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# Adverse Health Effects of ELF and RF Electromagnetic Fields that Serve as Basis for Setting Safety Limits

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*Abstract:* - As technology advances the general public is every day exposed to Extremely Low Frequency (ELF) electric and magnetic fields and radiofrequency (RF) electromagnetic fields emitted by existing as well as novel applications. Common sources of ELF electric and magnetic fields are high voltage power lines and electrical appliances, whereas RF electromagnetic fields are emitted by communication systems like mobile phones and their base stations. Though the possible long-term adverse health effects of these fields are the subject of on going scientific research and many controversial opinions are expressed about their existence, there are well known adverse health effects that serve as basis for setting safety limits. Many international organizations such as ICNIRP and IEEE have developed exposure guidelines after reviewing the scientific literature. The established effects that form the rationale of all existing safety standards are examined in this paper.

*Key-words:* Adverse health effects, EMF-safety, induced currents, SAR, thermal effects

## 1 Introduction

During the last twenty years, there is intense public concern about the possible negative effects of exposure to extremely low frequency (ELF) electric and magnetic fields on human health. Common sources of these ELF fields include power lines, household wiring and electrical appliances. Recently the development of mobile communication systems caused similar growing concerns about the RF electromagnetic fields emitted by their base stations and mobile phones devices. Due to the intensity of these concerns there is a great interest and a lot of ongoing scientific research about the effects of these fields. Competent national and international bodies such as the World Health Organization (WHO) have formed expert committees in order to reach general conclusions about the effects of these fields.

Competent prominent scientific institutions as the International Commission on Non Ionizing Radiation Protection (ICNIRP) [1] and IEEE [2-3] have developed exposure guidelines for limiting exposure to ELF and RF fields. ICNIRP's guidelines are very important for the European Union (EU) region since EU Council adopted their basic restrictions and reference levels for the general public [4] and for the occupational exposure in the EU [5]. ICNIRP developed its guidelines after reviewing all the available scientific data and based them on the established adverse health effects of electromagnetic fields. Note that as adverse health effects are considered those that cause detectable damage. However, there may be other biological effects, that are not considered to have detrimental effects on health.

Established effects can be divided into direct effects resulting from the direct coupling of the human body with the field and indirect effects involving the interactions of the human body with an object inside an electric or magnetic or electromagnetic field. Direct effects of low frequency electric and magnetic fields are the induction of internal currents and superficial charges. A direct effect of a high frequency electromagnetic field is the heating of the human body. Indirect effects are mainly the possibility of shocks and burns when an individual is touching or is approaching an object in the presence of a strong electric, magnetic or electromagnetic field. Direct as well as indirect effects may become adverse only if some basic physical quantities, such as induced current density or temperature elevation, exceed certain thresholds. For example, if the induced current density exceeds a certain value, then it is possible to excite some sensitive neurons and cause severe health effects. Also, if the temperature elevation is greater than a few degrees Celsius, then it is possible to cause overheating. These thresholds are evaluated from volunteer studies and extrapolations from animal experiments

Based on these thresholds, ICNIRP derived its basic restrictions that protect from the infliction of known adverse effects in any exposure situation, taking into account safety factors (to compensate for potential environmental strains and uncertainties in knowledge) in the order of 10 for occupational exposure and in the order of 50 for general public exposure. Basic restrictions are based directly on established health effects. Depending on the frequency, the dominant effect changes and so does the basic restriction. There are basic restrictions for the current density (up to 10 MHz), specific energy absorption rate (100 kHz – 10 GHz) and power density (10 – 300 GHz).

The occupationally exposed population consists of adults exposed under controlled conditions who should be trained to be aware of potential risks and to take appropriate precautionary measures. Furthermore occupational exposure is limited to the duration of working day and working lifetime. The general public is comprised of individuals of all ages and different health statuses. Individuals or groups of high susceptibility may be included in general public. The general public may not be aware of the presence of fields, so the limits set for this case are stricter in order to protect them under all possible exposure circumstances and without any limitation to the duration of exposure.

In most cases it is difficult and not practical to evaluate whether an ICNIRP's basic restriction is exceeded. So, ICNIRP has provided some reference levels that allow the practical exposure assessment. The non-excess of the reference levels ensures the non-excess of the basic restrictions but if a reference level is exceeded, then it is not certain that a basic restriction is also exceeded. The reference levels for the electric field strength, magnetic field strength (or equivalently magnetic flux density), power density and limp currents are derived from basic restrictions assuming worst case coupling of the field with the body. The reference levels for contact currents (up to 110 MHz) and specific energy absorption (for pulsed fields from 300MHz to 10 GHz) address perception and other indirect effects. Figs 1 and 2 show the distribution of ICNIRP's reference levels for the electric field intensity and the magnetic flux density.

