside the mobile phone (normal position). For the FFT analyses at least 4 periods were recorded.

For the drill the probe surface was positioned at distances of 0, 5.0 and 10 cm from the surface of the drill. The speed of the drill was locked at the same setting for all the measurements. For the hair dryer and the fluorescence desk lamp the measurement position was as close as possible to the sources. The magnetic flux densities were evaluated from 50 Hz up to 550 Hz. The background magnetic flux density measured in the laboratory was less than 0.02 μT and could be disregarded compared to the magnetic flux densities around the electrical devices.

Measurements of the frequency spectra from the current probe

A Fluke 80I-1000s AC current probe (Fluke Industrial B.V., Almelo, The Netherlands) was used to measure AC-currents continuously (working range: 100 mA - 1000 A rms). The frequency range was 5 Hz - 100 kHz and the specified uncertainty 3% of the read off value in the 0-20 A range.

In order to derive the frequency content of the *current* drawn from the battery, the battery was disconnected and two extension wires were used to connect the battery to the phone. The current probe was held near the middle of a 1m wire extension and connected to the Fluke 199 scopemeter (Fluke Industrial B.V., Almelo, The Netherlands). The data was later frequency analyzed with the computer program FlukeView v.3.0 by which the frequency components were calculated with 4 periods of the signal. There was no difference between using 2, 4 and 8 periods.

When the wave shapes of the current to the other electrical devices (see above) were recorded, an extension cord with two separated wires between the device and the plug was used.

The frequency spectrum (FFT analysis) was derived by using the Fluke 80I-100s AC current probe connected to the Fluke 199 scopemeter. These measurements were compared with the spectrum derived when using the Chauvin Arnoux C.A 42 LF field meter. Both measurements were done at the same position of the wire and the difference between the frequency components when comparing the two methods did not exceed 6% for any components.

Measurements of magnetic flux densities around the mobile phones

A three axes EMDEX II magnetic flux density meter (Enertech Consultants Cambell, CA, USA) was chosen for the magnetic flux density measurements. This is an instrument which is not affected by radio frequency fields. The RMS values of the magnetic flux densities in the X, Y and Z directions are logged via three orthogonal coils. The magnetic flux densities were measured with the built in *broadband* filter (40-800 Hz). The signal picked up by a coil is processed through a “true root mean square” (TRMS) circuit before it is stored in the instrument. The EMDEX II measures magnetic flux densities in the range from 0.01 to 300 T. The typical accuracy is ± 3%, and the worst case is ± 10%.

The three magnetic flux density components of the mobile phones were measured one by one. Only one coil (“Y-coil”) of the EMDEX II was used to measure the flux density components *in parallel to each surface* of the mobile phones. The flux density component *perpendicular to a surface* was mapped by using another coil (the “X-coil”) of the instrument. For each position the resultant magnetic flux density was calculated as the root of square sum of the three components.

During the measurements the EMDEX II instrument was fixed and the mobile phone was moved in a square grid pattern (resolution 1 mm) and with a distance of 1 cm between the measurement points.

The flux densities were recorded at all sides of phone I: a 9x19 cm area for the front and back sides of the phone, a 7x19 cm area for the sides and, finally, an area of 5x8 cm for the bottom and top sides. Plexiglass holders supported the mobile phone when the sides and the bottom of the phone were measured (as expected, these holders did not influence the magnetic flux density). For phones II and III only flux densities at the front and back sides were measured with a 9x16 cm area.

The magnetic flux densities from the mobile phone (I) were determined at various distances (2.4, 3.4 and 5.0 cm) from the surface of the phone case to the centre of pick up coil. Only 2.4 cm was used for mobile phones II and III. The distance from the middle of the coil to the surface of the mobile phone was 2.4 cm which was the minimum distance that could be recorded due to the design of the instrument.

At each position about 8-12 measurements were taken with a sampling interval of 1.5 s. The last measurement in a certain position was marked with the event button of the EMDEX II before the phone was moved to the next position. To check that the flux density and thus the battery power were maintained throughout the procedure, the flux density at one position in the middle of the phone surface was measured again at the end of a session.

During the measurements on the drill, the hair dryer and the fluorescence desk lamp, the EMDEX II was used in a survey mode with all the coils activated to get the broadband resultant magnetic flux density as close as possible to the devices. The meter was in some cases in contact with the device. The highest measured magnetic flux density was used in the calculation to see if guidelines were exceeded.

