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Simultaneous Occupational Exposure to FM and UHF Transmitters

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Occupational exposure caused by large broadcasting transmitters exceeds current reference levels. As it is common for different radio and TV transmitters to share the location, we analysed combined exposure on a 40-m high mast. The frequency modulation (FM) transmitter, located between the 10th and 30th metre, had the power of 25 kW, whereas an ultra-high frequency (UHF) transmitter of 5 kW occupied the top 8 m of the mast. Measured and calculated values of the electric field strength exceeded the reference levels up to 10 times; however, the results for the specific absorption rate (SAR) values show that the reference levels are very conservative for FM exposure, i.e., basic restrictions are not exceeded even when the reference levels are exceeded 10 times. However, for UHF exposure the reference levels are not conservative; they give a good prediction of real exposure.

occupational exposure   simultaneous exposure   measurements   numerical calculation
SAR   FM   UHF   FDTD

1. INTRODUCTION

Broadcasting has long been used to deliver radio and TV programmes to the public. Although various new nonwireless technologies are used nowadays to bring the voice and picture to the end user (e.g., Internet Protocol TV or cable TV), broadcasting is still very important and with the introduction of digital broadcasting will remain so in the future. To cover most of the population with a good signal, transmitters with the power of up to tens or even a hundred kilowatts are necessary.

Exposure caused by broadcasting transmitters is of a great interest to the general public. Different methods are used to evaluate that exposure: from personal dosimeters [1] to fuzzy logic estimation [2]. Normally, exposure of the general public is below the reference levels as defined in the ICNIRP guidelines [3]. However, the occupational reference levels defined in the guidelines are often exceeded at transmission sites. Without proper management of occupational health and safety, high excessive exposure is possible [4].

Workers' occupational exposure on broadcasting towers and masts has already been analysed in various papers, but most focused on the values of the electric field strength, e.g., Jokela and Puranen [5] and Bolte and Pruppers [6]. The limits for the unperturbed electric field, when no human is present, are called reference levels in the ICNIRP

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guidelines [3] and action values in Directive 2004/40/EC [7]. These limits are more conservative but easier to use in practice than the basic restrictions in the ICNIRP guidelines and exposure limit values in Directive 2004/40/EC. They limit the specific absorption rate (SAR). SAR is the measure of absorbed power per mass of tissue, and reducing its value prevents excessive tissue heating. In this paper, we will use the terms from the ICNIRP guidelines: basic restrictions and reference levels. As the reference levels are exceeded close to the transmitters it is necessary to determine workers' exposure on the basis of the values of SAR.

In another paper in this issue of *JOSE*, we analysed exposure on a frequency modulation (FM) mast (see p. 149) [8]. We found that the reference levels were exceeded by a factor of 10, but the values of SAR only slightly exceeded basic restrictions. This means the reference levels are very conservative for near field exposure in the FM frequency range. Remkes had similar findings [9]. However, exposure caused by ultra-high frequency (UHF) transmitters has not been analysed yet. It is not possible to extrapolate the results for exposure to the FM transmitter to the UHF frequency range, as the wavelength is nearly 10 times shorter and the reference levels are not necessarily as conservative as for FM exposure. Therefore, in this study, exposure caused by the UHF transmitter and combined exposure caused by both systems on the mast were analysed with measurements and numerical calculations.

2. MATERIALS AND METHODS

The broadcasting mast we analysed was part of a large broadcasting facility (Figure 1) consisting of a combined very high frequency (VHF) and UHF transmitter tower, and an auxiliary 40-m high mast broadcasting FM and UHF, which was the focus of this paper. In addition to the FM transmitters located in the lower part of the mast (from the 10th to the 30th metre), there was an additional UHF system transmitting at 791.25 MHz in the top 8 m of the mast. The total power of the FM transmitters was 25 kW, measured on the mast at the connector of the main cable and the combiner (10 kW at 95.3 MHz, 5 kW at 88.6, 92.9 and 105.7 MHz). The total power of the UHF transmitter was 5 kW. We presented the results of a study of exposure to the electromagnetic field (EMF) of workers climbing a broadcasting in another paper in this issue of *JOSE* (see p. 149) [8]; however, we had not analysed the combined exposure caused by the UHF transmitter. As it is common that different transmitters are located on one mast, this study analyses exposure caused by the UHF transmitter

Figure 1. Broadcasting centre at the top of a hill: 3 transmission masts and the main building.

and combined exposure caused by both systems on the mast.

