FFI-rapport 2013/01926

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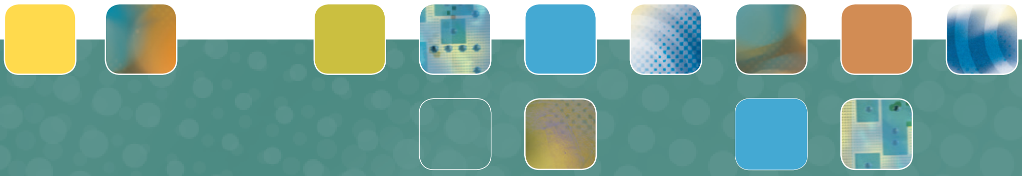

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30 May 2013

FFI-rapport 2013/01926

1193

P: ISBN 978-82-464-2278-7
E: ISBN 978-82-464-2279-4

Keywords

Elektromagnetisk stråling

Ikke-ioniserende stråling

Grenseverdier for stråling

Bærbar jammesystem

Bærbar kommunikasjonsradio

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English summary

The Norwegian Armed Forces follow the guidelines of ICNIRP for occupational exposure to non-ionizing radiation. This is consistent with civil regulations. For the frequencies we are interested in (from 100 kHz to 10 GHz) mainly thermal effects are relevant. Only for the lowest frequencies (up to 10 MHz) excitation of nerve tissue may occur.

This report discusses the relationship between the basic restrictions or BR (norw. basisverdier), which are legal limits for electromagnetic fields inside the human body, and maximum permissible exposure (MPE) limits (norw. referanseverdier), which are recommended limits of radiation levels in areas where personnel may be present ensuring that the BR are not exceeded. There are two types of BR, a combined or average value for the whole body of 0.4 W/kg, and local BR for various body parts of 10 W/kg for head and torso and 20 W/kg for the extremities.

Since the few specific MPE limits listed in the ICNIRP Standard are only valid for exposure to the far field and in relation to the BR for the whole body, there are clear limitations on their use. The IEEE Standard, which rests on the same BR, goes one step further by also providing local MPE limits related to the local BR - but still with the limitation that exposure should not happen in the near field of a transmitter. Also NATO’s NSA STANAG follows mostly the IEEE MPE limits.

When using ICNIRPs whole-body MPE limits for fields with varying strength across the body (still excluding near field exposure) the correct procedure is to use an averaged value, provided that local BR are not exceeded.

In light of this, we discuss earlier measurements of a portable jamming system as an example. For this case, it can be concluded that:

a. the radiation level is acceptable compared to the whole-body MPE limits of the ICNIRP Standard if one uses an averaged value and exposure is considered in the far field of the transmitter,
b. the local MPE limits of the newer IEEE Standard suggest that local BR are not exceeded at any single point if exposure is considered in the far field of the transmitter,
c. measurements and simulation of thermal effects in the human body of communication radios with similar power indicate that local BR of the ICNIRP Standard will not be exceeded for exposure in the near field of the transmitter. This can, however, be affected by the frequency band and the physical design of the jamming system.

The discussion and results in this report may be used as background material for the assessment of improved safety procedures for approval of equipment in the Norwegian Armed Forces, where one also takes into account other thermal loads.

Sammendrag

Forsvaret følger retningslinjer fra ICNIRP for yrkeseksponering til ikke-ioniserende stråling. Dette samsvarer med sivil forskrift. For de frekvenser vi er interessert i (fra 100 kHz til 10 GHz) er det stort sett termiske effekter som er relevante. Bare for de laveste frekvenser (opp til 10 MHz) kan eksitasjon av nervevev forekomme.

I denne rapporten diskuteres sammenhengen mellom basisverdier (engl. basic restrictions, BR) dvs. legalt tillatte nivåer i kroppen, og referanseverdier (engl. maximum permissible exposure, MPE), dvs. anbefalt maksimalt tillatt strålingsnivå der hvor personell oppholder seg, slik at basisverdiene ikke overskrides. Det fins to typer basisverdier, en sammenlagt eller gjennomsnittlig verdi for hele kroppen på 0,4 W/kg, og lokale basisverdier for ulike kroppsdeler på 10 W/kg for hode og torso og 20 W/kg for ekstremiteter.

