And when I squinted
The world seemed rose-tinted
And angels appeared to descend
To my surprise
With half-closed eyes
Things looked even better
Than when they were opened
(Martin L. Gore, Depeche Mode)
Radiofrequency fields – exposure, dose and health

Jonna Wilén

Department of Radiation Sciences
Radiation Physics
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ABSTRACT

The overall aim of this thesis is to increase our knowledge of relevant exposure parameters when discussing possible health implications from exposure to radiofrequency electromagnetic fields (RF), especially effects that might occur at non-thermal levels.

In this thesis an effort is made to broaden the exposure assessment and to take the exposure time into account and combine it with the Specific Absorption Rate (SAR) and the field parameters (electric and magnetic field strength) to approach a dose concept.

In the first part of the thesis self-reported subjective symptoms among mobile phone users were studied. As a basis for this an epidemiological study among mobile phone users was completed with the main hypothesis that users of the digital transmission system GSM experience more symptoms than users of the older analogue NMT transmission system.

The hypothesis was falsified, but an interesting side finding was that people with longer calling time per day experienced more symptoms than people with shorter calling time per day. The time-aspect (long duration phone call etc.) was also found to be relevant for the occurrence of symptoms in association with mobile phone use as well as duration of symptoms. The new suggested dosimetric quantity Specific Absorption per Day (SAD), in which both calling time per day as well as the measured SAR1g are included showed a stronger association to the prevalence of some of the symptoms, such as dizziness, discomfort and warmth behind the ear compared to both CT and SAR1g alone.

In the second part whole body exposure conditions were considered. Methods to measure the induced current were examined in an experimental study, where different techniques were compared in different grounding conditions. The results were used in a study of operators of RF plastic sealers (RF operators) where the health status as well as the exposure were studied. The results showed that RF operators are a highly exposed group, which was confirmed by the fact that 16 out of 46 measured work places exceeded the ICNIRP guidelines. Headaches were found to be associated with the mean value of the time integrated E-field during a weld (E-weld) and the warmth sensations in the hands (warm hands) with the time integrated E-field exposure during one day (E-day).

The general findings in this thesis indicated that time should be included in the exposure assessment when studying non-thermal effects such as subjective symptoms in connection with RF exposure. The thesis proposes two different methods for doing this, namely time-integrated exposure [V/m x t and A/m x t] and dose [J/kg].

Keywords: electromagnetic fields, SAR, Specific Absorption, subjective symptoms
ORIGINAL PAPERS

The thesis is based on the following papers, which in the text are referred to by the Roman numerals:


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### ABBREVIATIONS

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSM</td>
<td>Global Service for Mobile communication</td>
</tr>
<tr>
<td>ELF</td>
<td>Extremely Low Frequency</td>
</tr>
<tr>
<td>EMF</td>
<td>Electromagnetic fields</td>
</tr>
<tr>
<td>MP</td>
<td>Mobile phone</td>
</tr>
<tr>
<td>NMT</td>
<td>Nordic Mobile Telephone</td>
</tr>
<tr>
<td>RF</td>
<td>Radiofrequency</td>
</tr>
<tr>
<td>RF operator</td>
<td>Operator of RF sealers</td>
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<tr>
<td>RF sealer</td>
<td>RF plastic sealer</td>
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<tr>
<td>RF exposure</td>
<td>Exposure to radiofrequency fields</td>
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<tr>
<td>VDT</td>
<td>Visual Display Terminal</td>
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</table>

### SYMBOLS

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>CT</td>
<td>Calling time per day (min)</td>
</tr>
<tr>
<td>E</td>
<td>Electric field strength [V/m]</td>
</tr>
<tr>
<td>f</td>
<td>Frequency [Hz]</td>
</tr>
<tr>
<td>H</td>
<td>Magnetic field strength [A/m]</td>
</tr>
<tr>
<td>I</td>
<td>Induced current [A]</td>
</tr>
<tr>
<td>NC</td>
<td>Number of calls per day</td>
</tr>
<tr>
<td>SA</td>
<td>Specific Absorption [J/kg]</td>
</tr>
<tr>
<td>SAC</td>
<td>Specific Absorption per Cay (1 g average)</td>
</tr>
<tr>
<td>SAD</td>
<td>Specific Absorption per Dall (1 g average)</td>
</tr>
<tr>
<td>SAR</td>
<td>Specific Absorption Rate [W/kg]</td>
</tr>
<tr>
<td>SAR_{1g}</td>
<td>Specific Absorption Rate average over 1g tissue (cube)</td>
</tr>
<tr>
<td>ρ</td>
<td>Density [kg/m³]</td>
</tr>
<tr>
<td>σ</td>
<td>Electrical conductivity [S/m]</td>
</tr>
</tbody>
</table>
INTRODUCTION

Radio frequency electromagnetic (RF) fields have been used for various purposes for a very long time, for example in radio and TV transmission, microwave ovens, and during the last decade also in mobile telecommunication.

Since RF fields have the ability to cause heating in the exposed individual, there are concerns about possible health implications. In most countries today, RF exposure is regulated so as not to produce thermal effects in humans. The International Commission of Non-Ionizing Radiation Protection, ICNIRP [1998] formed guidelines some years ago to avoid thermal effects in exposed individuals.

The main concern today in the scientific society is about possible non-thermal effects from RF exposure, e.g. effects that occur at levels below the present guidelines. Some of the discussed effects are symptoms such as headaches, fatigue, dizziness, warmth sensations etc. There are also concerns about long-term effects such as cancer [Stewart, 2000].

A general problem is that the exposure assessment has been a shortcoming in many studies and that the concepts of exposure and dose have not been taken into account to a great extent.

The Specific Absorption Rate (SAR), measured in watts per kilogram, is a suitable parameter for characterizing the absorption of RF fields in the body when discussing thermal effects, but this parameter might, however, not be the appropriate one to use when discussing possible non-thermal effects. As will be discussed later in this thesis, SAR is a measure of the momentary, time independent absorption in the body. Non-thermal effects might not be time independent and it could therefore be necessary to incorporate the time factor in the concept of dose.

In addition, the interaction mechanism is unclear and we do not know what regions in the body might be most sensitive to absorption of RF fields. It would therefore be informative to define the exposure/absorption in terms of anatomical localization, something which has not been done in most of the studies.

In this thesis two exposure categories will be studied; mobile phone users (MP-users) and operators of plastic welding machines (RF operators). This provides the opportunity to describe both local exposure (head) to levels below present guidelines and whole body exposure often exceeding permitted levels.
AIMS OF THE THESIS

The overall aim of this thesis is to increase our knowledge about health outcome caused by RF exposure, and what exposure/dose parameters are relevant especially when discussing exposure to RF fields at non-thermal levels.