## 2 Coupling to ELF electric and magnetic fields

The exposure of the human body to a low frequency electric field external to the body causes the formulation of surface electric charges on it, due to its internal conductivity. The distribution of these charges depends on the position of the body in the field and is generally greater in the areas of the body where there is a high convexity and lower where there is concavity. The presence of this surface charge may cause annoyance or shock to the exposed person. A person inside a strong electric field can perceive its presence as a result of hair vibration. The majority of people can perceive 50/60 Hz fields stronger the 20 kV/m and a small minority can perceive fields below 5 kV/m. As the electric field is time varying, the surface charge is moving and forms electric currents inside the body. The total current inside the body is proportional to the frequency of the applied electric field and its magnitude. Although the total current is independent of the electric properties of the body tissues, the paths it follows inside the body depend on them (mainly their conductivity). The conductivity and permittivity of tissues vary with the type of tissues and also depend on the frequency of the applied field.

The magnetic permeability of living matter is close to that of vacuum and air and the conductivity is generally too low to affect the magnetic field. So, in contrast to the electric field, there is generally no disturbance of the magnetic field due to the presence of a human body. The exposure of the human body to a time varying magnetic field causes the induction of electric fields and circulating electric currents (Faraday induction). The magnitude of the induced current is proportional to the magnitude of the magnetic flux density, its frequency and the radius of the formed loop inside the body.

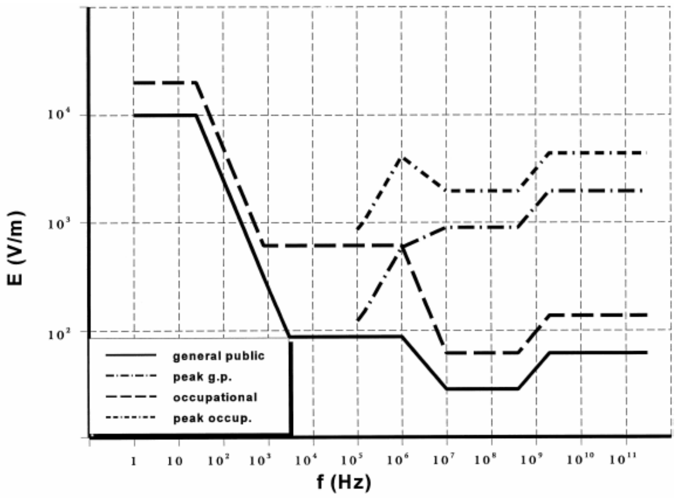


Fig. 1.ICNIRP's reference levels for electric field intensity [1]

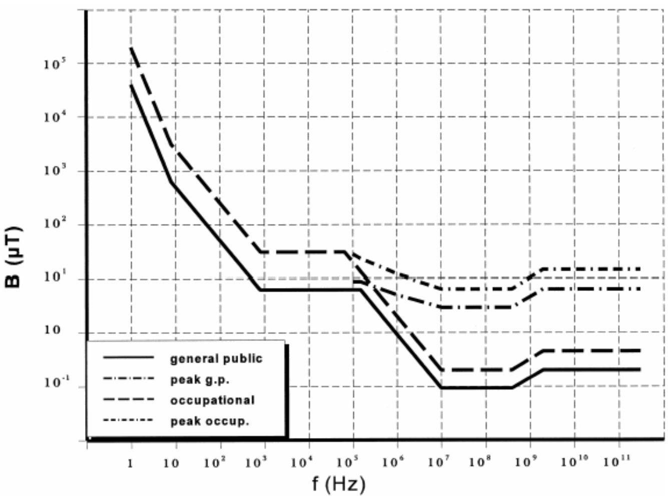


Fig. 2.ICNIRP's reference levels for magnetic flux density [1]

In both electric and magnetic field exposure, the existence of internal currents may result in stimulation of nerve and muscle cells as well as effects on central nervous system functions. Volunteer studies have shown that current densities above 10 $mA/m^2$ are considered capable to affect mental functions and to induce sensations of phosphenes. A pulsed field with a changing rate of 10 000 T/s is able to stimulate the median nerve trunk. If the induced current density in tissue is above 1 $A/m^2$, it is even considered capable of producing irreversible biological effects such as cardiac fibrillation. The induced current threshold for acute changes in the central nervous system excitability and other acute effects such as reversal of the visually evoked potential, is 100 $mA/m^2$. ICNIRP's occupational restriction for induced current density was set to 10 $mA/m^2$ (safety factor 10) and for general public restriction was set to 2 $mA/m^2$ (safety factor 50).