Exposure calculation according to the multiple frequency rule

The magnetic flux density measured with the EMDEX II is a broadband value that (in general) contains contributions from different frequencies f_0, f_1,..f_n of the signal within the bandwidth of the instrument. Since the magnetic flux density consists of discrete frequencies, the measured flux density will be

$$B_{measured}^2 = \sum_{i=0}^{n} B_{emdex_i}^2 \qquad (1)$$

where B_{emdex_i} is the flux density of the i'th signal component of a spectrum with n components .

The frequency response of the EMDEX II was measured and used to calibrate the frequency components of the magnetic flux density. The signal value B_i of frequency i is related to B_{emdex_i} by the corresponding sensitivity factor, s_i, of the instrument.

$$B_i = \frac{B_{emdex_i}}{s_i} \qquad (2)$$

The amplitude of the basic frequency, f_0, derived from the Fast Fourier Transform (FFT) of the magnetic flux density spectrum or the current measurement, FFT(f_0), is set to 1 (or 100%). Then the signal value of the i'th frequency f_i will be related to the i'th component of the FFT, denoted $FFT(f_i)$ by

$$B_i = B_0 \cdot FFT(f_i) \qquad (3)$$

We get from (2) and (3)

$$B_{emdex_i} = B_0 \cdot s_i \cdot FFT(f_1) \qquad (4)$$

Combining this with (1) one gets

$$B_{measured}^2 = B_0^2 \cdot \sum_{i=0}^{n} \left[s_i^2 \cdot FFT^2(f_i) \right]$$

And thus

$$B_0 = \frac{B_{measured}}{\sqrt{(s_0^2 + \sum_{i=1}^{n} \left[s_i^2 \cdot FFT^2(f_i) \right]}}$$

The components B_i are, finally, calculated from eq. (3).

The multiple frequency rule (ICNIRP 1998) now implies that the different ratios (Denoted R further on) $B_i/B_i^{Guideline,}$ where $B_i^{Guideline}$ is the limit given for the frequency of component *i*, are summed up in the proper frequency range and the sum R should be ≤ 1.

$$R = \sum_{i=0}^{n} \frac{B_i}{B_i^{Guideline}} \leq 1 \qquad (5)$$

For all the calculations in this paper the limits for the general public has been used.

EXPERIMENTAL RESULTS

Mobile phone measurements – spectral distributions.

The spectral components of the current in the wire from the battery to mobile phone I and the magnetic flux densities above the wire and on three positions on the front surface of the phone are presented in Fig. 1 (battery in place). The components have been normalized to 100% for the basic frequency 217 Hz. The two measurement techniques (current probe and magnetic field probe) applied on the wire connecting the mobile phone to the externally placed battery resulted in quite similar results except for three of the harmonics.

Fig. 2 shows the magnetic flux densities as a function of time. The measurements on the phone surface were done with the battery in place. The waveform of the magnetic flux density above the wire deviated from those measured above the mobile phone. When the magnetic flux was measured above the mobile phone connected to the battery via extension wires, the waveform above the mobile phone still deviated from that above the wire (not shown), but the difference was less than with the battery in place (Fig. 2). This was also revealed by the frequency spectra showing lower magnitudes of the highest frequencies when the battery was in the normal place (Fig. 1) compared to the situation with externally placed battery (not shown).