The specific aims are:

- To assess the relationship between the occurrence of subjective symptoms among mobile phone users and the transmitter system used, and time spent on the phone.
- To study the specific group of people who claims that their symptoms are caused by their use of mobile phones, how the time parameter affects the occurrence of the symptoms, and what measures are taken to avoid the symptoms.
- To test alternative exposure parameters where the time factor is incorporated in the SAR concept, to explain the occurrence of subjective symptoms among MP users.
- To develop an appropriate measurement procedure for induced current measurement.
- To assess the relationship between health problems among operators of RF sealers and exposure to RF fields, paying specific attention to the exposure time.
BACKGROUND

Electromagnetic fields

The electromagnetic spectrum (Figure 1) extends from extremely low frequency fields, such as those associated with power lines and electrical appliances up to X-rays and high-energy gamma rays.

![Electromagnetic spectrum](image)

Figure 1. The electromagnetic spectrum.

The characteristic of the electromagnetic field is mainly described by its energy content, which is easily derived from its frequency. In the higher frequency region \( f \geq 10^{12} \) Hz, the energy in each photon is high enough to break electron bounds (~5 eV). Therefore, this frequency band is identified as ionizing radiation (Table 1).

<table>
<thead>
<tr>
<th>Energy (eV)</th>
<th>Ionizing radiation</th>
<th>Non-ionizing radiation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gamma radiation</td>
<td>( 10^3 ) - ( 10^6 )</td>
<td></td>
</tr>
<tr>
<td>Ultraviolet radiation</td>
<td>~6</td>
<td></td>
</tr>
<tr>
<td>Optical radiation</td>
<td>~3</td>
<td></td>
</tr>
<tr>
<td>RF</td>
<td>( 10^{-6} )</td>
<td></td>
</tr>
<tr>
<td>ELF</td>
<td>( 10^{-13} )</td>
<td></td>
</tr>
</tbody>
</table>

For electromagnetic fields with lower frequencies, the energy is not high enough to cause ionization, and this region is referred to as non-ionizing radiation.
Radiofrequency fields

The RF band of the electromagnetic spectrum can generally be defined as the region between 3 kHz and 300 GHz. Sometimes RF is divided into HF (high frequency, 3-30 MHz), VHF (very high frequency, 30-300 MHz), UHF (ultra high frequency, 300-1000 MHz), and various microwave bands (1-300 GHz).

RF fields are used in various applications in modern society, and new uses are steadily being introduced. Transmitting information is one important application of RF fields, e.g. in radio and television broadcasting and telecommunication. Amplitude and frequency modulated (AM and FM) signals are used in broadcasting and telecommunications, but today even more sophisticated systems exist, especially in telecommunications where digitalized signals are being used and very advanced coding techniques are applied. For a brief summary, see Bach Andersen and Pedersen [1997].

Another RF application is heating, used for example in microwave ovens and industrial applications such as RF welding and glue drying. Since RF fields penetrate the matter, not just the surface of the object is heated, which provides a fast, timesaving heating process.

Biological effects

The only well documented effects of exposure to RF fields are heating effects. The heating effect depends on the absorption of RF fields (described below), but in general, the greater the absorption rate, the more likely it is that significant heating occurs [Durney et al, 1986].

Thanks to the thermoregulatory system, the body has the ability do dissipate thermal energy and to avoid thermal stress, but at certain levels of absorption the body is no longer able to regulate the heating and thermal stress responses such as heat exhaustion, heat stroke, and physiological heat stress can not be excluded [Adair, 1996].

Non-thermal levels

There have been concerns about possible health effects of exposure to RF fields at levels below the thermal threshold. Both short-term (acute) and long-term effects have been discussed. The latter mainly focus on cancer risks, which are not considered in this thesis. Below, a short summary of some of the studies relevant to
this work is given. ICNIRP [1997] and Stewart [2000] provide more comprehensive reviews.

Former East European and Russian studies report neurasthenic symptoms, such as headaches, fatigue, drowsiness, and cardiovascular effects among people occupationally exposed to RF fields compared to a control group [Baranski and Czerski, 1976; Marha et al, 1971]. These findings have also been seen by more recent studies [Szmigielski et al, 1998; Zhao et al, 1994]. Neurasthenic symptoms have also been reported among mobile phone users [Chia et al, 2000; Hocking and Westerman, 2000], but an association to RF exposure has not been seen in recent provocation studies [Hietanen et al, 2002; Koivisto et al, 2001].

**Exposure metric**

The E and H-fields are normally assessed when characterizing RF exposure, since these field parameters are rather easy to measure. In the far-field region E and H are coupled e.g. $E$ is perpendicular to $H$ and both are perpendicular to the direction of motion, and in free-space $E/H=377 \, \Omega$. However, in most cases as in exposure from RF sealers and from mobile phones, the distance from the source to the exposed individual is too short and near-field conditions exist. Here E and H have to be treated separately, since they both contribute to the absorption.

**Induced current**

During whole body exposure to RF fields, a current is induced in the body. For a human in an up-right position in a vertically polarized electric field, the current will flow in vertical direction. The current density ($j$), expressed in $A/m^2$, will reach the highest value in the wrists due to their relatively small electrical cross sectional area. Since the SAR is proportional to the square of $j$, this is also where the risk of heating is most pronounced.

**What is SAR?**

A common way to describe the absorption of RF fields in matter is to calculate the Specific Absorption Rate (SAR) expressed in $W/kg$ and defined as the energy imparted from electric and magnetic fields to charged particles in an infinitesimal volume of an absorber per unit mass and time. A brief evaluation of SAR is given here. For a more detailed explanation, see Durney et al. [1986].
The SAR is derived from the Poynting vector $S = \mathbf{E} \times \mathbf{H}$ [W/m²] that describes the energy stored in the radiofrequency field, which is transferred to charge particles in the matter. The energy transportation causes for instance rotation of dipoles, such as water molecules, which is the basis of heating effects [Grandolfo et al, 1983].

Many factors influence the thermal effects. The most important one is the power density ($S$), which can be derived from the absolute value of the Poynting vector assuming that plane-wave conditions exist and that $\mathbf{E}$ and $\mathbf{H}$ are in phase;

$$S = \frac{E^2}{377} = 377 \cdot H^2$$

where $S$ is expressed in [W/m²], $E$ [V/m] and $H$ in [A/m].

The absorption in the object is also dependent on the frequency of the applied RF field. Roughly speaking, for $E$ polarization the SAR will increase with increasing frequency as a function of $f^2$ up to the resonance frequency for the object, and then decrease as a function of $1/f$.

Other factors that affect the absorption are the polarization, the density, and the electrical properties of the exposed object.

The SAR value can be calculated by for example measuring the field strengths or the induced current. In this thesis, two different methods have been used to calculate SAR.

