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CORRELATING ELECTRIC AND MAGNETIC FIELD STRENGTH WITH INDUCED FOOT CURRENTS – OCCUPATIONAL EXPOSURE ASSESSMENT OF PERSONNEL OPERATING PROFESSIONAL RADIO EQUIPMENT

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We have measured induced foot current for eleven human volunteers during the use of professional military radio equipment. The operator finds himself in the reactive near-field zone of the radio source so, complementary to these measurements, both electric and magnetic field strengths were measured with a broadband exposimeter destined for occupational assessment. The study includes analysis of induced foot current with respect to exposed body surface area for various operating modes, working positions or frequencies. Incident electric and magnetic field strengths were also measured and variations discussed. We have conducted the case study in order to find possible correlation of measured currents with electric and/or magnetic field strength. If determining compliance with the dosimetric basic restrictions is not possible, a proper exposure assessment should however refer to all parameters that are set as reference levels in the safety standards.

Keywords: radiofrequency radiation, occupational exposure, measurement procedures, near-field region, induced foot current, reference levels/action levels

1. Introduction

When electromagnetic radiation interacts with the human body a series of unanimously recognized biological / adverse health effects occur. Exposure to electromagnetic fields results in internal body currents and energy absorption in tissues that depend on the coupling mechanisms and the frequency involved. Taking into consideration these established adverse health effects, available protection standards have set basic restrictions [1] or dosimetric reference limits [2] that incorporate appropriate safety factors. Dosimetric limits for radiofrequency fields are expressed on a specific absorption rate (SAR) of energy

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deposition basis and are intended to protect against a rise in temperature of approximately 1℃ or more.

ICNIRP (International Council for Non-Ionizing Radiation Protection) guidelines for limiting occupational exposure to electromagnetic fields were adopted by most of European countries as national legislation, and have been recently transposed in European law [3]. International standardization in the military is possible through the NATO (North Atlantic Treaty Organization) Standardization Agency that has recently worked together with specialists from the IEEE (Institute of Electrical and Electronics Engineers), in order to issue a new protection standard for military workplaces concerning limitation of personnel exposure to electromagnetic fields [2].

Specific absorption rate is used to describe the amount of energy absorbed by a mass of tissue in a given time. The value of SAR depends on a series of factors among which field parameters, the characteristics of the exposed body, ground and reflector effects. Experimental determination of SAR is difficult and requires a lot of resources, not always available when assessing compliance with protection standards. Thus, in order to simplify the procedure, exposure reference levels were established for cases when it is complicated to assess compliance with the basic restrictions. For radiofrequency fields, reference levels are expressed in terms of external electric and magnetic unperturbed field strength and power density for plane-wave (far-field) exposure condition. Additionally, up to 110MHz, protection standards have set reference levels in terms of induced limb current or induced foot current. Considered an “internal” parameter, induced foot current, allows the control of the compliance with the limits of the local SAR in the limbs, where the strongest thermic effects may occur.

Open public literature provides scarce studies concerning occupational exposure of personnel operating military equipment. A study concerning exposure assessment for military boats in the Royal Norwegian Arm can be found in [4], but like most of the exposure assessment scenarios it is based only on measuring the electric or magnetic field strength of the radiation source. Few occupational exposure assessment studies are based on measuring both electric/magnetic field strength and induced foot currents, as [5], but none was found for personnel operating professional military radio equipment.

Previous studies concerning induced foot current measurements, are either based on computational methods [6] or do not discuss electric and magnetic field strength as well [7]. We found no study of a possible correlation analysis of induced foot current and external measured electric and magnetic field strength.

World Health Organization (WHO) has subdivided the radiofrequency range into four regions, according to the field absorption in the human body [8]. SAR value was found in good correlation with different body dimensions, especially at whole body resonant frequencies. A simple estimation of whole body

SAR in terms of body mass index of the human body is proposed in [9]. Moreover, simulation results show that the body resonance frequency and whole-body average SAR at resonance frequency are inversely proportional to the body height [10].