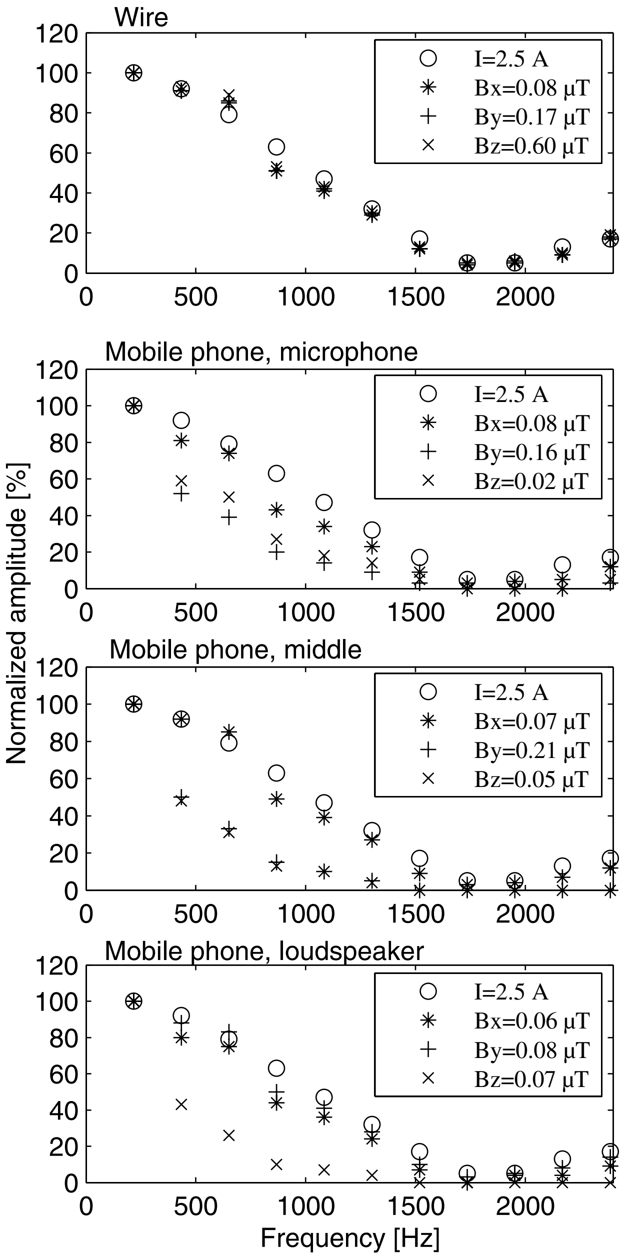

Fig. 1. Spectral distribution (FFT) of the current (*I*) in the wire connecting mobile phone I to an externally placed battery and the magnetic flux density (B) above the wire connected to the mobile phone and near three positions on the front surface of mobile phone (with the battery in place). Amplitudes of the frequency components are shown relative to the amplitude of the basic frequency 217 Hz. Flux densities relative to the wire: X parallel to the wire, Y and Z perpendicular to the wire. Flux directions relative to the mobile phone: X parallel to the bottom and top, Y parallel to the lateral sides, Z perpendicular to the surface.

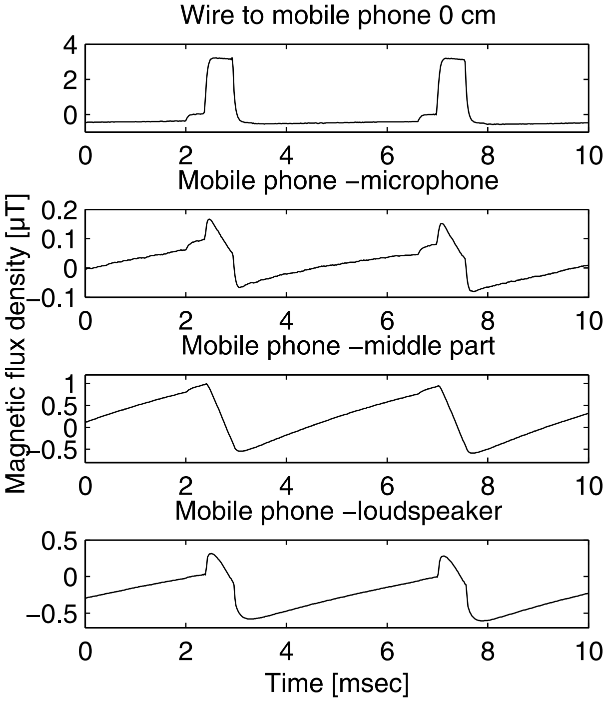

Fig. 2. The waveform of the magnetic flux density near the wire connecting mobile phone I to the externally placed battery (upper curve) and near three positions on the front surface of mobile phone I with the battery in the normal place (lowermost three curves).

Mobile phone measurements – magnetic flux densities

Fig. 3 shows contour plots of magnetic flux densities measured near mobile phone I. The components and the resultant magnetic flux density (B_R) are presented for the front and back side. As shown in the Fig. 3 the magnetic flux density distributions are complex and the variation is large, both with respect to the spatial variation and the direction (Table 1 for phone I). The corresponding components recorded near the front and back side of the same phone however, have the same features. The main characteristics of the contour plots for the different mobile phones are similar when comparing the same magnetic flux density components.

Table 1. Magnetic flux densities 2.4 cm from the surface of mobile phones I, II and III.

