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Analysis of the norms regarding the protection of shipboard personnel to electromagnetic fields

I Ciocioi[1], V Dobref[2], F Deliu[3], G Samoilescu[3] and T Pazara[4]

[1, 2, 3, 4] „Mircea cel Batran” Naval Academy
iancu.ciocioi@anmb.ro, vasile.dobref@anmb.ro, florentiu.deliu@anmb.ro, gheorghe.samoilescu@anmb.ro, tiberiu.pazara@anmb.ro

Abstract. National and international standards for personnel exposure to time-varying electric and magnetic fields and to electromagnetic fields up to 300 GHz typically include minimum safety and health requirements for exposed personnel. These norms also address the risks to the health and safety of personnel arising from recognized short-term harmful effects on the human body caused by the flow of induced currents and energy absorption, as well as contact currents. In consideration of the protection of personnel on board a maritime ship in the paper, the norms/ standards regarding the limitation of exposure and the protection of personnel to electromagnetic fields and especially those generated by the functional sources on board are analyzed.

1. Introduction

Ensuring the health of the crew members of maritime vessels requires, among other things, limiting their exposure to the electromagnetic fields that are generated on board due to the operation of various equipment. As a result, it is necessary to assess the potential for exposure of crew members to electromagnetic fields with reference to action levels and exposure limit values.

Many effects of the action of the electromagnetic field have been reported as being based on functional disturbances of the nervous system, manifested by symptoms such as: headaches, asthenia, increased fatigue, insomnia, dizziness.

Domestic and international norms regarding the exposure of personnel to static electric fields, static magnetic fields, as well as time-varying electric, magnetic and electromagnetic fields with frequencies up to 300 GHz, usually include minimum safety and health requirements for personnel exposure [1].

Also, these rules refer to risks to the health and safety of personnel due to recognized short-term harmful effects on the human body caused by the circulation of induced currents and energy absorption, as well as contact currents. Potential long-term effects of exposure are not covered [1].

2. The effects of the electromagnetic field on the human body

The direct coupling mechanisms (basic) by which time-varying electric and magnetic fields directly interact with the human body are [2, 3, 5, 6]:

- coupling to low frequency electric fields;
- coupling to low frequency magnetic fields;
- absorption of energy from electromagnetic fields.

Indirect coupling mechanisms [2, 3, 5, 6]:

- contact currents that occur when the human body comes into contact with an object with a different electric potential (the body or the object is charged by an electromagnetic field);

- electromagnetic field coupling with electrical devices worn or implanted in a person.

The effects of the electromagnetic field on the human body can be [2, 3, 5, 6]:

- direct biophysical effects - the effects on the human body directly caused by its presence in an electromagnetic field, including:
  - thermal effects, such as the heating of tissues through the absorption of energy from electromagnetic fields in the tissues;
  - non-thermal effects, such as stimulation of muscles, nerves or sensory organs - harmful consequences on the mental and physical health of exposed personnel. Stimulation of sensory organs can lead to transient symptoms, such as vertigo or phosphenes;
  - induced currents in the limbs.
- indirect effects - effects caused by the presence of an object in an electromagnetic field, which may cause a health or safety risk, such as:
  - contact currents;
  - interference with electronic medical equipment and devices, including pacemakers and other medical devices implanted or worn on the body;
  - the risk of projecting ferromagnetic objects in static magnetic fields;
  - initiation of electro-explosive devices (detonators);
  - fires and explosions resulting from the ignition of flammable materials due to sparks produced by induced fields, contact currents or spark discharges.

3. Personnel exposure limits

Personnel exposure to electromagnetic fields is described using the following physical quantities [2]:

- electric field intensity (E), expressed in volts per meter (V/m);
- the electric current in the limbs (IL) - the electric current that appears in the limbs of a person exposed to electromagnetic fields in the frequency range 10MHz - 110MHz following contact with an object in an electromagnetic field or the circulation of capacitive currents induced in the exposed body (is expressed in amperes (A));
- electric contact current (IC) - the electric current that occurs when a person comes into contact with an object in an electromagnetic field (expressed in amperes (A));
- electric charge (Q) - the corresponding quantity used for spark discharge (expressed in coulombs (C));
- magnetic field intensity (H), expressed in amperes per meter (A/m);
- magnetic induction (B), expressed in tesla (T);
- the power density (S) is the appropriate quantity used for very high frequencies for which the depth of penetration into the body is low and it represents the ratio between the incident radiant power perpendicular to a surface and the area of that surface (expressed in watts per square meter (W /m2)).