Electromagnetic fields at frequencies greater than 1 kHz are also capable to induce significant current densities. However, the threshold for adverse effects increases proportionally with frequency after 1 kHz, and so ICNIRP has set a basic restriction for current density that increases proportionally as a function of frequency till 10 MHz.

The reference levels for low frequency electric fields are expressed in terms of electric field intensity values. The worst-case situation of exposure to electric field is a grounding man standing into a field in vertical direction. The induced current density distribution varies inversely with the body cross-section and may be relative high in the neck and ankles of the exposed individual. ICNIRP set its reference level at 5 kV/m for 50 Hz general public exposure, as the induced current density is not considered to exceed 2 $mA/m^2$ for lower electric field values even at worst case conditions. (The value of 10 kV/m was selected as a reference level for 50 Hz occupational exposures to protect from stimulation effects of conduct currents - see paragraph about indirect effects.)

The reference levels for low frequency magnetic fields are expressed in terms of magnetic flux density values. In order to calculate the magnetic field levels that induces a given current density, many theoretical models have been proposed. The simplest of them consider the human body or its regions (for example the head) as a conductive loop, where the following relation gives the current density $J$, induced by a time varying field at frequency $f$:

$$J = \pi R f \sigma B \qquad (1)$$

where $B$ is the magnitude of the magnetic flux density normal to the loop surface, $R$ is the loop radius and $\sigma$ is the conductivity of the loop. Assuming, for simplicity, an average conductivity of 0.2 S/m, a magnetic flux density of 100 μT (ICNIRP's reference level for general public exposure) will induce a current density of 2 $mA/m^2$ in the peripheral of the body for a radius of 0.64 m.

## 3 Coupling to RF electromagnetic fields

Low frequency electric and magnetic fields (below 100 kHz) do not cause any significant energy absorption. However, exposure to electromagnetic fields at frequencies above 100 kHz can lead to significant absorption of electromagnetic energy from the human body. This energy is mainly converted into heat, which raises the cells temperature. If the temperature rise is more than 1 – 2 $^oC$, then it can have adverse health effects such as heat exhaustion and heat stroke. It is noted that in the frequency range 100 kHz to 10 MHz, ICNIRP has set simultaneously basic restrictions for current density and specific energy absorption rate (SAR) to protect from both nerve stimulation and thermal effects.

If the whole body SAR is beneath 4 W/kg, then the thermoregulatory mechanism of a human is considered capable to maintain the temperature rise beneath 1 $^oC$. Exposure to intense fields producing whole body SAR levels above 4 W/kg, can overwhelm the thermoregulatory mechanism of the body and produce harmful effects and excessive tissue heating. ICNIRP's occupational restriction for whole body SAR is set to 0.4 W/kg (safety factor 10) to allow for thermally stressful environments such as high ambient temperature, humidity, or level of physical activity. Considering that there may be higher thermal sensitivity in certain population groups, such as the frail or the elderly, infants or young children and people with diseases or taking medications, ICNIRP's general public restriction for whole body SAR is set to 0.08 W/kg (safety factor 50).

The deposition and distribution of this energy inside the body is generally non-uniform and depends heavily on the frequency of the incident field. Two basic phenomena have to be considered when examining the effect of frequency on the absorption of electromagnetic energy from the human body. These are the resonance and the penetration depth.

The resonance phenomenon has to do with the function of the human body or parts of it like an antenna absorbing maximum energy at a specific frequency and less energy at other frequencies. For far field exposures where the long axis of the human body (not grounded) is parallel to the electric field vector and the body height is 40 % of the incident field wavelength, the whole body SAR reaches maximal values. This phenomenon also depends on the incident field polarization, direction etc.

An ungrounded tall man has a resonant frequency of about 70 MHz or less. For a shorter individual or a kid or a baby or a seated individual, this frequency may exceed 100 MHz. For grounded individuals these values are lowered by a factor of 2 (see Fig.3). In order to avoid excessive local heating ICNIRP has set basic restrictions for the localized SAR at the head and trunk area at 10 W/kg for occupational exposure and 2 W/kg for general public and also for the localized SAR at the limps at 20 W/kg for occupational exposure and 4 W/kg for general public exposure. Figure 3 also shows the incident power density required to produce a whole body SAR equal to ICNIRP's basic restriction.