2.1. Measurements

Since there were various sources at the location, selective measurements were preferable to broadband ones. Due to the inability to securely position the measurement equipment, selective measurements were only performed on the platform between the FM and UHF part of the mast and on the ground. Additionally, broadband measurements were taken at another 16 points. We described the measurement equipment and the measurement procedures in another paper in this issue of *JOSE* (see p. 149) [8]. Contact current, which is also limited by reference levels and was not measured in the study, according to the literature, cannot exceed reference levels close to amplitude modulation (AM), FM, VHF and UHF transmitters [10]. Nevertheless, the influence of the contact current was considered when calculating the values of SAR; therefore, a comparison with basic restrictions was appropriate.

2.2. Numerical Calculations

The electric field and the values of SAR were numerically calculated with the SEMCAD version 14[1] (Speag, Switzerland) program package, which is based on the finite-difference time-domain (FDTD) method. The entire mast was included in the model, but the simulations were split into two separate areas: one for calculating the FM transmitters, the other for calculating the UHF one. In both cases, the calculations were first done in an empty space to find areas with the highest electric fields. The electric field in an empty space was determined as root-mean-square (RMS) values of the local electric field strength, i.e., without any spatial averaging.

The model of the FM transmitter consisted of 28 four-dipole antennas distributed over eight floors at 3-m intervals. In three horizontal directions, there were eight antennas, whereas in one there were only four. For the UHF transmitter, which was located in the upper 8 m of the mast, the model consisted of the metal construction and 18 four-dipole antenna arrays. Antenna panels, which were 1-m high, were distributed over six floors with 0.15-m vertical gaps between them. They were oriented in three horizontal directions.

Both transmitters were fed with two 120-m 3-1/8″ cables and through three step power splitters located on the mast so that power was distributed to each dipole array separately. The attenuation of the whole system of cables and power splitters was 1.1 and 1.2 dB for the FM and UHF transmitters, respectively. For the FM transmitter, the 25 kW power on the connector of the main cable to the combiner was reduced to ~20 kW on all 112 dipoles, whereas for the UHF transmitter it was reduced from 5 kW to ~3.8 kW on 72 dipoles. The power splitters and the cables were not included in the simulations; instead, the excitation of each dipole was individually set to the corresponding power level and phase as determined by the power splitter system and cable lengths. The phase shift between different antennas and different power distribution determined the desired radiation pattern of the whole antenna system. The excitation frequency in the model was set to 98 and 791 MHz.

When it was necessary to climb to the top of the mast, workers used a ladder, which was positioned inside the mast where the FM antennas were mounted, but on the upper part, where the UHF antennas were mounted, the mast diameter was smaller and, therefore, the ladder was located on the outer side of the mast. UHF antennas were placed on three sides of the top part of the mast, whereas the ladder was located on the fourth side (Figure 2). The anatomical human model used was a 34-year-old male, 1.74 m tall with a weight of 70 kg [11].

To simulate the FM part, the anatomical human model was placed in the centre of the mast at three different heights [8]. To simulate the UHF part, the anatomical human model was placed on the outer side of the mast on the ladder at 32.1, 33.5, 34.4 and 35 m above the ground (between 0.6 m 3.5 m from the bottom of the UHF transmitter). Figure 2 illustrates the location of the