The external electromagnetic field incident on the human body can be expressed by power density (mW/cm2), electric field intensity (V/m) or magnetic field intensity (A/m).

To express the effects induced by the penetration of electromagnetic radiation into the human body, the current density (A/m^2), „specific absorption rate" (SAR) and/or specific absorption energy, can be used.

Current density (J) is defined as the current passing through a unit of area perpendicular to the flow of current in a conducting volume such as the human body or body part and is expressed in amperes per square meter (A/m^2) [1, 3].

The specific absorption energy represents the energy absorbed by the unit mass of biological tissue, expressed in joules per kilogram (J/kg) and is used to establish limits to the effects of pulsed microwave radiation [1, 3].

Specific Absorption Rate - SAR represents the time variation of the amount of energy (dW) absorbed by a volume element (dV) with density (ρ) and elemental mass (dm) [4, 7, 8].

$$SAR(W/kg) = \frac{d}{dt}\left(\frac{dW}{dm}\right) = \frac{d}{dt}\left(\frac{dW}{\rho dV}\right) \quad (1)$$

Specific Absorption Rate - SAR, expressed as an average over the whole body or parts of it, represents the rate at which energy is absorbed per unit mass of biological tissue and is expressed in watts per kilogram (W/kg). The „whole body" SAR is a widely accepted quantity for establishing the relationship between harmful thermal effects and radio frequency exposure. In addition to the SAR average on the „body between", local SAR values are needed to evaluate and limit excessive energy absorption in small parts of the body as a result of special exposure conditions [1, 3].

For the physical quantities listed above, the standards provide [2]:

- exposure limit values (ELV) - values established on the basis of biophysical and biological considerations, especially on the basis of scientifically proven short-term and acute direct effects (thermal heating, stimulation of nervous or muscular tissues, transient disturbing sensory perceptions and some changes transient minor cerebral functions);
- action trigger levels (AL) - the operational levels established in order to simplify the process of proving compliance with the relevant exposure limit value or, as the case may be, to take the relevant protection or prevention measures provided for by the rules.

The absorption of electromagnetic energy by the human body depends on: its dielectric parameters, the relationship between the relative size of the body and the wavelength of the radiation, the orientation of the body in relation to the incident wave, the geometric shape of the irradiated environment (organ, part of the body, etc.), polarization of the incident electromagnetic field, modulation of the incident electromagnetic field [1, 9, 18, 19].

The main criterion in personal protection is the effects of electromagnetic radiation on the human body.

Directive 2013/35/EU defines for:

- non-thermal effects - exposure limit values (ELV) and action trigger levels (AL) in the frequency range 0Hz - 10 MHz (Annex II/Directive 2013/35/EU);
- thermal effects - exposure limit values and action trigger levels in the frequency range 100kHz - 300 GHz (Annex III/Directive 2013/35/EU).

Considering only the thermal effects of the electromagnetic field on the human body, in the frequency range 100kHz - 300 GHz, the directive provides [2]:

- exposure limit values for [2]:
  - energy and power absorbed per unit of tissue mass for frequencies between 100kHz - 6GHz (SAR values averaged over any 6-minute period): 0.4 W/kg - at the level of the whole body, 10 W/kg - at the level of the head and the trunk, 20 W/kg – at the level of the limbs;
  - the energy absorbed in a reduced mass of tissue from the head level following exposure to electromagnetic fields for frequencies between 0.3GHz - 6GHz: 10mJ/Kg;
  - the power density of an electromagnetic wave incident on the body surface for frequencies above 6GHz: 50W/m^2.
- action trigger levels for:
  - the electric field intensity of the electric field variable in time;
  - the magnetic induction of the variable magnetic field in time;
  - power density of electromagnetic waves (table 1);
  - electric contact current;
  - the electric current in the limbs.

Table 1. Action Levels (ALs) for exposure to electric and magnetic fields between 100kHz – 300GHz [2].