	Phone	Average magnetic field [μT]								Highest magnetic field [μT]			
		B_x		B_y		B_z		B_R		B_x	B_y	B_z	B_R
Front side	I	0.21	0.14	0.16	0.11	0.27	0.24	0.42	0.27	0.60	0.43	1.01	1.04
	II	0.24	0.22	0.18	0.15	0.22	0.22	0.42	0.27	0.83	0.64	0.99	1.11
	III	0.08	0.08	0.14	0.15	0.14	0.17	0.24	0.21	0.36	0.64	0.90	0.91
Back side	I	0.34	0.26	0.20	0.13	0.28	0.33	0.56	0.34	0.88	0.59	1.29	1.33
	II	0.24	0.25	0.38	0.41	0.35	0.49	0.65	0.62	0.98	1.92	2.68	2.72
	III	0.09	0.08	0.08	0.05	0.12	0.09	0.20	0.10	0.34	0.25	0.41	0.44

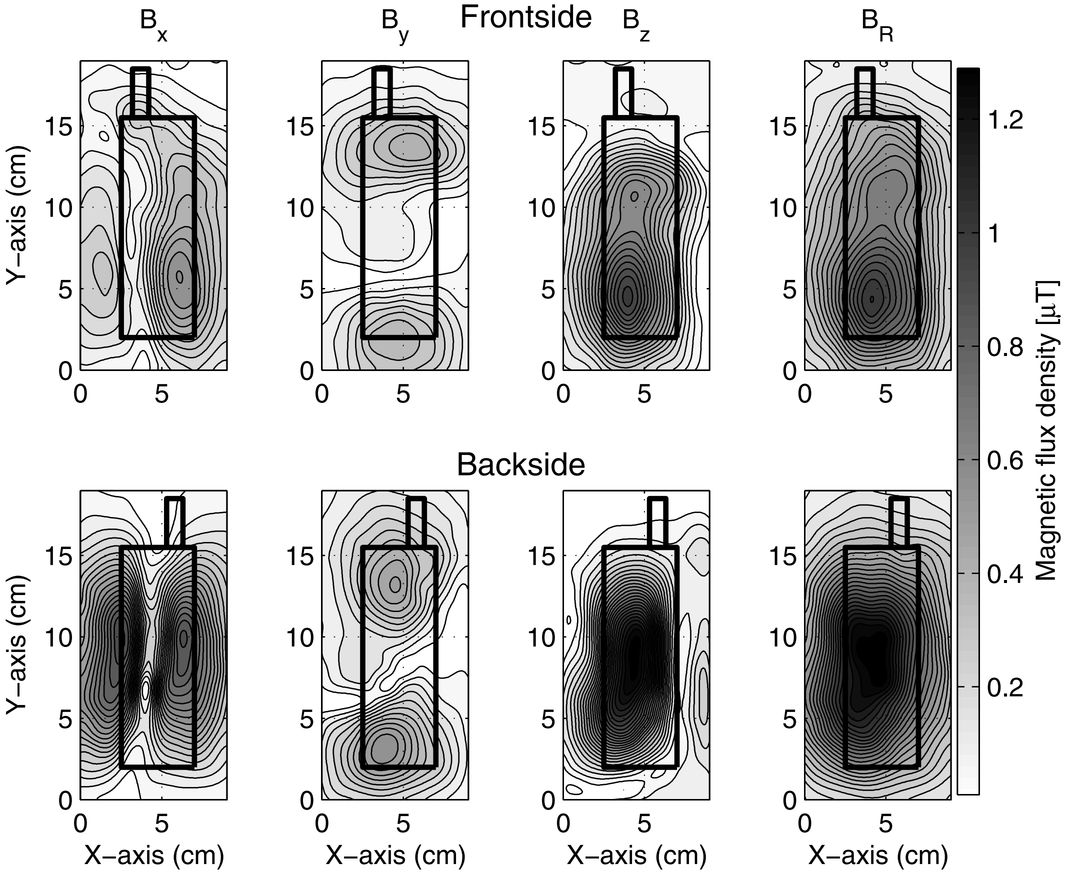

Fig. 3. Contour plots of magnetic flux density components (B_x, B_y, B_z) and the resultant flux density (B_R) 2.4 cm from the front and the back surfaces of mobile phone I. X: parallel to the bottom and top, Y: parallel to the lateral sides, Z: perpendicular to the surface.

In Fig. 4 the resultant of the magnetic flux densities (B_R) sidewise and at the bottom of the device are shown. The magnetic flux density did not exceed about 0.6 μT. The top side (not shown) gave very low values, below 0.1 μT.