[1] http://www.speag.com/

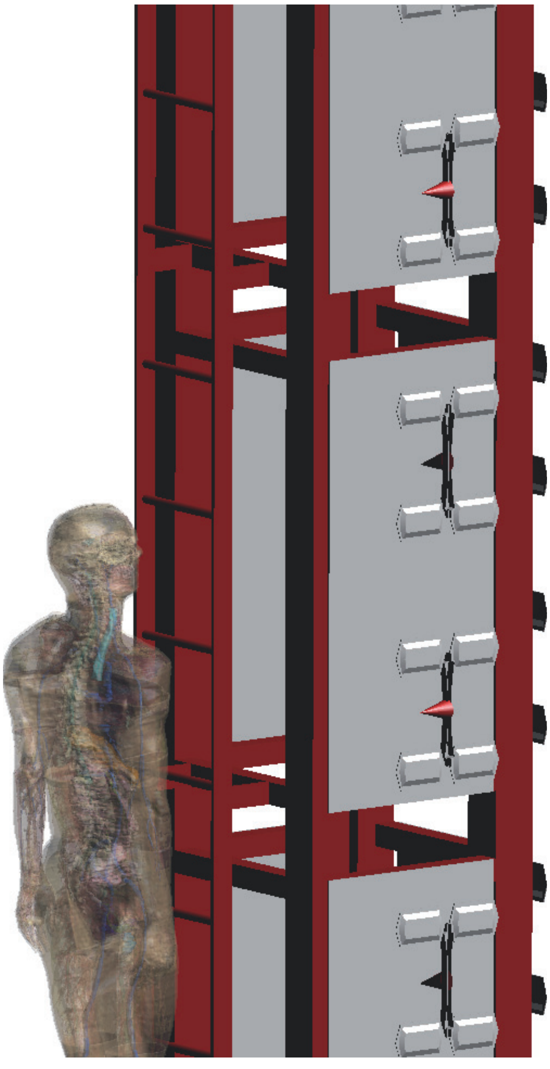

Figure 2. Model of the top part of a steel lattice mast with 4-dipole ultra-high frequency (UHF) antennas and a human model climbing the ladder outside the mast.

human model for the lower position. At three heights the human model was isolated, i.e., not in contact with the metallic structure of the mast, but at 34.4 m, two situations were analysed: isolated and nonisolated.

The whole model of the mast was large compared to the preferred resolution of the human model, which was in the range of a few millimetres. Therefore, a lower resolution human model with the spatial discretization of 5 × 5 × 8 mm was used first. After recording the incident field, Huygens box excitation was used in the second simulation with finer spatial discretization of 3 × 3 × 3 mm. Tissue properties were in accordance with the literature [12, 13].

After the calculations, an averaging algorithm based on Standard No. C95.3:2002 [14] was used to determine the 10-g averaged value of SAR (SAR_{10g}). On the mast, the workers were exposed at the same time to the EMF from the FM and UHF transmitters. Therefore, for the lowest and the highest position (32.1 and 35 m above the ground), combined exposure from the FM and UHF was analysed. For combined exposure, the ICNIRP guidelines give the following formula for determining whether the basic restrictions have been exceeded [3]:

$$\sum_i \frac{SAR_i(f_i)}{SAR_L(f_i)} \leq 1,$$

where SAR_i—SAR caused by the field at frequency f_i, SAR_L—basic restriction at this frequency. Therefore, the values of SAR calculated for each of the two frequencies were later added. For the whole-body value of SAR (SAR_{wb}), the addition was straightforward, as it was only necessary to add the value of SAR_{wb} at 98 and 791 MHz. However, when dealing with SAR_{10g}, it was possible that the maximum values at different frequencies had different locations. By simply adding the value of SAR_{10g} at 98 and 791 MHz, we overestimated the exposure.

3. RESULTS

3.1. Electric Field

The strength of the electric field was measured at 16 measurement points on the mast in the part where the FM transmitter was located (see p. 149 in this issue of *JOSE* for the results). Since the measurements were broadband and were taken close to FM transmitters, they were not suitable for estimating exposure caused by to the UHF transmitter.

In addition to broadband measurements, selective measurements were taken at two locations (Table 1). At the bottom of the mast, the measured electric field values for the UHF transmitter (791.8 MHz) located 30 m above the ground were very low (<2 V/m); therefore, they are not shown. However, there was one UHF signal, emitted at 631.4 MHz, which was not transmitted from the analysed mast but from another

TABLE 1. Results of Selective Measurements on the Mast on the Ground and on the Platform Located Between FM and UHF Transmitters at ~30 m