In this study we discuss correlation of the measured induced foot current with body surface area (BSA), as the most relevant parameter to characterize the exposed body.

We also underline possible correlations between the measured induced foot current and external electric and magnetic field strength, measured in reactive near field exposure condition, for a group of eleven operators using professional military radio equipment.

2. Materials and methods

The current passing through the feet of eleven human subjects was measured using a Holaday manufactured induced current meter, while using the Harris 5800 V radio transceiver.

The selected radiofrequency source was the Harris 5800 V radio transceiver. It is a member of the Falcon II tactical radio family, capable of providing continuous coverage in the 30 to 108 MHz frequency band. The measurements were performed during the use of its 48-inch (approximately 122 cm) antenna, that is a blade antenna attached to an adjustable “gooseneck” base. We have set up a number of communication networks (emission cases), as presented in Table 1.

Table 1

Harris network settings

NET Number	NET Settings	Frequency [MHz]	Observation
NET 1	Fixed Frequency Data/Voice Wide band frequency shift keying 8kHz deviation modulation High power (10W)	32	Continuous wave (CW) emission
NET 2		65	
NET 3		106	
NET 4	Wideband – frequency hopping (100 jumps/second) High power (10W)	31-33	Spread spectrum emission
NET 5		64-66	
NET 6		105-107	
NET 7	Fixed Frequency 8kHz deviation modulation User selectable power: High power (10W) Medium power (5W) Low power (1W)	30	Continuous wave (CW) emission
NET 8		40	
NET 9		50	
NET 10		60	
NET 11		70	
NET 12		80	

NET 13		90	
NET 14		100	
NET 15		108	

Measurements were performed both indoor and outdoor, for various working positions and operating modes. Subjects were equipped with the army field uniform, wearing the same boot type (insulated from the ground by the boot soles). When analyzing results we have to consider that previous findings have reported that foot currents are reduced by a factor of about 0.72~0.91 when the condition is changed from standing barefoot to wearing shoes, respectively [7]. This observation is also supported by computational approach as found in [6], whom reported that insulation of the base reduced the foot current several times in comparison to the worst case, when feet are short-circuited.

Both SAR values and induced foot current depend a lot on the subject posture with respect to the exposure fields. When the long axis of the human body is parallel to the electric field vector and under plane-wave exposure conditions (far-field exposure), whole-body SAR reaches maximal values [11]. However it is difficult to predict field behavior in the near field region, thus we have scanned induced foot current for various working positions, as described in [12].

BSA represents the measured or calculated surface of the human body. Various calculations have been published to arrive at the BSA without direct measurement, but the most widely used is the Du Bois formula [13], presented in Eq.1

$$BSA = 0.007184 * W^{0.425} * H^{0.725} \quad (1)$$

Where BSA is in m2, W is the weight in kg and H is the height in cm.

Additional information regarding the experimental methodology, i.e. human subjects, radio station configuration, measurement procedure and equipment can be found in [12].

Given the radio transceiver frequency range (30-108MHz) and the distance the operator finds himself while using it (a few centimeters) we had to consider that measurements were taken in the reactive near field region of the radiation source. The situation in this region is complicated because the maxima and minima of E and H fields do not occur at the same points along the direction of propagation as they do in the far field. In the near field, the electromagnetic field structure is highly inhomogeneous. In such situation, power density is no longer an appropriate quantity to use in expressing exposure restrictions (as in the far field) [1]. Thus, apart from taking technical care not to perturb near field region with conducting objects we also considered measuring both electric (E) and magnetic (H) field components of the field.

We used the RadMan XT series ESM-30 device, provided by the company Narda Safety Test Solutions to measure the electric and magnetic field strength. It is a personal exposimeter equipped with two isotropic field probes (for electric and for magnetic component) of few millimeters in diameter, placed at a distance of 4.5cm from each other (typical deviation= ±3dB in the measured frequency range). The personal monitor was put in the upper pocket of the operator, thus field measured values are not for unperturbed fields as specified in all considered standards.