For phone positions where the contour plots showed flux densities that were fairly regular and cone shaped we plotted the flux density data as a function of distance to the surface. The results showed in many cases good fits in log-log presentations. The equation for the function describing the resultant flux density at the front: $B_R(z) = 4.26 \cdot z^{-1.6}$μT (z measured in cm, $R^2 = 0.9999$) and at the back side of phone: $B_R(z) = 4.53 \cdot z^{-1.4}$μT ($R^2 = 0.9993$). Extrapolated magnetic flux densities 1 cm above the phone surface could thus be approximated to be about 4 μT and higher than 10 μT at a distance of 0.5 cm. The details of the ELF magnetic flux densities close to the source are, however, difficult to measure and map in an unequivocal way and the estimates extrapolated are uncertain but gives an idea of the magnitude of the flux density levels close to the phone.

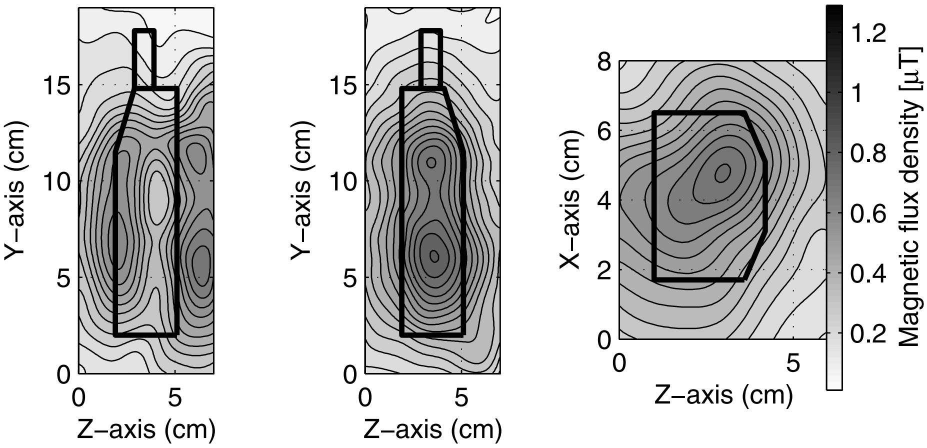

Fig. 4. The contour plots of the resultant magnetic flux density (B_R) 2.4 cm from the lateral sides and under the mobile phone I.

For the calculations according to the multiple frequency rule (Equation (5)) for the three positions above the mobile phone, the frequency spectrum of the axis with the strongest magnetic flux density for the basic frequency was used. Because of the dimension of the MF 400 probe, the magnetic flux densities are also quit low compared to that obtained by the EMDEX II. Therefore we chose to use a presumed realistic value of 3.0 µT (RMS) to exemplify the calculations for the three positions (Table 2). This value is close to the highest value measured 2.4 cm from one of the mobile phone backsides.

Other electrical devices

Spectral distributions obtained from measurements of an electric drill are shown in Fig. 5 and the waveforms of the magnetic flux densities are shown in Fig.6. The harmonics above the wire are smaller than above the drill. The spectral distributions of the magnetic flux densities did not vary much with the magnetic flux meter distance from the phone.

The FFT-spectra of the current probe signals and of the magnetic flux density measured just above the surface of the hairdryer are depicted in Fig. 7 (with the fan at level 2). The spectral distributions differed substantially: the amplitudes of the highest frequencies of the magnetic flux densities were larger than those of the current probe signals. At fan level 1 the difference was smaller (not shown).

For the desk lamp the harmonics of the magnetic flux density spectrum were larger than these components from the current probe. At 150 Hz the magnetic flux density component was 39% and the current component 18% of the magnitude of the basic frequency (i.e. 50 Hz). At 250 Hz the magnetic flux density component was 8% and the current component 4% of the 50 Hz component.