Frequency range	Electric field strength* E [V/m] rms	Magnetic induction* B [μT] rms	Power density** S [W/m^2]	Observations
100 kHz $\leq$ f < 1 MHz	6,1 x 10^2	2 x 10^6/f	-	"f" is the frequency expressed in hertz (Hz)
1 $\leq$ f < 10 MHz	6,1 x 10^8/f	2 x 10^6/f	-	
10 $\leq$ f < 400 MHz	61	0,2	-	
400 MHz $\leq$ f < 2 GHz	3 x $10^{-3}f^{1/2}$	1x $10^{-5}f^{1/2}$	-	
2 $\leq$ f < 6 GHz	1,4 x 10^2	4,5 x 10^{-1}	-	
6 $\leq$ f $\leq$ 300 GHz	1,4 x 10^2	4,5 x 10^{-1}	50	

Considering whole body SAR, the IEEE (Institute of Electrical and Electronics Engineers), NCRP (National Council on Radiation Protection and Measurements) and IRPA (International Radiation Protection Association) standards and recommendations require that for personnel working long-term in an electromagnetic radiation risk environment, in a controlled/occupational environment, the SAR should not exceed 0.4 W/ kg and for an uncontrolled / public environment 0.08 W/kg [3, 4, 5, 6].

Controlled environment can be defined by [3, 10]:

- the intensities (characteristics) of the electromagnetic field are known as a result of measurements, calculations or simulation;
- the persons exposed in controlled conditions as a result of their professional duties, are adults and are aware of the intensities of electromagnetic fields;
- occupationally exposed persons are aware of the potential health risks of working in that environment and can control their risk using mitigation strategies.

Situations that do not meet all of the above specifications are considered uncontrolled environments [3, 10].

For shipboard situations, the entire ship, both upper and lower decks, are considered controlled environments.

4. Near field and far field of antennas

On board marine vessels, special attention must be paid to the access of crew members to the installation area of the transmitter antennas on board, an area characterized by a high level of the electromagnetic field.

Knowing the radiation areas, the directivity characteristics of the antennas and the power density allow taking measures to limit the exposure of personnel to electromagnetic radiation and ensure the compatibility of the equipment on board the ship and in particular by reducing the coupling between the antennas.

The space around the antenna can be divided into three regions (D being the largest dimension of the antenna, D > λ) [7, 8, 11]:

- the near zone (the area in the immediate vicinity of the antenna where the reactive field predominates - up to a distance $R_1<0,62(D^3/\lambda)^{1/2}$ - the near field);
- the transition zone or the Fresnel zone (the zone between the near field, $R_1<0,62(D^3/\lambda)^{1/2}$ and the beginning of the far field $R_2 = 2D^2/\lambda$);
- far zone – the far field (Fraunhofer region), the zone starting from the distance $R_2 = 2D^2/\lambda$ (this is a distance at which the rays of the electromagnetic waves radiated by the antenna are parallel).

For monopole and dipole antennas, D is the electrical length of the antenna, D = λ/2.

In the far field area, the power density for an antenna with a certain aperture and wire antennas can be calculated using relation (2) [7, 8, 11].

Power density is calculated using the maximum output power of the transmitter and the antenna gain relative to a 3dB antenna directivity characteristic opening.

$$S = \frac{P_E \cdot G}{4 \cdot \pi \cdot d^2} \tag{2}$$

where: S – power density (W/m2), P_E – average or maximum transmitter power (W), G – antenna gain, d – distance from the antenna (m).

Since the antenna gain and characteristic antenna directivity aperture are in the near-field region, the power density is modified by a near-field correction factor F [7, 8].

$$S = \frac{P_E \cdot G}{4 \cdot \pi \cdot d^2} F \tag{3}$$

The near-field correction factor, F, depends on several parameters, namely [7, 8]:

- impedance mismatch with the antenna;
- attenuation of the signal on the antenna feeder;
- loss of signal on the secondary lobes (especially at reflector antennas);
- illumination efficiency, which is the ratio of the directivity of an antenna to the directivity of a uniformly illuminated antenna of the same aperture size.
- phase error loss or loss resulting from the antenna aperture not being a uniform phase surface.