As the frequency of the electromagnetic radiation increases, its penetration depth is decreased and the outer layers of the body absorb most of it. For frequencies above 10 GHz, the power density of the incident field is used as a more appropriate dosimetric quantity than SAR to evaluate exposure. For frequencies above 10 GHz ICNIRP's basic restriction is set for power density and is equal to 50 W/m$^2$ for occupational exposure and 10 W/m$^2$ for general pubic exposure.

ICNIRP's reference levels for high frequency electromagnetic fields took into account additional safety factors considering differences in absorption of electromagnetic energy by individuals of different sizes and different orientations relative to the field and reflection, focusing and scattering of the incident field which can result in enhanced localized absorption of high frequency energy. The reference levels are intended to be spatially averaged values over the entire body with the important proviso that the basic restrictions for local exposure are not exceeded.

In the frequency range 10 – 400 MHz where there is a chance of resonance, ICNIRP's reference levels for the equivalent plane wave power density is set to 10 W/m$^2$ for the occupationally exposed and 2 W/m$^2$ for general public. In the frequency range 400 – 2 000 MHz no resonance is expected and the reference level for power density increases proportionally with frequency. Above 2 GHz the reference level is set to to 50 W/m$^2$ for occupational exposure and 10 W/m$^2$ for general pubic exposure matching the mentioned values for the basic restrictions above 10 GHz. The corresponding reference levels for the electric and magnetic field intensity are derived from these values assuming far field plane wave conditions.

For frequencies in the range 100 kHz to about 20 MHz there is small energy absorption in the trunk with relative higher absorption in the neck and legs of the human body. The absorption in the trunk is increasing with increasing frequency. A sensation of warmth has been reported by volunteers experiencing high frequency current of about 100 – 200 mA through a limb or frequencies up to about 110MHz. If the limb current is below 100 mA the temperature rise, will be below 1 $^o$C. So, ICNIRP has set an additional reference level for induced limb current in the frequency range from 10 to 110 MHz at 100 mA for occupational exposure and 45 mA for general public exposure to prevent exceeding of local SAR basic restrictions.

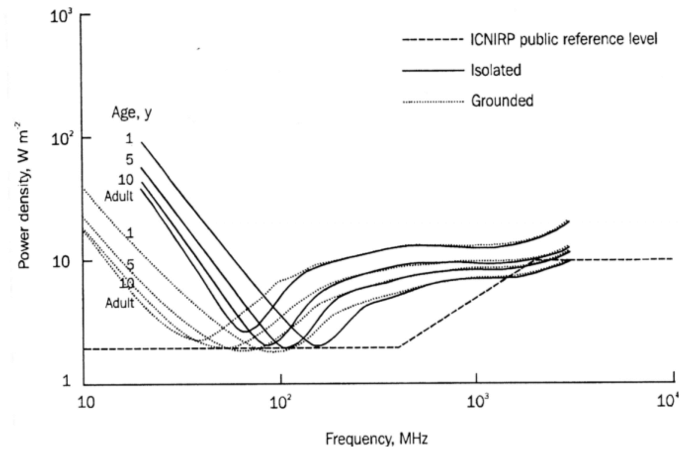

Fig. 3. Power density required to produce a whole-body SAR equal to the ICNIRP general public basic restriction [6].

## 4 Pulsed Modulated Fields

The microwave hearing effect describes the ability of people with normal hearing to perceive pulse-modulated fields such as those produced by radars with frequencies between about 200 MHz and 6,5 GHz, through an auditory sensation. This effect is attributed to a thermoelastic interaction of the auditory cortex of the brain, with a threshold of perception of about 100 – 400 mJ/m$^2$ for pulses of duration les than 30 μs at 2.45 GHz, which corresponds to specific absorption of energy (SA) of about 4-16 mJ/kg (or 30 μs pulses giving peak SAR values in the brain of 130 – 5200 W/kg). For pulsed electromagnetic fields in the frequency range 0,3 – 10 GHz and for localized exposure of the head, ICNIRP in order to limit or avoid auditory effects caused by thermoelastic expansion recommended an additional safety factor for SA of 10 mJ/kg for occupational exposure and 2 mJ/kg for the general public.

Regarding peak values of pulsed fields, ICNIRP suggested that for frequencies exceeding 10 MHz, the averaged power density over the pulse width should not exceed 1 000 times the reference levels.

## 5 Indirect coupling mechanisms

Indirect coupling mechanisms consider the contact currents when the human body comes into contact with an object at a different electric potential due to an electric, magnetic or electromagnetic field. The charging of a conducting object causes electric currents to pass through the human body in contact with the object. The magnitude of this current depends on the field frequency, the size of the object and the size of the person.