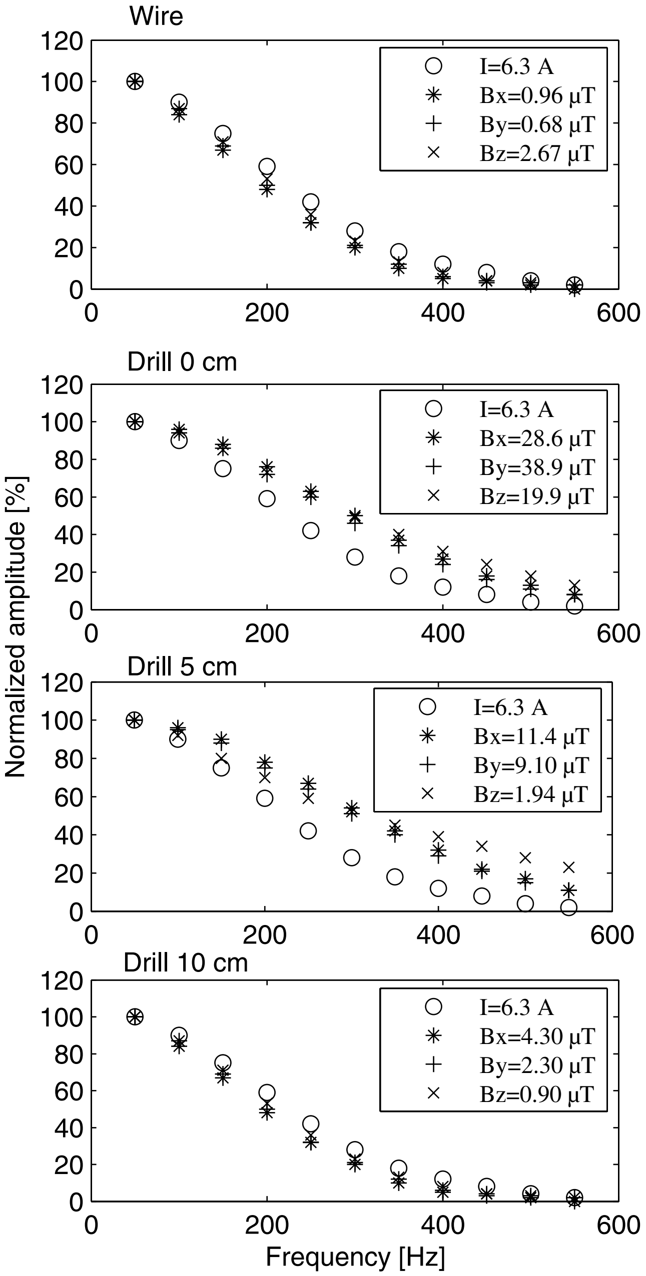

Fig. 5. Spectral distribution (FFT) of the current (*I*) in the wire connected to the drill and the magnetic flux density (B) near this wire and at three distances from the drill. Amplitudes of the frequency components are shown relative to the amplitude of the basic frequency 50 Hz. Magnetic flux densities for directions relative to the drill: X and Y parallel to and Z perpendicular to the surface.

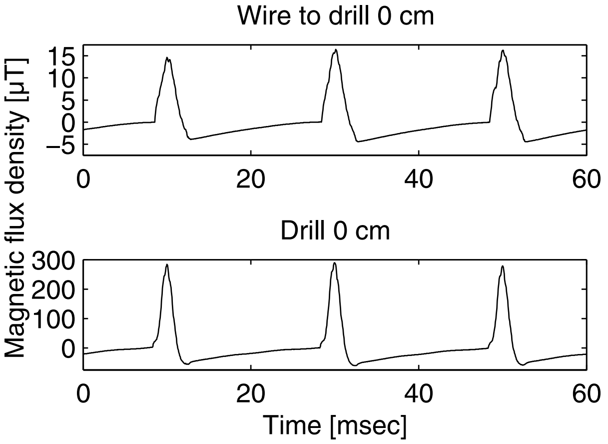

Fig. 6. The waveform of the magnetic flux density near wire connected to the drill (upper curve) and near the drill (lower curve).