Siden de få spesifikke referanseverdiene som er listet i ICNIRP-standarden forutsetter fjernfelt og kun er knyttet til basisverdien for hele kroppen, er det klare begrensninger på bruken av disse. IEEE-standarden, som er bygget på de samme basisverdiene, går ett skritt lenger ved også å oppgi lokale referanseverdier knyttet til de lokale basisverdiene – men fremdeles med den begrensning at eksponeringen ikke skal skje i nærfeltet til senderen. Også NATOs NSA STANAG følger stort sett IEEEs referanseverdier.

Ved bruk av ICNIRPs referanseverdier for felt med varierende styrke ved ulike steder på kroppen (samtidig som man ikke er i nærfelt) vil det være korrekt å benytte gjennomsnittlige verdier, så lenge lokale basisverdier ikke overskrides.

I lys av dette diskuteres tidligere målinger av et bærbart jammesystem som eksempel. I dette tilfellet kan det konkluderes med at:

a. strålingsnivået er akseptabelt i forhold til referanseverdiene for hele kroppen i ICNIRP-standarden dersom man benytter gjennomsnittlige feltverdier og eksponering betraktes å være i fjernfelt til senderen,
b. lokale referanseverdier i den nyere IEEE-standarden tilsier at lokale basisverdier ikke overskrides i noe punkt dersom eksponering kan betraktes å være i fjernfelt til senderen,
c. målinger og simulering av termiske effekter i kropp på kommunikasjonsradioer med tilsvarende effekt sannsynliggjør at lokale basisverdier i ICNIRP-standarden ikke vil overskrides ved eksponering i nærfelt til senderen. Dette kan imidlertid påvirkes av frekvensbånd og fysisk utforming av jammeren.

Diskusjon og resultater i rapporten kan inngå som bakgrunnsmateriale for vurdering av bedre HMS-prosedyrer for godkjenning av utstyr i Forsvaret, hvor man også tar hensyn til øvrig termisk belastning.

Contents

1 Introduction

The new IEEE Standard and the older ICNIRP Standard dealing with health hazards related to non-ionizing radiation are formulated in terms of basic restrictions (BR) which limit the *in situ* electric field (3 kHz to 5 MHz), the specific absorption rate (100 kHz to 3 GHz) or incident power density (3 GHz to 300 GHz). In the case of frequencies below 3 GHz, this means the limit is based on physically measureable quantities inside human tissue.

While not impossible, these quantities are often somewhat impractical to measure in a particular exposure scenario. To aid the practitioner in the field of radiation safety, a set of maximum permissible exposure (MPE) limits has been derived from the BR for frequencies below 3 GHz. They limit the field strengths or power densities to which a person may be exposed, i.e., they are based on physically measureable quantities outside of human tissue. (For frequencies above 3 GHz the BR are already formulated in terms of incident power density - they are identical to MPE limits).

The MPE limits are derived or estimated from the fundamental BR including a safety margin. This means that if the MPE limits are met, the BR are guaranteed to be satisfied. Conversely, lack of compliance with the MPE limits does not necessarily mean lack of compliance with the fundamental BR and hence the Standard. As for the BR, MPE limits are divided into upper and lower tier limits (occupational and general public exposure) as well as limits on whole-body averages and localized exposure. However, the older ICNIRP Standard does not list specific local MPE limits. Only the newer IEEE Standard gives explicit numbers for the relaxation of the (whole body) power density MPE limits for localized exposure. We will in the following discuss the connection between those BR and MPE limits above 100 kHz which are derived to limit thermal effects in the human body. Additional BR and MPE up to 5 MHz have to be considered to limit effects due to excitation of nerve tissue.