In the frequency range up to approximately 100 kHz, the flow of electric current from an object in the field to the body of the individual may result in the stimulation of muscles and peripheral nerves. With increasing levels of current this may be manifested as perception, pain from electric shock or burn, inability to release the object, difficulty in breathing and, at very high currents, cardiac ventricular fibrillation.

The following table shows the threshold currents for indirect effects, including children, women and men. For the frequency of 1 MHz there are no data available for painful shock/let go threshold or for severe shock/breathing difficulty. However the data show that there is not a significant change of contact current values from 100 kHz to 1 MHz.

Table 1. Threshold currents for indirect effects, including children, women and men

| Indirect Effect | Threshold current (mA) at frequency: | | | |
|---|---|---|---|---|
| | 50/60Hz | 1 kHz | 100 kHz | 1 MHz |
| Touch perception | 0.2 – 0.4 | 0.4 – 0.8 | 25 – 40 | 25 – 40 |
| Pain on finger contact | 0.9 – 1.8 | 1.6 – 3.3 | 33 – 55 | 28 – 50 |
| Painful shock / let go threshold | 8 – 16 | 12 – 24 | 112 – 224 | N/A |
| Severe shock / breathing difficulty | 12 – 23 | 21 – 41 | 160 – 320 | N/A |

ICNIRP's reference level of 10 kV/m for occupational exposure to 50 Hz electric fields includes a sufficient safety margin to prevent stimulation effects from contact currents under all possible conditions. The reference level of 5 kV/m for general public exposure to 50 Hz electric fields prevents adverse indirect effects for more than 90% of exposed individuals.

Regarding the electromagnetic fields below 10 MHz, the reference levels for the electric field intensity $E$ and magnetic field intensity $H$ do not satisfy the far field formula $E/H = 377\ \Omega$, since the magnetic field does not contribute significantly to the risks of shocks, burns, or surface charge effects, in contrast with the electric field. ICNIRP's occupational reference values in these frequencies are based on direct effects for the magnetic field and indirect effects for the electric field.

When a person comes into close proximity to a conducting object inside a strong field some transient discharges – sparks can occur. About 10% of the people is considered to perceive spark discharges when they hold a finger close to a grounded object inside an ELF electric field of about 0.6 – 1.5 kV/m. The field levels for feeling annoyance under the same conditions is about 2.0 – 3.5 kV/m.

For frequencies up to 110MHz, ICNIRP has set additional reference levels for contact currents from conductive objects in order to avoid shocks and burns. The reference level is set to 1 mA for occupational exposure at frequencies below 2.5 kHz and to 40 mA for frequencies in the range 100 kHz to 110 MHz. In the frequency range 2.5 – 100 kHz the reference level is increasing proportionally with frequency. Since the threshold contact currents that elicit biological responses in children and adult woman are approximately one half and two thirds, respectively, of those for adult men, the reference levels for general public exposure are set to one half of those for occupational exposure.

## 5 Conclusions

The adverse health effects of ELF electric and magnetic fields and RF electromagnetic fields that serve as basis for setting safety limits (focusing in ICNIRP's Guidelines) have been reviewed. These effects address only established effects such as: the formulation of surface charges by low frequency electric fields, the induction of internal currents by low frequency electric and magnetic fields, the development of contact currents with conductive objects caused mainly by low and medium frequency electric fields, heating caused by RF electromagnetic fields and the auditory effect caused by pulsed modulated electromagnetic fields.

All the above effects are linked to threshold values, beneath which no adverse effect is expected. Based on these thresholds, ICNIRP set basic restrictions, taking into account large safety factors (in the order of 10 for occupational exposure and in the order of 50 for general public exposure). For the practical estimation of exposure, ICNIRP has provided reference levels of measurable physical quantities. These levels were derived assuming worst-case coupling of the human body with the incident field and so a greater safety factor is finally accomplished in practice.

Taking into account that any uncertainty that inevitably appears in the evaluation of these fields when testing compliance with the safety limits will probably err on the safe side, the application of ICNIRP's reference levels leaves an enormous safety margin. It is not therefore without reasoning to believe that ICNIRP's limits would also protect from unknown health effects, if such effects do exist. But on the other hand several legislations of certain countries (like Italy, Greece and Belgium) that have imposed arbitrary factors lowering ICNIRP's reference levels, in order to ensure greater protection, are lacking any scientific rationale. ICNIRP's limits protect from all known health effects implementing large safety factors. If there are reasons to believe that there exists some other adverse health effects, not covered by ICNIRP's guidelines, the authors propose the development of new safety limits based on these effects. Otherwise, setting safety limits as an arbitrary percentage of ICNIRP's reference levels, is clearly a political decision and not a scientific procedure.

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