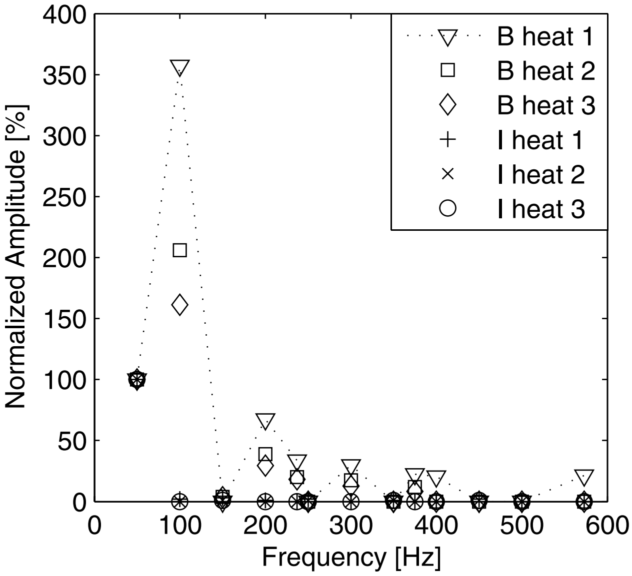

Fig. 7. Spectral distribution (FFT) of the magnetic flux density (B) near a hairdryer and of the current (*I*) in the wire connected to the hair dryer with different heat levels. Amplitudes of the frequency components are shown relative to the amplitude of the basic frequency 50 Hz.

Table 2 shows results when applying the multiple frequency rule and sums up some essentials R-values (Equation (5)). For the drill, the hair dryer and the lamp the multiple frequency rule gives highest value when the spectrum from the magnetic flux density measurements is applied. For the mobile phone current measurements give the highest values.

Table 2. Magnetic flux densities (*B*) and calculated values according to the multiple frequency rule (Equation 5 in the text) by applying the magnetic flux density frequency spectrum (R_M) and the current probe signal spectrum (R_I), and the ratio between these values (R_I/R_M).

	B[μT]	R_M	R_I	R_I/R_M
Mobile phone I microphone (217 Hz)	3.0	0.52	0.95	1.8
Mobile phone I middle (217 Hz)	3.0	0.44	0.95	2.2
Mobile phone I loudspeaker (217 Hz)	3.0	0.86	0.95	1.1
Drill (50 Hz)[a]	72	7.8	6.1	0.78
Hair dryer (50 Hz)[a]	5.0	0.18	0.08	0.44
Lamp (50 Hz)[a]	30	0.72	0.51	0.71

[a] 5.6 cm from the centre of the probe

DISCUSSION

We have concentrated on two themes – both emanating from a focus on health aspects of ELF magnetic flux densities close to everyday electric devices. The first theme has concerned methods to determine the frequency content of the magnetic flux density close to the devices. The second one has been a mapping of magnetic flux densities close to and around mobile phones. The results have been discussed in relation to guidelines of ICNIRP (1998) and specifically to the multiple frequency rule.

The frequency spectrum found by measuring the current drawn by the devices deviated substantially from the magnetic flux density spectrum measured near the devices. This was true both for mobile phone I and for the other devices. Such deviations were also found in the mobile phone recordings published by Pedersen (1997). These results have not been discussed with respect to ICNIRP (1998).

When applying the multiple frequency rule, the resulting ratio, R (Equation 5), may in certain cases depend strongly on whether the frequency spectrum of the magnetic flux density near the device or of the current probe signal from the wire is used. For the mobile phone in the present case, the current probe signal resulted in an R-value that was more than two times higher than the value derived from the magnetic field measurement above the middle of the phone (Table 2). For the drill, the hair dryer and the lamp the resulting R-values were lower when applying the current probe spectra than when applying the magnetic flux density spectra.

One problem is the size (radius 5.6 cm) of the probe used for the FFT-measurements of the magnetic flux density. With this probe it is not possible to measure the field within a small volume, e.g. close to the surface of a mobile phone. Close to the surface the field decreases rapidly with the distance. Furthermore, the relative values of the three spatial components will not be exact, since the magnetic field is not linearly related to the distance from the source. It would have been advantageous to have a smaller probe. With a smaller probe the spatial differences in the frequency spectra would be better resolved and the reason for the differences might be better understood. Also the fields closer to the surface could have been recorded. This might have led to values exceeding the reference level at very short distances.

Another question is how the results from the various directions should be used to evaluate the result with respect to the exposure limits. One possibility is to use the spectral distribution of , - hvthe direction with the highest magnetic flux density and this is done in the present article. An alternative would be to use the resultant magnetic flux density. It could also be argued that measurements at one position (as in the present case) are not sufficient, but that an average of all the measurements over a surface should be used.

Based on the flux density spectral distribution above of the mobile phone loudspeaker the INCIRP ratio of 1.0 obtained by the multiple frequency calculations was achieved for a flux density of 3.5 μT. Numerical calculations by Ilvonen (2005) of the induced current inside the head, however, suggest that the levels would not violate the basic restrictions. One could tentatively have applied the multiple frequency rule by using flux density values extrapolated to close to the phone surface, and thereby calculated the distance at which the flux density levels coincide with the ICNIRP guidelines (reference values for the public). We have not pursued this, considering the difficulties getting precise amplitude and frequency measurements close to the phone and the fact that an unrealistic worst case estimate would have been achieved.