Field levels expressed by exposimeter are posted in a log file by using ESM-TS software, in the form of percentage from ICNIRP reference levels of occupational exposure [1] – which are identical to those in [2] and [3]. The data set saved at the end of the save interval contains the root mean square (rms) value, the maximum and the minimum value of all the H field and the E field values that were measured during the save interval (measurement interval=5 ms). All field strengths that are referred to in this paper, unless otherwise specified, are the maximum values of both E and H components of the field, returned in the log file of the exposimeter. Based on the reference levels for occupational exposure in the 10MHz-300MHz frequency range found in [1] we calculated the absolute values of the electric and magnetic field strength using Eq.2 and 3.

$$E_{abs} = \%E_{ref} * 61V/m \tag{2}$$

$$H_{abs} = \%H_{ref} * 0.16A/m \tag{3}$$

Where %Eref and %Href are the electric field strength respectively magnetic field strengths as a percentage from ICNIRP occupational reference levels, Eabs is the electric field strength in V/m and Habs is the magnetic field strength in A/m.

3. Results and discussion

In Fig.1 we have represented the measured induced foot current as a function of calculated body surface area for all 11 subjects (see Eq.1), for both standing upright and down on one knee positions. We observed a linear correlation of the two parameters for 65MHz operating frequency. The average calculated standard deviation was of 1.427 mA for standing upright position and 2.77 mA for standing down on one knee position. The coefficient of determination was 0.4353 for the first standing position and 0.10 for the second position.

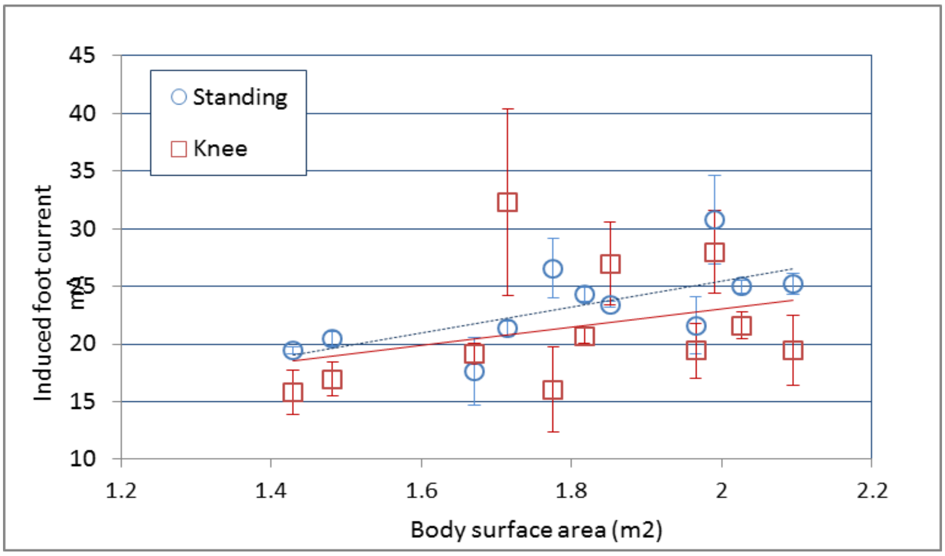

Fig. 1 - Induced foot current as a function of body surface area
– Outdoor, NET 2 (65MHz fixed frequency), high power (10W) -

When standing down on one knee it is difficult to adopt the same position by all of the tested subjects, so that due to different body dimensions and flexible antenna gooseneck, one can be situated closer to the radiation source (radio station antenna) than other. However standing upright is a more rigid position so that we can appreciate that all tested subjects were standing at the same distance from the radio transceiver. This observation can be explained by the fact that the 65 MHz operating frequency is very close to the resonant absorption frequency of the standard reference man (standing upright) – 70MHz, if not grounded. For this communication equipment (similar configuration), at frequencies close to the human body resonant frequency, body surface area is well correlated with the induced foot current and could be used to estimate induced foot current with a calculated error of 6.14%.