**Exposure from mobile phones**

The most commonly used method to assess the SAR from exposure to MP is by measuring the internal electric field ($E_{\text{int}}$) inside a phantom model of the human head. The SAR in each point is then calculated by:

$$SAR = \frac{E_{\text{int}}^2 \sigma}{\rho}$$
where $\sigma$ [S/m] is the electrical conductivity of the phantom liquid and $\rho$ [kg/m$^3$] is the density. For more detailed information see Kuster and Balzano [1997].

$SAR_{1g}$ has been used in this thesis, which is an average value in a 1 gram cube of tissue.

**Whole body exposure to RF fields**

During whole body exposure to vertically polarized electric fields the maximum SAR is measured in the ankles. By measuring the induced current passing through both feet ($I$), the SAR can be calculated by using:

$$SAR = \frac{j^2}{\sigma \cdot \rho}$$

where $j = \frac{I}{2 \cdot A_e}$

where $A_e$ is the electrical cross sectional area of the ankle ($9.5 \times 10^{-4}$ m$^2$ [Gandhi et al., 1986]), $\sigma$ is the electrical conductivity (0.6 S/m [Gandhi et al., 1985]), and $\rho$ is the density ($1 \times 10^3$ kg/m$^3$).

**ICNIRP guidelines**

The International Commission on Non-Ionizing Radiation Protection [ICNIRP, 1998] has established guidelines for limiting the exposure to electromagnetic fields to provide protection against known adverse health effects. The guideline is valid for electromagnetic fields of frequencies up to 300 GHz, which includes the radio frequency range discussed in this thesis.

The biological basis for limits in the frequency range 100 kHz to 10 GHz is whole-body heat stress and excessive localized tissue heating. This is achieved by limiting the absorbed power per unit mass in the whole-body, localized in the head and the trunk, and in the limbs.

ICNIRP guideline provides basic restrictions, directly based on established health effects. For the frequencies covered by this thesis, specific absorption rate (SAR) expressed in W/kg forms the basic restriction.
ICNIRP specifies three SAR limits which all have to be fulfilled irrespectively:

- The whole-body average SAR limit is set to avoid general thermal stress.
- The localized SAR for the head and trunk is established to avoid local heating and is based on cataract. (This is the limit that is used for mobile phones).
- A localized SAR limit for the limbs is also provided.

Since the SAR is difficult to measure in a real life situation, ICNIRP also provides reference values, which are measurable quantities derived from the basic restriction. If the reference levels are fulfilled, it is not likely that the basic restrictions are exceeded. On the other hand, if the measured values do not comply with the reference values, one has to make sure that the basic restriction is not exceeded by numerical calculation. The reference values are electric and magnetic field strengths and currents flowing in the limbs.

ICNIRP has adopted more stringent exposure restrictions for the general exposure than for occupational exposure, and the division factor is 5 between those two. In Table 2-3, a short summary of basic restrictions and reference values for the frequency range 1-2000 MHz is given.

The limits for induced currents in any limbs at frequencies between 10 and 110 MHz are 100 mA for occupational exposure and 45 mA for general exposure.

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>General public [W/kg]</th>
<th>Occupational exposure [W/kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Whole-body average</td>
<td>Localized SAR (head and trunk)</td>
</tr>
<tr>
<td>100 kHz -10 GHz</td>
<td>0.08</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>0.4</td>
<td>10</td>
</tr>
</tbody>
</table>

*For frequencies up to 10 MHz, ICNIRP also set limits for current densities.
Table 3. Reference levels in the frequency range 1-2000 MHz (ICNIRP)

<table>
<thead>
<tr>
<th>Frequency (MHz)</th>
<th>General public</th>
<th>Occupational exposure</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E-field (V/m)</td>
<td>H-field (A/m)</td>
</tr>
<tr>
<td>1-10</td>
<td>87f^{1/2}</td>
<td>0.73/f</td>
</tr>
<tr>
<td>10-400</td>
<td>28</td>
<td>0.073</td>
</tr>
<tr>
<td>400-2000</td>
<td>1.375f^{1/2}</td>
<td>0.0037f^{1/2}</td>
</tr>
</tbody>
</table>

f is the frequency expressed in MHz.
PARTIAL BODY EXPOSURE FROM MOBILE PHONES AND SUBJECTIVE SYMPTOMS

(PAPER I-III)

Material and methods

Design of the study

The study was performed in three parts. In the first part, the main hypothesis that GSM users experience more subjective symptoms than NMT users was tested (Paper I). The second part (Paper II) is a description of the people experiencing subjective symptoms in connection to MP use. The main focus was on time related factors, such as the duration of the symptoms and when (in time) the symptoms occurred. Paper III is an explorative study where the importance of absorption of RF fields to the prevalence of subjective symptoms was evaluated.

Papers I-III are all based on the outcome of a single questionnaire, which was sent out in 1996 to 12 000 Swedish and 5000 Norwegian MP users. A more detailed description of the general method as well as the specific methods for each individual paper are given below.

Selection criteria and procedure

Since only one net operator supported both GSM and NMT 900 in 1996 the registers of that particular operator were selected. The decision was based on the same argument in Norway, where there was also only one net operator supporting both GSM and NMT 900.

To include people with both a low and an intense use of MPs, the operators company registers were used, i.e. registers of subscriptions where a company is the subscriber, but an individual is assigned to the phone.

A pilot study involving 160 people selected from the register tested the questionnaire during the spring of 1996.

The final mailing lists consisted of 6379 GSM and 5613 NMT users in Sweden and 2500 in each category in Norway.
PARTIAL BODY EXPOSURE FROM MOBILE PHONES AND SUBJECTIVE SYMPTOMS

The questionnaire

Based on interviews made by Drs. Bengt Knave and Arne Wennberg (National Institute for Working Life, Stockholm) and knowledge from the literature on low-level effects from exposure to RF fields, questions about subjective symptoms were formulated.

The symptoms included were dizziness, general discomfort, difficulties concentrating (concentration), memory loss, abnormal drowsiness/fatigue, headaches, sensations of warmth behind/around the ear, sensations of warmth on the ear, burning sensations in the facial skin and tingling/tightness sensations in the facial skin. Each individual was asked to state whether he or she had experienced any of the symptoms during the last year. The answer options for each symptom were: never, less than once a week, 1-4 times a week, and more than 4 times a week. In all three studies (Papers I-III) individuals were defined as having a symptom if they experienced it at least once a week.

Transmission system, manufacturer, model, calling time per day and number of calls per day as well as confounding factors such as age, gender, geographical location, VDT work, occupation, and psychosocial factors were included in the questionnaire.

The questionnaire was divided into two parts, the first to be filled in by all participants and the second by those who experienced symptoms in connection with MP use.