2 Standards

In the region of 100 kHz to 3 GHz, the BR are formulated in terms of the Specific Absorption Rate (SAR) given by the absorbed (electromagnetic) power per (body) mass. The (upper tier or occupational) BR in both Standards are 0.4 W/kg for whole-body exposure, 10 W/kg for localized exposure and 20 W/kg for localized exposure at the extremities. The rationale for the different BR will be discussed in Section 4. The lower tier or general public BR are a factor 5 below the occupational BR. The rationale for the two different tiers is that the population of the upper tier is supposed to consist of healthy adults, while the lower tier also include among others the aged, infirm and minors which should be afforded additional protection. We will, in the following focus on the upper tier (occupational) BR.

Whole-body MPE limits are derived from the (most stringent) whole-body BR of 0.4 W/kg. These MPE limits assume a reasonably uniform field which can be averaged over the dimensions of the exposed human body, as it is typical for exposure to the far-field of radiation sources. In the frequency region between 100 MHz and 300 MHz this has been translated by both Standards to an MPE limit on the intensity of radiation $I = 10\ \mathrm{W/m^2}$. This limit can be rationalized assuming that (i) the projected surface of the human body is 2 m^2, i.e., 2 m high and 1 m wide (more realistic is about 0.9 m^2), (ii) the body mass is 50 kg (more realistic for an adult is some 70 kg), and (iii) the entire radiation is absorbed by the human body (realistic is that about half or more of the radiation will be reflected). Within these assumptions, radiation at the MPE limit will produce a whole-body SAR of 0.4 W/kg, i.e., the value given by the BR. For frequencies below 100 MHz, the wavelength of the associated radiation increases above 3 m, i.e., $\frac{\lambda}{2} \gtrsim h$, where h is the typical height of the human body. For magnetic fields, which have to first induce currents along electric field lines according to $Bf \sim \frac{E}{\lambda}$ in order to exhibit thermal effects, the typical height of the human body limits the ability to deposit power. Hence for frequencies below 100 MHz, the MPE limit for magnetic fields is formulated as $\frac{Bf}{\mu_0} = 16.3\ \frac{\mathrm{A}}{\mathrm{m}}\mathrm{MHz}$. At the transition frequency of 100 MHz, the MPE on power density and on magnetic field strength coincide. Similar considerations hold for the electric field, however, the large real part of the permittivity of human tissue will shorten the effective *in situ* wavelength. Hence the transition point from a straightforward limit on E to the limit on $Ef = 1842\ \frac{\mathrm{V}}{\mathrm{m}}\mathrm{MHz}$ is at a lower frequency of 30 MHz.

For frequencies higher than 300 MHz, more of the radiation will be absorbed at the surface and less will penetrate deep inside the body. The penetration depth or skin depth of electromagnetic radiation is in the order of a few centimeters and is decreasing with increasing frequency, hence the concept of a whole-body SAR becomes less meaningful. The MPE limits are therefore (linearly) interpolating between the 10 $\mathrm{W/m^2}$ limit at 300 MHz and the 100 $\mathrm{W/m^2}$ limit at 3 GHz which is identical to the BR at and above this frequency. In other words, the MPE limit between 300 MHz and 3 GHz is given as $I/f = \frac{1}{30}\ \frac{\mathrm{W}}{\mathrm{m^2}}/\mathrm{MHz}$.

The whole-body MPE limits discussed so far are conservative estimates derived from the BR (above 100 kHz) on the (most stringent) whole-body SAR. Since the BR on localized SAR allow for higher limits, the MPE limits for localized exposure are also relaxed. However, it is important to remember that in contrast to the connection between MPE limits and BR for exposure of the whole body, the connection between relaxed MPE limits and BR for localized exposure is a bit more tenuous. The IEEE Standard itself cautions that assessment of exposure (in terms of relaxed MPE limits for localized exposure) under conditions wherein the fields are strongly non-uniform may not ensure compliance with the BR on localized SAR. This becomes particularly important when the source of radiation is very close such that the individual is in the reactive near field of the source where substantial coupling may take place. In fact, it seems impossible to formulate relaxed MPE limits for localized exposure which guarantee under all conceivable circumstances compliance with the BR on localized SAR.