No effort was done to compensate for phase variations between the different harmonics and the basic frequency. This means that the procedure overestimates the flux densities calculated (since the peak values of the frequency components do not normally add directly due to phase differences).

The drill was the only electrical device to violate the reference values of the ICNIRP-guideline, but only close to the drill. For distances of approximately 10 cm the derived values would be within the guideline limits. For a normal working position the head would not be that close to the electric drill, and since there has been no compensation for phase the basic restrictions would probably not be violated.

The ELF magnetic flux density contour plots from several mobile phones were shown to have a similar shape when comparing the flux density components in the same directions. For each telephone there are large spatial variations in the magnetic flux density in the different directions both at the front and back side of the mobile phones. This shows that one can not measure on a random position above a mobile phone to estimate the maximal or average value. All field components are of importance to get an exact value of the mean resultant magnetic flux density over the whole surface of the phone. The component perpendicular to the different surfaces of the mobile phone is usually the dominant one and therefore a good estimate for the highest measured magnetic flux density value.

The magnetic flux density components parallel to the surface of the front and back side of the phone (B_x and B_y) have two peaks with an interspaced “valley” with low magnetic flux density. This could be explained to emanate from two parallel conductors with currents in opposite directions, e.g. from a rectangular-shaped conductor inside and parallel to the main plane of the mobile phone. When new mobile phones are designed, the configuration of the wiring and of the electronic components inside the phone could be taken into account to reduce the magnetic flux density around the device. One mobile phone showed a higher magnetic flux density value on the back side of the phone than on the front side (2.7 μT versus 1.1 μT).

CONCLUSIONS

Summing up, this paper shows that there are differences between the magnetic flux density spectra from the current wires of devices as compared to the spectra measured around the device. As a consequence, the frequency spectrum of the current in the wires does not reflect the magnetic field frequency spectrum around an electrical device. Therefore, the current probes should only be used when the major contribution to the field of interest is caused by the current in the wire.

One has to measure and use the direct magnetic flux density spectra from an electrical device and not the spectra from the supply current in further calculations to estimate if basic restrictions or the reference values are violated. There was no indication that the devices studied would exceed the reference levels at the working distances normally used.

ACKNOWLEDGEMENT

We would like to express our gratitude to Prof Kjell Hansson Mild at National Institute for Working Life (NIWL) for valuable comments during the project. Also Olle Stensson and Hans Pettersson (NIWL) deserve our appreciations for help with measurements.

REFERENCES

Andersen, J. B.; Pedersen, G. F. The technology of mobile telephone systems relevant for risk assessment. – Rad. Prot. Dosim. 72:249-257; 1997.

International commission on Non-Ionizing Radiation Protection. Guidelines for limiting exposure to time-varying electric, magnetic, and electromagnetic fields (up to 300 GHz). Health Phys. 74:494-522; 1998.

International commission on Non-Ionizing Radiation Protection. Guidance on determining compliance of exposure to pulsed and complex non-sinusoidal waveforms below 100 kHz with ICNIRP guidelines. Health Phys. 84:383-387; 2003.

Ilvonen, S.; Sihvonen, S. P.; Kärkkäinen, K.; Sarvas, J. Numerical assessment of induced ELF Currents in the human head due to the battery current of a digital mobile phone. Bioelectromagnetics 26:648-656; 2005.

Jokela, K. Electrophysiological considerations relevant to limiting of pulsed electric and magnetic fields. Health Phys. 72:408-417; 1997.

Jokela, K. Restricting exposure to pulsed and broadband magnetic fields. Health Phys. 79:373-388; 2000.

Jokela, K.; Puranen, L.; Sihvonen, A. P. Assessment of the magnetic field exposure due to the battery current of digital mobile phones. Health Phys. 86:56–66; 2004.

Linde, T.; Mild. K. H. Measurement of Low Frequency Magnetic Fields from Digital Cellular Telephones. Bioelectromagnetics 18:184-186; 1997.

Pedersen, G. F. Amplitude Modulated RF fields stemming from a GSM/DCS-1800 phone. Wireless Networks 3:489-498; 1997.

Paper III

Paper III is not included due to copyright.

Paper IV

Paper IV is not included due to copyright.