Measurements	System	Frequency (MHz)	*E* (V/m)
On platform between FM and UHF transmitters *h* = 30 m	FM	88.6	13.3
	FM	92.9	28.4
	FM	95.3	83.4
	FM	105.7	46.3
	UHF*	631.4	5.4
	UHF	791.8	17.5
	UHF	796.8	4.7
At the bottom *h* = 1 m	FM	88.6	5.7
	FM	92.9	6.0
	FM	95.3	8.0
	FM	105.7	5.6
	UHF*	631.4	4.0

Notes. *E*—electric field, FM—frequency modulation, UHF—ultra-high frequency. Values under 2 V/m are not shown. The contribution at 631.4 MHz originates from a transmitter located on a nearby mast, not from the one analysed in this study.

one nearby. Since the distance between both masts was ~58 m, the contribution of the nearby transmitter was quite uniform across the whole investigated mast: 4 V/m for measurements 1 m above the ground and 5.4 V/m for measurements 30 m above the ground. At the measurement point 30 m above the ground, which was located between the two transmitters, the transmitter at 791.8 MHz (and an audio component at 796.82 MHz) contributed much more to the total exposure than on the ground. Despite the similar radiated power of each FM transmitter (at 88.6, 92.9 or 105.7 MHz) and UHF transmitter (at 791.8 MHz), the measured values of the electric field strength were higher for the FM transmitter than for the UHF one of at the same power. This was so because the UHF antenna was more directional and the electric field decreased faster when we moved away from the main beam compared to the FM antenna. Figure 3 shows this; the electric field strength is shown in a horizontal cross-section. As the antennas of the UHF system were located on three sides of the mast, on the fourth side, where the ladder was mounted, the worker was significantly less exposed than if he had to climb over the antennas.

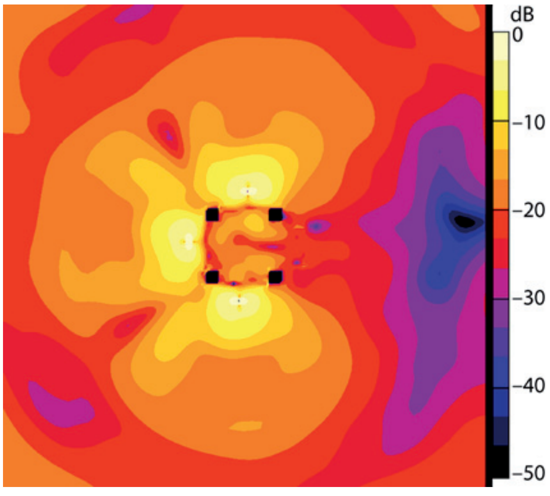

Figure 3. Electric field strength in a horizontal cross-section. *Notes*. The results are normalized to 1000 V/m and shown in logarithmic scale.

Figure 4 shows the electric field strength on the vertical line close to the ladder located outside of the mast, where the workers climbed to the top of the mast. The results were obtained with numerical FDTD calculations. Three cases are illustrated: without the presence of a human and a worker climbing the ladder at two different heights above the ground. Although the ladder was located in close proximity to the antennas of the UHF transmitter (the distance between a human and the antennas was under 1 m), the values of the electric field were below the reference levels, i.e., 84 V/m at the frequency of the UHF transmitter.

Figures 4–5 show that the electric field was greatly reduced inside the human model. It was also lower in the region behind the human model