In fig.2 we present the measured peak values of the electric field strength for 65MHz fixed frequency operating mode, for both indoor and outdoor cases, for three of the tested subjects. Just like in the case of induced currents higher values of electric field strength were measured for the indoor scenario than for the outdoor one. The elevated levels are also due to scattering and re-radiating objects that were present in the laboratory, even if not placed in the near field region. Indoor resonant reflections also result in more spread values of the measured electric field strength, as compared to outdoor measurements. Compared to induced current values, where indoor results revealed an increase of a few mA, we have measured that indoor electric field strength values overpass outdoor result with a factor of 4.6-8.9.

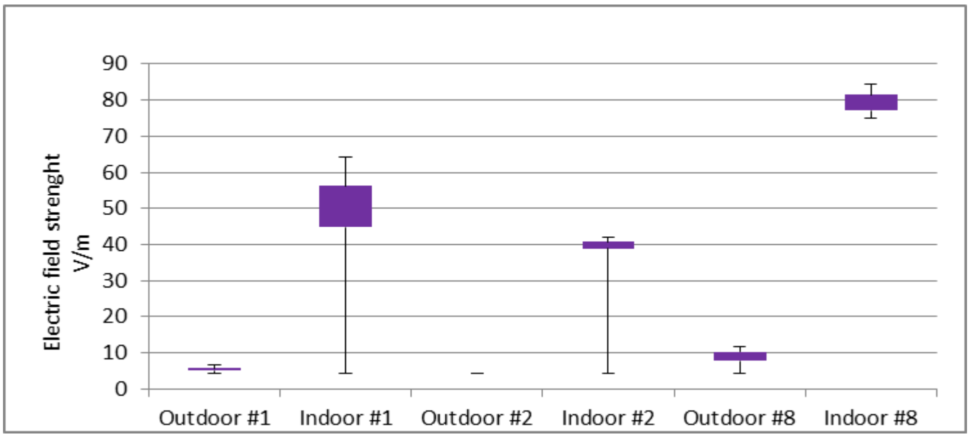

Fig. 2 - Electric field strength – indoor/outdoor comparison
NET 2 (65MHz fixed frequency), high power (10W), standing

Because the operator finds himself in the near field region of the radiating source we also measured the magnetic field strength. Unlike the case of electric field, we observe that if magnetic field strength is of interest, higher values were obtained for the outdoor measurements for all tested subjects. In fig.3 we have represented the average measured magnetic field strength (for all eleven subjects) for both fixed frequency (NET 1-3) and frequency hopping operating modes (NET 4-6). One notes the sensitive higher median values and spreading of the magnetic component for the lower frequency of 32MHz, and sensitive lower medians and reduced spreading for the higher frequency of 106MHz.

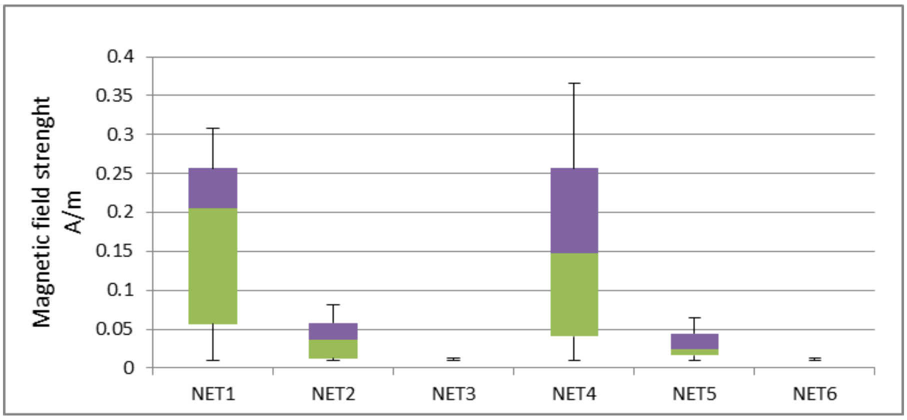

Fig. 3 Magnetic field strength – outdoor measurements
NET 2 (65MHz fixed frequency), high power (10W), standing