The importance of transmission system
(Paper I)

The main hypothesis that GSM users experience more subjective symptoms than NMT users was tested in Paper I by a cross-sectional study of GSM and NMT 900 users. Only people who used one device (GSM or NMT 900) were included in the study. All people who stated that they experienced symptoms in general were included, irrespective of any connection to MP use.

Description of symptoms experienced in connection to MP use
(Paper II)

The aim of this part was to get a deeper understanding of the conditions and measures experienced to be of importance to the occurrence of symptoms. Only
people who claimed that their symptoms appeared in connection to MP use were included, i.e. those who had answered part two of the questionnaire.

To get an idea of how the time parameter affected the occurrence of symptoms, questions about the duration of the symptoms, the duration of the phone call needed before the symptoms occurred and how quickly the symptoms disappeared where included in the questionnaire.

The influence of the absorption of RF and subjective symptoms (Paper III).

The aim of this study was to explore the role of absorption and the absorption rate (SAR) in the prevalence of subjective symptoms. The SAR distributions for the four commonly used GSM devices were measured. The anatomical localization of the maximum SAR was also evaluated.

The phone was held in the intended use position [CENELEC, 2001] and measurements were taken on both the left and the right hand side of the phantom.

Three volumes in the head were defined as the volume above the ear (Volume 1), the volume on and behind the ear (Volume 2) and the volume below the ear, on the cheek (Volume 3). The depth of each volume is approximately four centimeters.

In addition to the SAR averaged over one gram of tissue, two new exposure parameters were introduced; the specific absorption per phone call (SAC) and per day (SAD), both expressed in J/kg and calculated as:

\[ SAD = SAR_{1g} \cdot CT \cdot 60 \]

\[ SAC = \frac{SAD}{NC} \]
Results (Papers I-III)

The importance of transmission system
(Paper I)

In our study, the symptoms among MP users reported to occur most often, i.e. at least once a week, were fatigue in Sweden (11 %) and warmth on the ear and warmth behind the ear in Norway (22 and 25 %, respectively).

The hypothesis that GSM users experience more symptoms than NMT users was falsified. In fact, GSM users had a statistically lower risk of sensations of warmth on the ear compared to GSM users. An interesting side finding was that the calling time per day (CT) and the number of calls per day (NC) seem to be of importance for the prevalence of most of the symptoms. The same tendency can be seen for the exposure factor number of calls per day.

Description of symptoms experienced in connection to MP use
(Paper II)

In Sweden, 13% of the NMT users reported symptoms in connection with MP use and the corresponding number for the GSM users was 9.9%. The prevalence of MP-related symptoms in general (any symptom) was higher for people with a longer CT (significant linear trend).

The most commonly reported MP-related symptoms were warmth on the ear, warmth behind the ear and headaches.

For sensations of warmth on the ear and warmth behind the ear, the symptoms were usually experienced during phone calls or shortly after the call were made. Most of the other symptoms typically appeared during the call or within 30 minutes after the call was made. The symptoms warmth on the ear and warmth behind the ear lasted in general for less than two hours, while the other symptoms typically continued for two to six hours. People also reported more MP-related symptoms with an increasing CT and NC in both countries (statistically significant).

The influence of the absorption of RF and subjective symptoms
(Paper III)

When comparing the measured SAR values in each specified volume (Vol. 1-Vol. 3) for the people reporting symptoms in general (not necessarily in connection
to MP-use) only small differences were seen. However, the differences were statistically significant for discomfort and dizziness in Vol. 2 (on the ear) and 3 (below the ear) and for warmth behind the ear in Vol. 2.

Some of the symptoms, especially dizziness, discomfort and warmth sensations behind the ear, were correlated with $SAR_{1g} > 0.5 \text{ W/kg}$ in combination with $CT > 15 \text{ mins/day}$.

When also taking calling time into account, $SAC$ and $SAD$ showed more pronounced differences between people with symptoms (W-S) and people without symptoms (WO-S). This is particularly true for dizziness, discomfort and warmth behind the ear where $SAD$ was a better explanation compared to $CT$, $SAR$ and $SAC$.

General results

$CT$ was found to be of importance to the prevalence of self-reported subjective symptoms. The most pronounced effect of $CT$ and the prevalence of symptoms (experienced irrespectively of an association to MP use) were found for warmth on the ear and warmth behind the ear. This effect was seen both for NMT and GSM users. GSM users had a statistically significantly lower risk of warmth on the ear compared to NMT users.

For people experiencing symptoms in connection to MP use, warmth on the ear and warmth behind the ear were the most frequently reported symptoms. These symptoms were most commonly experienced during calls and lasted for less than two hours. $CT$ and $NC$ were associated with a higher prevalence of MP-attributed symptoms.

The measured $SAR_{1g}$ gave a small non-significant difference between the W-S and WO-S groups, except for warmth behind the ear were the difference was statistically significant. However, $SAD$ seemed to be more relevant for the prevalence of symptoms, especially for dizziness, discomfort and warmth behind the ear since the difference increased compared to $CT$, $SAC$ and $SAR_{1g}$. 
WHOLE-BODY EXPOSURE TO RF FIELDS AND POSSIBLE HEALTH CONSEQUENCES

(PAPER IV-V)

Paper IV and V address whole body exposure to levels of RF fields close to the recommended guidelines.

In the plastic welding industry, RF fields are used to seal plastics and to achieve waterproof seams. Since the operator of the RF sealer is rather close to the electrode during the weld, he/she will experience electric and/or magnetic fields often close to or above the ICNIRP guidelines. In many cases, the operators are exposed in grounded conditions, which means that currents of the order of tens to hundreds of milliampere are induced in the body during the weld.

The aims of the projects described in Paper IV and Paper V were: to evaluate techniques to measure the induced current (Paper V), to assess the exposure close to plastic welders, to perform a health examination including sensory motoric tests, self-reported subjective symptoms and ECG recordings and to find possible correlations between time-integrated exposure parameters and health outcome.

Measurement of induced current

Methods to measure the induced current in the body during whole-body exposure to RF fields were tested in an experimental study(Paper IV). A symmetrical stripline was constructed to produce vertically polarized homogenously electric fields in the frequency range of 1-20 MHz.

Three aspects were considered:
- the measurement technique used (parallel plate meters and current probes),
- the subjects wearing shoes or not,
- the separation distance between the subject’s feet and ground (grounded and ungrounded conditions).
WHOLE-BODY EXPOSURE TO RF FIELDS AND POSSIBLE HEALTH CONSEQUENCES

The current factor expressed as:

\[ K_{b,\text{instr}} = \left( \frac{h^2 \cdot f}{\varepsilon_{\text{subject}}} \right) \left( \frac{V}{E} \right)_{\text{instr,subject}} \]

was used for comparison of the different exposure situations described above.