Considering the above, the protection of personnel requires the provision of a safe distance. The following table shows, as an example, the safety distances for some radio communication equipment installed on board marine vessels, distances given by the manufacturer in the installation manuals (table 2).

Table 2. Safety distances [12 - 16].

Equipment	Power [W]	Safety distance [m]	Frequency [MHz]
MF/HF Radio Equipment (1)	125	3	1.6 – 27.5
VHF Radio Equipment (2)	25	0.9	156 – 161.450
Echipament radio VHF (3)	25	2	156 – 157.425
AIS Equipment (4)	12.5	3	156.025 – 162.025
Satellite communication equipment (5)	15	4	1626.5 - 1660.5

Considering the satellite communication equipment, the ship's crew members must not approach at a distance less than 4m from the surface of the radome, a distance at which the radiation level is approximately 10 W/m^2.

Figures 1 to 4 show the simulations regarding the determination of SAR located at the level of a man's head (parameters according to IEC/IEEE 62704-4), considering a dipole antenna in λ/2 (P = 25W, f = 156MHz) arranged at different horizontal distances and vertically [17].

Ensuring the reproducibility of simulations requires maintaining the same settings and reference values in order to ensure correct conclusions regarding the variation of SAR or power density (values that depend on tissue properties). In the case of changing the specific IEC/IEEE 62704-4 reference values and using a material density of 1908 kg/m3 (https://itis.swiss/virtual-population/tissue-properties/database/density/), the SAR values are will modify, figure 5 [20, 21].

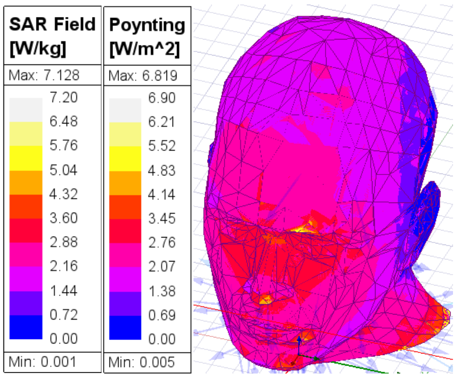

Figure 1. d$_{\text{horizontal}}$ (antenna, head) = 1m.

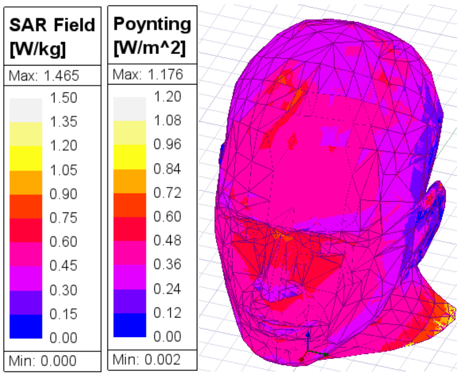

Figure 2. d$_{\text{horizontal}}$ (antenna, head) = 2m.

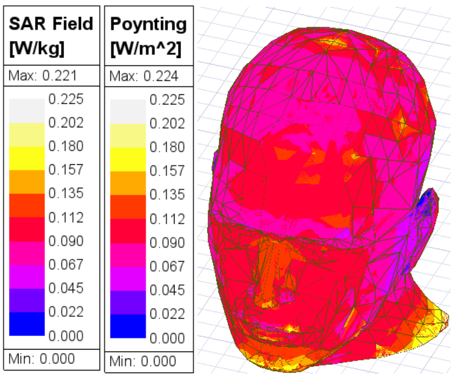

Figure 3. d$_{\text{horizontal}}$ (antenna, head) = 2m, d$_{\text{vertical}}$ (antenna, head) = 1m.

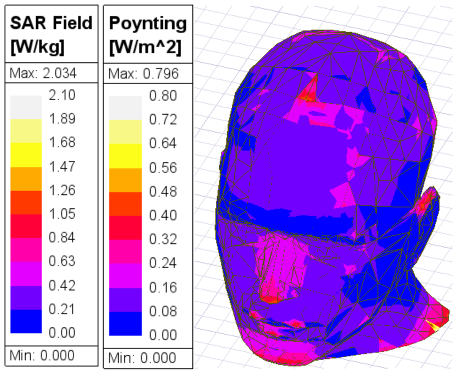

Figure 4. d$_{\text{horizontal}}$ (antenna, head) = 2m, d$_{\text{vertical}}$ (antenna, head) = 2m.