Similar magnetic field values were measured for fixed frequency and frequency hopping networks. As theoretically expected because of the inhomogeneous structure of the near field zone, at the same spot we have measured high values of magnetic field strength and insignificant values of electric field strength and vice versa. Due to radio transceiver frequency range operators are mainly located in the near field zone, so in order to properly assess exposure it is important to measure both electric and magnetic field components.

Fig.4 presents measured electric field strength versus incident frequency. We measured very high values of both electric and magnetic field strength around the 30 MHz operating frequency (NET 1,4 and 7), regardless of the applied power level while indoor use of radio station. When discussing this observation we should be aware that RADMAN personal exposimeter does not register values that exceed by 150% the ICNIRP reference levels. Further investigations, with equipment that is currently unavailable on the market, are necessary to provide accurate measurements in the 30-40MHz frequency band.

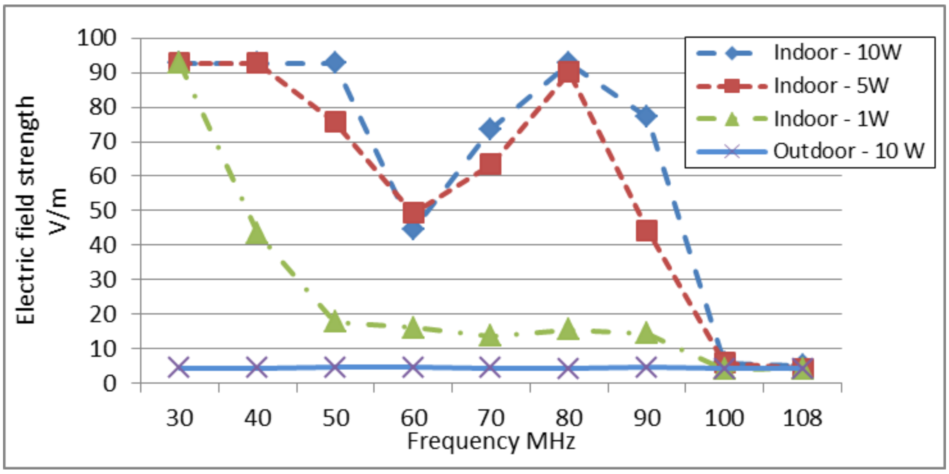

Fig. 4 Electric field strength – NET 7-15, standing, different power levels

The variation in Fig. 4 indicates how the radiation pattern of the emitting antenna varies with frequency in the near field and was captured by RADMAN detection in the very proximity of the body. One notes that indoor, both at medium and high power of emission there are frequencies (30-50MHz and 80MHz) where the field level is very high, while for other frequencies the incident field is highly diminished. For such reason, in the reactive near field it is necessary to measure both the field strengths and the induced current for occupational conformity reasons.

In this regard a resonance effect was previously demonstrated for measured induced current values [12] and it is also observable if magnetic field strength is of interest.

We observed that generally increased levels of induced current are correlated with higher levels of electric field strength (50-70MHz). The same values of electric and magnetic field strengths that induce a current of approximately 15mA at 50MHz operating frequency induce values of 20mA when operating frequency is changed to 80MHz. Moreover a rapid decrease in induced foot current for the 40MHz operating frequency can be correlated with a decrease in magnetic field strength, as compared to 30MHz operating frequency.

Induce current values rapidly decrease above 90MHz operating frequency, while electric and magnetic fields strength become close to environmental background radiation levels above 100 MHz.