RF plastic welding

A total of 35 ready-made clothing and tarpaulin workers were included, both male and females. The control group included workers with similar work tasks (sewing machine operators and assembly workers), and they were selected to give a gender and age distribution equal to that of the RF operators.

In addition to spatial mean values of the exposure and a 6-min average exposure in accordance with ICNIRP guidelines, time-integrated exposures were also calculated using different time ranges. A detailed description of the different exposure quantities is given in Paper V.

Results

Induced current measurements
(Paper IV)

The current factors measured with the different techniques are comparable in grounded conditions \((K_0 = 0.078\), rel. SD = 6.3%), but when wearing shoes and/or standing on a wooden plate (ungrounded condition), which is common in industrial situations, the difference increased (Table 4).

Table 4. The current factor \( K_0 \) (mA m\(^2\) MHz Vm\(^{-1}\))

<table>
<thead>
<tr>
<th></th>
<th>Grounded without shoes</th>
<th>Grounded with shoes</th>
<th>Ungrounded without shoes</th>
<th>Ungrounded with shoes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Holaday</td>
<td>0.076</td>
<td>0.048</td>
<td>0.042</td>
<td>0.028</td>
</tr>
<tr>
<td>Narda</td>
<td>0.075</td>
<td>0.040</td>
<td>0.036</td>
<td>0.016</td>
</tr>
<tr>
<td>GC-2</td>
<td>0.081</td>
<td>0.044</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>H 3702</td>
<td>0.085</td>
<td>0.060</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Eaton</td>
<td>0.071</td>
<td>0.060</td>
<td>0.055</td>
<td>0.057</td>
</tr>
<tr>
<td>Average</td>
<td>0.078</td>
<td>0.050</td>
<td>0.044</td>
<td>0.034</td>
</tr>
<tr>
<td>Relative SD</td>
<td>6.3%</td>
<td>18%</td>
<td>21%</td>
<td>63%</td>
</tr>
</tbody>
</table>
Due to capacitive coupling, the larger sized parallel plate meter (Holaday) read a higher value in ungrounded conditions than the smaller sized Narda instrument. The cross-sectional area of the current probes is formed by the size of the subject’s both feet, which is smaller than both the Narda and the Holaday instrument. There are obviously other factors separating the different current meters, since the current probes measured a higher value than the smaller sized parallel plate meter in ungrounded conditions.

The results also confirmed previous findings [Gandhi et al, 1985] that the SAR in the ankle can be above the basic restrictions even though the electric field strength is below the guidelines, which points to a need of an accurate method of measuring the induced current in the ankles.

RF plastic welding (Paper V)

RF operators are a highly exposed group; this was confirmed by the measurements of electric and magnetic field strength at the workplaces (16 out of 46 measured work places exceeded the ICNIRP guidelines). In Table 5 the E-fields and in Table 6 the H-fields for the different parts of the body are shown.

<table>
<thead>
<tr>
<th>Tarpaulin</th>
<th>Mixed group</th>
<th>Ready-made clothing</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>head</td>
<td>30 (0-529)</td>
<td>51 (0-176)</td>
<td>193 (68-541)</td>
</tr>
<tr>
<td>trunk</td>
<td>46 (0-566)</td>
<td>58 (5-185)</td>
<td>318 (163-458)</td>
</tr>
<tr>
<td>waist</td>
<td>49 (0-472)</td>
<td>47 (12-129)</td>
<td>84 (50-128)</td>
</tr>
<tr>
<td>knees</td>
<td>0 (0-77)</td>
<td>19 (14-114)</td>
<td>147 (18-294)</td>
</tr>
<tr>
<td>hands</td>
<td>58 (0-1047)</td>
<td>21 (9-721)</td>
<td>157 (35-350)</td>
</tr>
<tr>
<td>feet</td>
<td>0 (0-86)</td>
<td>17 (0-124)</td>
<td>115 (24-144)</td>
</tr>
</tbody>
</table>

Note, a zero value indicates a non-measurable value.
Table 6. Median (min-max) values of the measured H-field (A/m) at different positions.

<table>
<thead>
<tr>
<th></th>
<th>Tarpaulin</th>
<th>Mixed group</th>
<th>Ready-made clothing</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>head</td>
<td>0.07 (0-0.40)</td>
<td>0.09 (0.01-0.19)</td>
<td>0.19 (0.12-0.44)</td>
<td>0.09 (0-0.44)</td>
</tr>
<tr>
<td>trunk</td>
<td>0.13 (0-0.77)</td>
<td>0.13 (0.02-0.28)</td>
<td>0.39 (0.32-0.70)</td>
<td>0.15 (0-0.77)</td>
</tr>
<tr>
<td>waist</td>
<td>0.16 (0-0.85)</td>
<td>0.19 (0.13-0.27)</td>
<td>0.61 (0.21-0.66)</td>
<td>0.20 (0-0.85)</td>
</tr>
<tr>
<td>knees</td>
<td>0.04 (0-0.46)</td>
<td>0.13 (0.03-0.14)</td>
<td>0.67 (0.14-0.69)</td>
<td>0.11 (0-0.69)</td>
</tr>
<tr>
<td>hands</td>
<td>0.17 (0-1.47)</td>
<td>0.12 (0.03-1.13)</td>
<td>0.94 (0.13-1.84)</td>
<td>0.15 (0-1.84)</td>
</tr>
<tr>
<td>feet</td>
<td>0.03 (0-0.19)</td>
<td>0.07 (0.01-0.14)</td>
<td>0.27 (0.13-0.56)</td>
<td>0.07 (0-0.56)</td>
</tr>
</tbody>
</table>

Note, a zero value indicates a non-measurable value.

By the use of the measured induced current in the ankles and wrists, the SAR values can be calculated. The results are shown in Table 7, where also the induced current passing is given.

Table 7. Median (min-max) values of the measured induced current (mA), expressed as the sum of left and right wrist/ankle and the calculated SAR values (W/kg).

<table>
<thead>
<tr>
<th></th>
<th>Induced current (mA)</th>
<th>SAR (W/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Wrist</td>
<td>Ankles</td>
</tr>
<tr>
<td>Tarpaulin</td>
<td>60 (0-650)</td>
<td>62 (0-800)</td>
</tr>
<tr>
<td>Mixed group</td>
<td>20 (0-345)</td>
<td>51 (0-128)</td>
</tr>
<tr>
<td>Ready-made clothing</td>
<td>50 (0-115)</td>
<td>74 (50-125)</td>
</tr>
</tbody>
</table>

In general, not many RF operators have severe health problems (subjective symptoms, disturbed 2-PD or ECG). There are, however, differences between the RF operators and controls indicating an effect of the RF exposure.