Figure 6 shows the SAR values for whole body exposure (antenna 1m from the chest and 0.5m below the head).

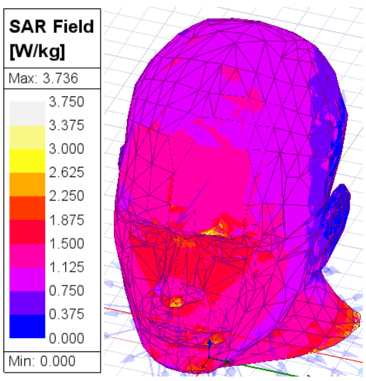

Figure 5. Changed tissue property values, d$_{\text{horizontal}}$ (antenna, head) = 1m.

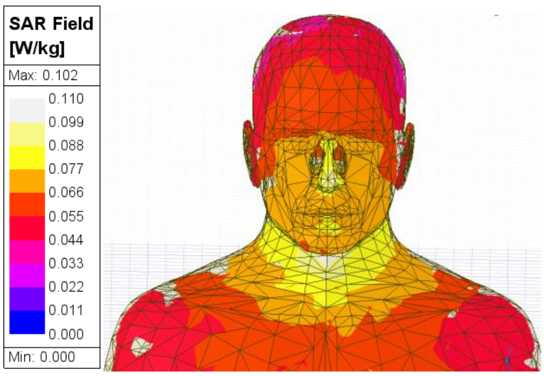

Figure 6. The SAR values for whole body exposure. Antenna 1m from the chest and 0.5m below the head.

5. Personnel protection measures on board ships

For the protection of personnel on board ships it is important to do the following:

- identification of electromagnetic field sources at the places where crew members work;
- assessment of the exposure of crew members to the electromagnetic field in the places where the activity is carried out;

- establishing measures for the protection of crew members regarding exposure to electromagnetic fields;
- assessment and control of any risk of crew exposure to electromagnetic fields.

Given the nature of crew members' activities on board ships, the following measures may be taken:

- identification and marking of areas prohibited to personnel from the point of view of exposure to electromagnetic radiation;
- the delimitation of areas for staff access;
- the use of warning signs, sound and light warnings;
- reduction of working time in areas with electromagnetic radiation;
- establishing the situations in which the staff can be exposed and assessing the staff's exposure to these sources;
- training the ship's crew members on the risk of exposure to electromagnetic radiation exposure in high-level areas and the control measures imposed to limit exposure;
- investigating and documenting overexposure incidents and establishing additional protective measures;
- the use of individual protective equipment adapted according to the characteristics of the electromagnetic environment on board;
- checking the proper installation of the equipment on board;
- the use of shielding means;
- not installing and removing unnecessary metal objects near the antennas, which can cause an increase in the intensity of the electromagnetic field in the respective areas.

6. Conclusions

Ensuring the safety of the ship implicitly also requires ensuring the health of the crew members of maritime vessels by limiting their exposure to the electromagnetic fields that are generated on board due to the operation of radio communication equipment, radars as well as various equipment.

Directive 2013/35/EU provides exposure limit values for energy and power absorbed per unit mass of tissue for frequencies between 100kHz - 6GHz (SAR values averaged over any 6-minute period) of 0.4 W/kg - at the level of the whole body, 10 W/kg - at the level of the head and trunk and 20 W/kg - at the level of the limbs and 50 W/m^2 for the power density of an electromagnetic wave incident on the surface of the body for frequencies above 6GHz.

Directive 2013/35/EU provides, for a controlled environment, only external magnetic induction values.

The IEEE, NCRP, and IRPA standards/recommendations regarding SAR values at the whole body level are established according to the environment in which personnel work long-term – controlled/occupational environment or uncontrolled/public environment.

The SAR values for working in a controlled / occupational environment must not exceed 0.4 W/kg and for an uncontrolled / public environment 0.08 W/kg.

In the situation of simulating the exposure of personnel to radiofrequency fields, ensuring the reproducibility of the simulations requires maintaining the same settings and reference values in order to ensure correct conclusions regarding the variation of SAR or power density, values that depend on tissue properties.

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