Exposure reference levels provided for the 30-110 MHz frequency range are calculated to comply with the dosimetric reference limits for the whole body average SAR. Reference levels are thus expressed for plane wave exposure condition for spatially averaged unperturbed field. The exposimeter is calibrated according to ICNIRP as occupational reference level, which provides limitations for the electric and magnetic field strengths in terms of spatially averaged unperturbed fields. The presence of the operator in the near field significantly alters the “unperturbed” condition set in the safety standard. As proven in [14] a correction factor of about 1.7 should be applied to values measured by the body worn exposimeter. However, the correction factor applies for the electric field measurements and it may dynamically change under different exposure scenarios.

In order to determine compliance with standards, for non-uniform exposure conditions, as the case here, the mean values of the exposure fields, as obtained by spatially averaging the squares of the field strengths over an area equivalent to the vertical cross section of the human body are compared with the provided reference levels. Measurements scenarios did not include a cross section scan of electric and magnetic field strengths; thus the obtained values have to be reported as localized exposure. For localized exposure condition the spatial peak value of mean squared field strength shall not exceed 20 times the square of the allowed spatially averaged values fields (61 V/m for E respectively 0.163A/m for H) [2]. However, such assumption is valid only for planar wave.

We obtained very high values for the in situ measured electric field strength. In table 2 we have calculated the rms value and mean square field strength for both electric and magnetic fields and compared it to 20 times the square limit provided by the protection standard (plane wave case).

Table 2

Electric and magnetic field strength, NET2, standing

	Outdoor #1	Indoor #1	Outdoor #2	Indoor #2	Outdoor #8	Indoor #8	20 * ERL^2 -
E - rms	5.39626	50.49131	4.36028	39.5781	9.47898	79.59038	74420 V/m
E^2 - averaged	29.11962	2549.373	19.01204	1566.426	89.85105	6334.628	
H -rms	0.065118	0.016005	0.052833	0.029937	0.106261	0.031287	0.531 A/m
H^2 -averaged	0.00424	0.000256	0.002791	0.000896	0.011291	0.000979	

If local exposure is considered no overexposure was found – reporting to far field conditions, even in the worst-case scenario (indoor measured electric field), but a proper exposure assessment should obligatory consider measurements for a cross section of the human body in order determine spatially averaged values of the field to be compared to reference levels, in case of reactive near field exposures.

Measured electric and magnetic field strengths, as well as induced foot current, vary a lot, according to the selected measurement scenario. Exposure scenarios are usually dynamically changing, especially in the battlefield, thus recommendations are to assess occupational exposure by spatially averaging the unperturbed field, as specified in the protection standards.

4. Conclusions

The presented investigations show a significant influence of the human body shape and posture on the measured induced foot current and external electric and magnetic field strength. Exposure is strongly dependent on operating mode, frequency, worker's position or environment.

Even if measured induced limb current values did not exceed reference levels we have measured very high values of the electric field strength, that in some cases exceeded even the reference levels specified for occupational exposure (61V/m) and in most of the indoor measurements the level for unrestricted environments/public exposure (27.5V/m). High levels of magnetic field strength were also measured, especially for outdoor exposure scenarios.

If used outdoor, as intended, the radio station does not cause operator overexposure, as it is defined by the protection standards. In order to reach such a conclusion it is not enough to measure only induced limb currents or electric and magnetic field strengths. Measurements that do not include determination of all possible exposure reference levels can lead to an over- or underestimation of human exposure.

Because of the complexity of the (reactive) near field zone and the limitations in measurement equipment and procedure we could not observe a correlation of the measured induced foot current and external electric and magnetic field strength.

We have to consider that protection standards impose limitations only on the basis of the proven thermal effect of human exposure to electromagnetic fields. Recent findings have revealed a lot of other non-thermal effects that exposure to electromagnetic fields can cause, thus limiting as much as possible human exposure to electromagnetic radiation would be a good measure until these effects will be considered when formulating recommendations.

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