A statistically significant difference in 2-PD was found between the three groups: ready-made clothing workers a mixed group and tarpaulin workers, but no association with exposure (E-field, H-field or induced current) was detected.

The prevalence of self-reported fatigue, headaches, warmth sensations and sleeping disorders was somewhat higher among the RF operators as compared to the controls (non-significant). The mean value of the time integrated E-field exposure...
 Whole body exposure to RF fields in the frequency range of around 27 MHz will induce considerable induced currents in the ankles. During RF welding where the subject often holds the hands close to the electrode, currents will also flow in the wrists.

As it has been shown in Paper IV, the choice of an appropriate measurement technique is not trivial, since grounding conditions might affect the measurements considerably.

The higher prevalence of headaches, fatigue and warmth sensations among RF operators compared to controls might be explained by a higher time integrated E-field exposure during one weld, during the entire length of their working life or during the day, respectively.

There was no obvious relationship between disturbed 2-PD and exposure.
DISCUSSION

The concepts of dose and exposure

When discussing possible effects from exposure to RF fields one needs to clarify the concept of exposure and dose, which are terms that have been used rather indiscriminately in many studies.

The term exposure is often used to describe the condition of being subject to some effect or influence, which in science can be used as a description of the incidence field, in terms of energy passing through a certain surface or the rate of the energy passing through the surface. The power density (S) has been used as an exposure parameter for RF fields in the far-field region. In the near field, where the exposure characteristics are more complex, the electric field strength (E-field) and the magnetic field strength (H-field) are used to characterize the exposure.

The word "dose" is used in many applications and with different definitions, but the term dose is generally used to describe the amount of something that is taken up by an object. For ionizing radiation, dose is often referred to as the absorbed dose, and in [ICRU, 1998] the absorbed dose (D) is defined as:

\[ D = \frac{d\bar{E}}{dm} \quad [J/kg] \]

where \(d\bar{E}\) is the mean energy imparted to the matter in an infinitesimally small volume of mass \(dm\). In other words, the absorbed dose is the expectation value of the energy imparted per unit of mass.

[ICRU, 1998] also defines the absorbed dose rate (\(\dot{D}\)) as

\[ \dot{D} = \frac{dD}{dt} \quad [J/kg^{-1}s^{-1}] \]

Against this background, the dose describes the energy absorption in a volume and can not be defined without also taking the time factor into account. This means that
the only established parameter used in RF field research that can describe the dose is the Specific Absorption (SA), which defines the quotient if the incremental energy \((dW)\) absorbed in an incremental volume \((dV)\) with a mass \(dm\) [NCRP, 1981] and is expressed as:

\[
SA = \frac{dW}{dm} = \frac{dW}{\rho dV} \quad \text{[J/kg]}
\]

The SAR, on the other hand, should be considered as a dosimetric quantity describing the dose rate, not the dose.

In this work, the Specific Absorption per Day (SAD) and the Specific Absorption per Call (SAC) were used as estimates of the dose for mobile phone users.

For operators of RF sealers, the complicated exposure conditions make a calculation of SAR and in the long run SA difficult. Instead, time-integrated exposures have been used to approach a dose concept. In this case only the exposure and the exposure time have been used, and the absorption of RF fields has not been considered.

**Mobile phone users**

When the questionnaire was sent out (1996), NMT and GSM were the available transmitter systems and there are some important differences between those two. In general, the analogue NMT MP gets warmer due to resistive heating compared to the GSM phone [Törnevik et al, 1998]. This is also the major reason why only GSM users were included in Paper III, since we were more interested in possible effects from RF exposure rather than conductive heating. However, conductive heating is an important parameter to investigate in relation to subjective symptoms and this is currently being done by Oftedal and co-workers in Trondheim, Norway. A measurement procedure for temperature measurement has recently been published [Straume, 2002].

In this thesis it was found that the calling time is an important parameter for the prevalence of subjective symptoms. This is true for MP users in general (Paper I), and this is also the most important factor pointed out by people who claim that their symptoms are caused by the use of an MP (Paper II). People with a longer calling
DISCUSSION

time per day might experience a more stressful work situation and there might also be other factors, which have not been adjusted for, that could affect the results.

When the questionnaire was sent out, people were not aware of the SAR levels of their mobile phone. If the higher prevalence of symptoms among those with a longer CT has anything to do with the absorption of RF fields, SAC and/or SAD would be a better estimate of exposure than CT alone. The approach in Paper III, where the calling time (CT) was compared with the absorption parameters SAC and SAD, is therefore one way of considering the effects of RF exposure. For some of the symptoms, SAD seems to be a better estimate of exposure compared to CT. However, the differences are small, which indicates that there are also factors other than absorption of RF fields that affect the prevalence of symptoms.

During an MP call, the side of the head where the MP is held is exposed to RF fields. Since RF fields with a frequency of 900 MHz has a penetration depth of approximately 5 cm and that the field decreases rapidly with the distance from the source, the most exposed parts of the head are the surface around the device and the antenna. One can therefore speculate that biological effects from exposure to RF fields emitted by mobile phones have as a “target organ” the peripheral part of the head, on the same side as the mobile phone is held. This is supported by Schuderer et al. [2002], who have shown that exposure to synthesized “talk–like” GSM signals, with a spatial peak SAR10g value of 1 W/kg, produces an increased regional blood flow on the side of the head where the device is held. The examination (PET scan) was done after a 30 min exposure session.

Preece et al [1999], who found that simulated mobile phone signals (915 MHz) have an effect on cognitive functions, also discussed their findings in terms of biologically important anatomical localization of the absorption. They speculate that the angular gyrus, located in the area close to the antenna of the mobile phone is the target organ for the observed effects on the brain function.

In the body of literature, which describes effects on the Blood Brain Barrier (BBB), an increase in permeability of the barrier was found already at relatively low SAR levels. The available literature on this issue, however, is contradictory. A summary of these findings is available in Stewart [2000].

Töre et al [2002] discuss their findings of an increase in BBB permeability in the dura matter as a possible explanation to the occurrence of headaches among mobile phone users. The target volume for this should be volume 1 (above ear), where we find that SAR1g values > 0.5 W/kg might be of importance among people with a
long calling time per day compared to those with a short calling time per day ($CT$). Since we also find that the specific absorption per day ($SAD$) might be a better estimate for exposure than the specific absorption per call ($SAC$), it would be of interest to evaluate potential differences in the BBB leakage after a fractionated exposure over one day compared to the same total exposure time applied on one occasion.