Irrespective of these limitations, the (new) IEEE Standard lists relaxations of the MPE limits for localized exposure. To at least avoid situations of possible coupling in the reactive near field and hence strengthen the connection between the relaxed MPE limits and the BR for localized exposure, the assessment of exposure is deemed meaningful by the IEEE Standard only if the source is at least 20 cm distant from the exposed individual. For sources closer than that, compliance with the Standard has to be assessed by measuring the SAR directly. With the distance requirement satisfied, the relaxed MPE limits for spatial peak (localized) exposure below 300 MHz are 20 times higher intensity or squared field values than the MPE limits ensuring compliance with the BR on whole-body SAR. This reflects the fact that the BR on localized SAR list 25 times higher values than the BR on whole-body SAR. Between 300 MHz and 3 GHz, the relaxed MPE limit is at an incident intensity of 200 W/m^2. Hence, contrary to the whole-body MPE limit, the relaxed MPE limit does not increase with frequency. Now, because of the increase of the whole-body MPE limit with frequency, the ratio of the relaxed MPE limit to the whole-body MPE limit decreases from 20 at 300 MHz to only 2 at 3 GHz. The two different MPE limits approach each other at high frequencies because the decreasing skin depth for electromagnetic radiation produces a pattern of localized exposure anyway, with most of the radiation absorbed at the surface. Hence, in that sense, the MPE limits at these high frequencies are based more and more on the BR on localized SAR.

Overall, the MPE limits in the frequency range between 100 kHz and 3 GHz are a useful tool for assessing compliance with the Standard provided that (i) the distance between source and exposed individual is 20 cm or more and (ii) it is realized that compliance with the relaxed MPE limits for localized exposure is no absolute guarantee for compliance with the BR on localized SAR and hence the Standard.

3 Assessment of previous work

Given the relaxed MPE limits listed in the new IEEE Standard, it is now interesting to assess previous measurements. In particular, RadHaz measurements of a portable jammer have been performed and are reported in the document VLE-34/10. In order to establish compliance with the Standard on the BR on the whole-body SAR, it is sufficient to establish compliance with the respective whole-body MPE limits. These limits are formulated as a spatial average over an area equivalent to the vertical cross section of the human body. For the measurement in question, to approximate this spatial average, we perform the averaging over measurement points 1-5 and 7 (we reject measurement points 6 and 8 which are on the far side of the individual, opposite to the position of the jammer). These averages always produce values below the whole-body MPE limits, hence compliance with the BR on the whole-body SAR is established.

In the next step, individual measurements are compared to the relaxed MPE limits for localized exposure which allow for $\sqrt{20} \sim 4.5$ times higher field values than the whole-body MPE limits. Again, it is found that none of the individual measurements exceed the relaxed MPE limits for localized exposure. However, as mentioned above, compliance with the relaxed MPE limits for localized exposure is no absolute guarantee for compliance with the BR on the localized SAR. Finally, we remark that for the sake of the argument in this chapter it is assumed that the radiation source has a distance of at least 20 cm to the exposed individual. If the distance requirement is not met, compliance with the Standard cannot be established by means of MPE limits.

In conclusion, assuming that the distance of the radiation source to the exposed individual is larger than 20 cm, we can conclude that the measurements establish compliance with the BR on the whole-body SAR and compliance with the MPE limits for localized exposure.

4 Heat stress

In the frequency range between 100 kHz and 3 GHz, the upper tier BR on the whole-body SAR of 0.4 W/kg is based on the observation that a ten-fold SAR of 4.0 W/kg often leads to an increase of core body temperature by 1℃ and the onset of behavioral responses. In other words, the BR on the whole-body SAR has a factor ten safety margin relative to such responses. Typical resting metabolic rates are in the order of 1.25 W/kg. Compared to that, the above-mentioned 0.4 W/kg corresponds to a 32% increase in thermal load. Heating at this level is deemed to be comparable to donning a light sweater by the IEEE Standard. Healthy young humans have the capacity to cope with thermal loads (either external or due to work load) that are up to 15 times the resting metabolic rate. We should point out, however, that contrary to common, surface-based heating mechanisms from, e.g., radiant heat sources, ambient air temperature, humidity, air velocity and clothing, exposure to high-frequency electromagnetic fields may deposit thermal energy in deep tissues and is therefore more comparable to thermal loads from vigorous exercise. Still, equivalent deposited heat from either exposure to radiation or exercise yields equivalent thermal responses.