Operators of RF sealers

RF operators are a group highly exposed to RF fields. In Paper V, it was shown that 16 out of a total of 46 measured work places exceeded the ICNIRP guidelines. The RF operators are seldom aware of their high exposure and measurements of the exposure are seldom or almost never made. In many cases it is possible to reduce the exposure by simple actions. Proper grounding of the machine can reduce the E-field and the risk of high contact currents and induced currents and the exposure can be reduced significantly by the use of a return electrode [ILO, 1998]. As it has been shown in Paper VI, introducing a separation distance between the operator and the ground will reduce the current induced in the body during exposure. For tarpaulin workers, who stand in front of the RF sealer, the use of a rubber mat on the floor in front of the RF sealer will reduce the induced current.

RF operators are in general whole-body exposed. Since the RF field decreases with the distance from the electrode, the highest exposure is close to the electrode. Therefore, depending on the work task, the head, trunk and the hands are often the most highly exposed parts of the body. Ready-made clothing workers sit in front of the electrode during the whole welding procedure, while the tarpaulin workers sometimes move along the table during the welding process. This means that ready-made clothing workers are more highly exposed than tarpaulin workers. In fact, all of the ready-made clothing work places measured in this study exceeded the Swedish regulations [Arbetarskyddsstyrelsen, 1987], as well as the international guidelines [ICNIRP, 1998].

It is difficult to calculate SAR in different anatomical positions for the RF operators and a simpler “dose” approach was therefore used, in which the exposure parameters E-field and H-field were integrated over time. This method has also been used by Bortkiewicz et al [1996] who evaluated the neurovegetative regulation of the heart rate in workers occupationally exposed to RF fields of a frequency range of 0.7-1.5 MHz. The time integrated exposure parameters used in that study
were a daily RF exposure “dose” and a RF cumulative lifetime ”dose”. These parameters are similar, but not equal to $E_{\text{day}}$ and $E_{\text{life}}$ used in Paper V.

Kolmodin-Hedman et al [1988] found that operators of RF sealers have a higher consumption of headache pills compared to a control group. This was not confirmed by this study, but the prevalence of self-reported headaches was higher among RF operators compared to the control group, and those reporting headaches had a significantly higher time integrated E-fields during a weld ($E_{\text{weld}}$) compared to those who did not report headaches. The results indicate an acute effect of RF exposure, where the energy deposition during a weld, which usually ranges for a couple of seconds, might (for some people) lead to headaches.

Warmth sensations in the hands and fatigue seem to be linked to exposure over a longer period of time ($E_{\text{life}}$ and $E_{\text{day}}$, respectively). Since the exposure levels in many cases are above thermal thresholds, it can not be excluded that the SAR values might exceed the stated limits, and therefore the warmth sensations might be a direct result of this.

Fatigue is a general symptom that may be caused by many other time related factors, which have not been considered in this study. The results in Paper V, however, indicated that the time integrated RF exposure might be of interest in this context.

During RF welding there is always a magnetic field present. As mentioned earlier, the H and E-field are coupled, but in the case of RF welding, where the operator is standing within the near field, the relation between the H and E-field is complicated. A high E-field does not necessarily imply a high H-field and vice versa. The results in Paper V showed that the time integrated E-field parameters were, in general, better correlated with the subjective symptoms than the H-field parameters.

The preliminary findings that RF operators show a decreased heart rate and increased episodes of bradycardia compared to the control group are in line with both previous Russian findings [Presman, 1970] as well as with more recent work among radio transmitting workers, exposed to 10-30 MHz [Szmigielski et al, 2000]. In a presently ongoing follow up study the HRV and the possible association to exposure is studied.
Subjective symptoms and RF exposure

A general result in this thesis was that the most commonly reported symptoms among mobile phone users and operators of plastic welding machines (RF operators) were warmth sensations and headaches. These are also the most reported symptoms among those who actually associate their symptoms to MP use/RF welding.

Previous Russian and Eastern European studies have also found a higher prevalence of subjective symptoms, such as headaches, among RF exposed individuals [Baranski and Czerski, 1976; Marha et al, 1971]. In more recent studies, the same results have been found among regulators of naval communication equipment [Nikitina, 2000; Zhao et al, 1994] and among mobile phone users [Chia et al, 2000; Hocking, 2001].

Together with the findings in this thesis, it seems reasonable to believe that some individuals are perceptive to RF fields and the health implication can for instance be headaches, and each individual might have a certain threshold at which the symptom occurs. In most previous studies possible dose/exposure - response relationships have not been evaluated, which makes it difficult to compare the studies and to come up with possible explanations to the findings.

In this thesis, the time-integrated exposure over a day (\(E_{\text{day}}\) and \(SAD\), respectively) shows the strongest association with experience of warmth sensations for both RF operator and MP users.

The prevalence of headaches and the time integrated E-field during a weld (\(E_{\text{weld}}\)) showed a strong association among RF operators. Headaches were also found among MP users, but the association with the dosimetric quantities (\(SAC\) and \(SAD\)) was not that clear. Among MP users with \(CT > 15\) mins/day, however, the prevalence of headaches is higher for those with \(SAR_{t5} > 0.5\) W/kg compared to those with \(SAR_{t5} \leq 0.5\) W/kg. This difference is not seen among MP users with \(CT \leq 15\) mins/day, indicating a threshold effects.

Possible reasons for this is that during an MP call, the absorbed energy in the head is on the lower limit of what is needed to cause headaches compared to the absorption during RF welding. To compare the absorption in the head during RF welding with the MP case, numerical calculations of the SAR during RF welding is needed, but for the RF welding frequencies (20-30 MHz) the penetration depth is approximately 20 cm [Durney et al, 1986]. Thus, the whole head will be exposed to...
DISCUSSION

RF fields during RF welding. The frequency used for the GSM devices in the study was 900 MHz (1800 MHz was not yet in use in the Nordic countries). It has a penetration depth of approximately five centimeters [Durney et al, 1986; Hombach et al, 1996] and therefore only the volume close to the area where the MP is held during a call will therefore be exposed.

When comparing MP users and RF operators it is important to remember that the exposure assessment is not quite comparable. For both groups, the self-estimated exposure time has been used in the calculation of the dose (MP-users) or time-integrated exposure (RF operators). The error for this might be comparable for both groups, but the measured $SAR_{1g}$ values, which have been used as a basis for MP users, are probably not comparable to the measured field parameters for RF operators, with respect to generalizations, misclassifications and measurement errors. This might also be an explanation to the differences found for headaches and the connection to the exposure/dose parameters.

There are also other factors that make a comparison between MP users and RF operators difficult. First, from an exposure point of view, there are some major differences, which are summarized in Table 8.

Table 8. Exposure characteristics for RF operators and MP users.

<table>
<thead>
<tr>
<th></th>
<th>MP users</th>
<th>RF operator</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>GSM</td>
<td>NMT</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>~900</td>
<td>~900</td>
</tr>
<tr>
<td>Time slot repetition rate</td>
<td>217 Hz</td>
<td>-</td>
</tr>
<tr>
<td>Modulation</td>
<td>TDMA</td>
<td>FM</td>
</tr>
<tr>
<td>DTX*</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Output power</td>
<td>0.4-250 mW</td>
<td>0.1-1 W</td>
</tr>
<tr>
<td>Exposed parts</td>
<td>Parts of the head</td>
<td>Parts of the head</td>
</tr>
<tr>
<td>Exposure time per call/weld</td>
<td>minutes</td>
<td>minutes</td>
</tr>
<tr>
<td>Exposure time per day</td>
<td>~15 min</td>
<td>~15 min</td>
</tr>
<tr>
<td>(estimated mean)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Penetration depth (cm)**</td>
<td>~5</td>
<td>~5</td>
</tr>
</tbody>
</table>

* Discontinuous transmission, which means that the transmitter is turned off when no information is to be sent. This takes place during a silent period during a conversation, for instance when the other party is talking. [Pedersen and Andersen, 1999]
** From Durney et al. [1986]
Additional factors distinguishing the two groups also make a comparison difficult. RF operators are often blue-collar workers with a low educational level, while the MP users in the study belong to many different occupational categories with the proviso that MPs are used in their work (which is not the case for the RF operator).

Future exposure assessment

For both groups it was found that the exposure time is critical for the prevalence of symptoms. These findings suggest that the time-integrated exposure, or perhaps the actual absorption, should be considered when discussing non-thermal effects. This thesis proposes two new dosimetric parameters (SAC and SAD) and also three time-integrated exposure parameters (E-weld, E-day and E-life). It would of course be interesting to evaluate the actual absorption in different parts of the body during RF welding, but for this appropriate calculation/simulation techniques are needed for this.

Studies on biological effects from RF exposure in general often lack clear hypotheses about what parameters characterizing the exposure are of importance for the studied effects [Veskovic et al, 2002]. These issues have been discussed in Morgan and Nair [1992] for ELF exposure (60 Hz), where alternative plausible effect functions for instance linear and non-linear effects, cumulative exposure parameters (which is quite similar to the time-integrated field strengths used in Paper V) and window effects are discussed. For RF fields, the main focus in many studies has not been thermal effects, and we do not know the possible interaction mechanism. Therefore, we probably need more information about the exposure than simply the SAR value. In further studies, a deeper discussion about these issues is needed.
CONCLUSIONS

Mobile phone users

GSM users do not report more subjective symptoms in general, irrespective of an association with MP use, than do NMT users. In fact, for warmth sensations on/around and behind the ear, the NMT users actually report more symptoms compared to the GSM users. Calling time per day (CT) was found to be associated with the prevalence of symptoms such as headaches, warmth on the ear and warmth behind the ear.

For those claiming that their symptoms are caused by MP use (in total around 10 %), the most commonly reported symptoms were warmth behind the ear and headaches. The symptoms generally appeared shortly after a phone call was made and people reported more symptoms with an increasing CT.

The specific absorption of RF energy during a day ($SAD$) seems to be best correlated with dizziness, discomfort and warmth behind the ear compared to CT alone and the specific absorption during a call ($SAC$).

Whole body exposure

The measured currents induced in the body during whole body exposure to RF fields (1-20 MHz) were found to be highly affected by the choice of measurement technique (parallel plate meters or current probes). This was especially important in ungrounded conditions where the difference in reading between the instruments increased to more than 20 %. This is partly explained by the capacitive coupling between the larger sized parallel plate meters and ground.

Operators of RF plastic sealers (RF operators) are a highly exposed group, which was confirmed by the fact that 16 out of 46 measured work places exceeded the ICNIRP guidelines. Headaches were found to be associated with the mean value of the time integrated E-field during a weld (E-weld) and the warmth sensations in the hands (warm hands) with the time integrated E-field exposure during one day (E-day).
GENERAL CONCLUSION

This thesis confirms previous results that occupationally RF exposed individuals report more symptoms such as headaches and warmth sensations compared to a control group.

The general findings in this thesis indicate that the time factor should be included in the exposure assessment when studying non-thermal effects such as subjective symptoms in connection with RF exposure. The thesis proposes two different methods for doing this, namely time-integrated exposure \([V/m \times s] \text{ and } [A/m \times s]\) and dose \([J/kg]\).
FURTHER STUDIES

To get new useful information from further epidemiological studies of subjective symptoms among MP users is probably very difficult. The awareness of the RF exposure from MPs has increased, and the measured SAR values are enclosed with many of the MP devices sold today. It is also difficult to find an appropriate control group.

To study other RF exposed groups with the aim to compare the prevalence of subjective symptoms to a control group would probably not give any new information without having a clear hypothesis about what characteristics of the exposure give rise to the symptoms, for example duration of exposure, energy deposition and anatomical localization of the exposure.

Provocation studies are an interesting, but also a very difficult “next step”. Careful exposure assessments as well as a clear hypothesis about the relation between the studied health outcome and the exposure and dosimetric quantities (dose and dose rate) are important [Hansson Mild and Wilén, 2002]. Also, when studying subjective symptoms caused by RF exposure the exposure should last at least 15 mins before the symptom occurs, as was found in this thesis. It was also found that for some of the symptoms, the absorption during a whole day seemed to be more critical than the absorption during a call (SAD compared to SAC), which means that one single exposure episode is perhaps not enough to cause symptoms. If also taking this into account, one realizes that designing a high-quality provocation study is not easy.

The most important step to take is to understand the origin of the observed findings from an exposure point of view, but this is also very important to understand from a physiological/medical point of view. Changes in blood-flow due to RF exposure might, as mentioned earlier, be an explanation to warmth sensations and plausibly also to headaches. It would therefore be of interest to explore the role of dose (SA)-effect responses or dose rate (SAR)-effect. Also, it would be interesting to compare local head exposure (as in the use of an MP) with whole head exposure (as during RF welding).

E-day, E-life and SAD, as used in this thesis, are all integrated over the exposure time with no respect paid to fractionation, which means that a single exposure of T minutes has been regarded as equivalent to two single exposures of T/2 minutes.
For RF operators as well as for MP users, the energy deposition is not even during the whole exposure period. For RF operators, there is a non-exposed period of seconds or minutes between each weld. This is also true for MP users, where each MP call is followed by a non-exposed period of seconds, minutes or hours before the next call. It would therefore be of interest to evaluate the importance of fractionation for the studied effects.

Analyses of the heart rate variability should be done to further understand the preliminary findings about lower heart rates and the increase in episodes of bradycardia among RF operators compared to the control group. A possible correlation between those findings and the level of exposure should also be evaluated.
ACKNOWLEDGEMENT

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