Changes in body temperature can be expressed by

$$c_V \frac{\mathrm{d}T}{\mathrm{d}t} = M - K - C + SAR, \tag{4.1}$$

where M, K and C are the metabolic heat rate, the heat loss due to thermal conduction and the heat loss due to convection (blood flow), respectively. The specific heat capacity c_V has a value of some 3.5 $\frac{\mathrm{kJ}}{\mathrm{kg{\cdot}K}}$. Assuming a steady state prior to exposure to high-frequency electromagnetic fields, i.e., $M - K - C = 0$, the SAR can be expressed as

$$c_V \frac{\mathrm{d}T}{\mathrm{d}t} = SAR. \tag{4.2}$$

A SAR of some 60 W/kg may therefore produce a (practically adiabatic) temperature increase of about $1℃/\mathrm{min}$. However, humans possess a thermoregulatory mechanism, therefore heat may be diffused efficiently through convection, even in organs with comparably low blood flow as the eye. This leads to a set of BR on the localized SAR (one for the trunk and one for extremities) which allows for higher levels of localized exposure. The enormous effectiveness of the human thermoregulatory mechanism is reflected by the fact that the BR on the localized SAR are 25 times or more above the one on the whole body SAR. The highest allowed levels are for the extremities, since the large surface area per volume promotes efficient heat dissipation through thermal conduction as well. At this point, it is important to mention that in studies with localized SAR values which exceeded the BR and which included additional, external cooling, detrimental effects on tissue have been shown to be caused only when tissue temperatures in fact got elevated, and not by the deposited electromagnetic power *per se*. It is therefore conceivable that future BR may be based on actual temperature increases, and not on deposited electromagnetic power, thereby requiring temperature measurements, not measurements of electrical fields.

It is now instructive to compare the heat stress from exposure to high-frequency electromagnetic fields (given by the SAR) to other sources of heat stress. For instance, an increase of $1 - 2$°C of ambient temperature will feel similarly as being exposed to the whole-body SAR limit of 0.4 W/kg and hence will create a similar thermoregulatory response (e.g., sweating and increased blood flow). As a second point of comparison, for ambient temperatures between $24 - 36$°C, a work load above resting of 4 W/kg results in an increase of equilibrium core temperature of less than 1°C. Only if the ambient temperature is increased to 46°C will a work load of 0.4 W/kg (or the equivalent heating caused by a whole-body SAR of 0.4 W/kg, i.e., the limit given by the BR) lead to a core temperature increase of 1°C.

Overall, although behavioral response to exposure of high-frequency electromagnetic fields has usually been correlated with increase in actual core body temperature, the response is more likely caused by thermal discomfort – a sensation related to the degree of the thermoregulatory response – which is a measure including work load, ambient temperature and humidity, wind speed, exposure to sunlight and other heat sources, the amount of clothing etc. Hence, SAR values should enter evaluation of the Heat Stress Index. The Heat Stress Index is defined as the ratio of the total evaporative heat loss required for thermal equilibrium to the maximum evaporative heat load possible for the environment, multiplied by 100, for steady-state conditions and with skin temperature held constant at 35°C.

5 Conclusion

In conclusion, we have investigated the connection between the Basic Restrictions and the Maximum Permissible Exposure given in the ICNIRP and IEEE Standards. In particular, we have discussed under what circumstances it is sufficient to perform the more practical measurements of external electromagnetic fields (related to the MPE limits) in order to determine compliance with the BR (which are related to the specific absorption rate and hence the *in situ* electrical fields) of the Standards. In light of this discussion, we have re-evaluated the measurements of a previous work in correspondence to the relaxed MPE limits for localized exposure listed in the IEEE Standard. Finally, we have discussed the temperature response of the human body to different values of the SAR and put it into context of other, more commonly experienced sources of thermal stress and discomfort such as work load and ambient temperature.

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