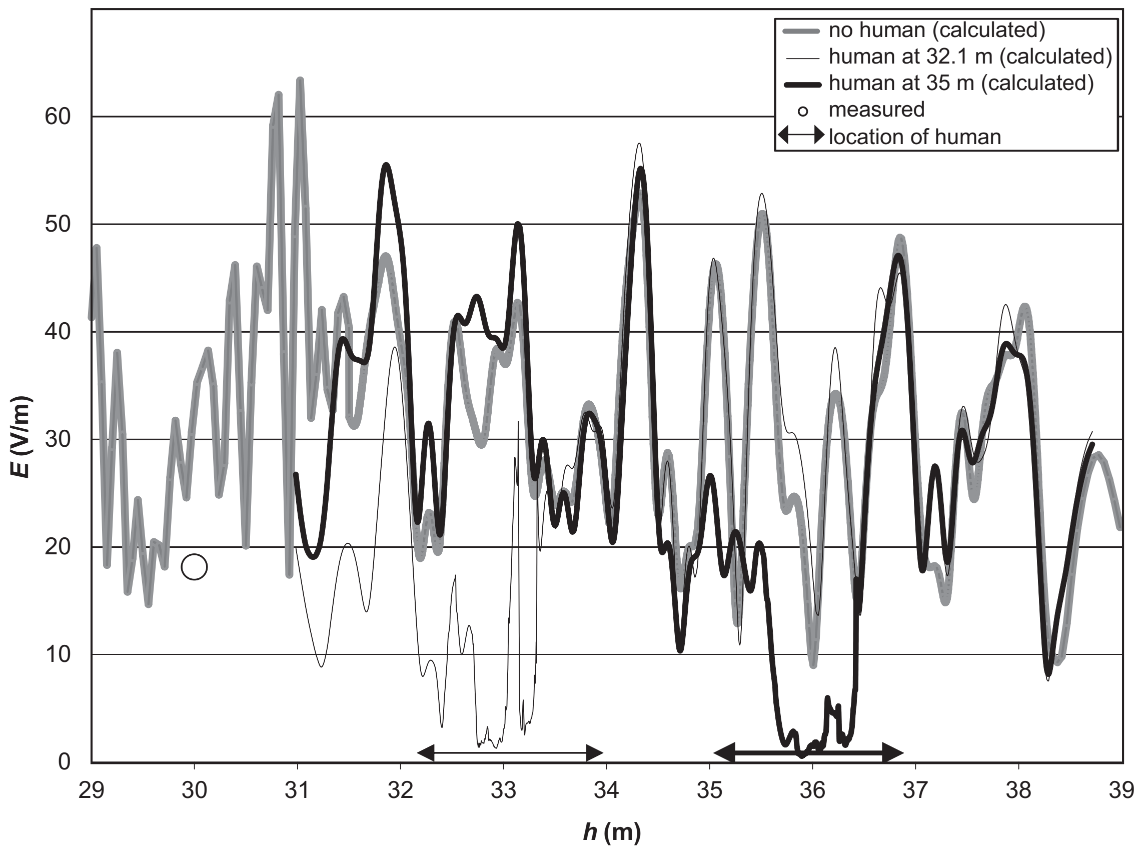

Figure 4. Comparison of measured and calculated values of the electric field on the ladder outside the upper part of the mast, where the ultra-high frequency (UHF) transmitter was located (31.5–38.35 m). *Notes*. Values were calculated for the same position close to a ladder mounted on the outer side of the mast.

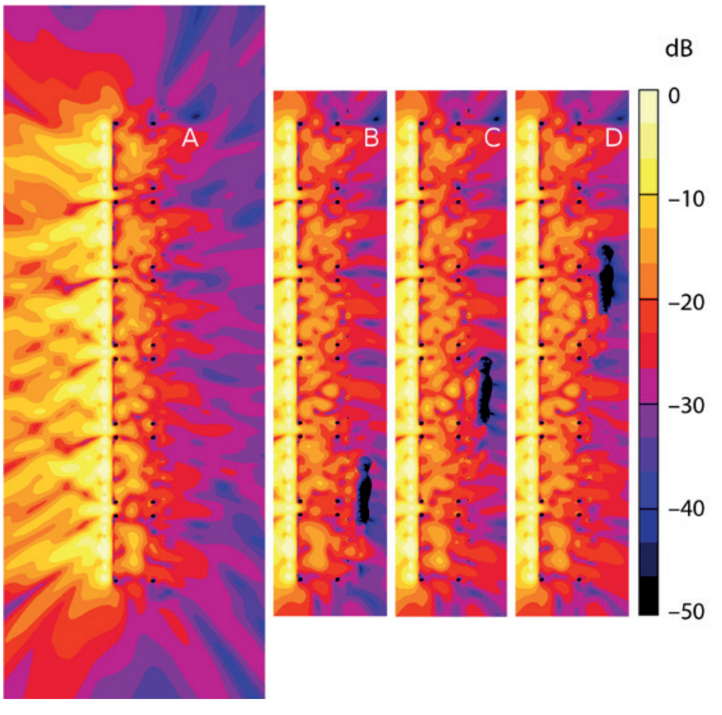

Figure 5. Electric field in a vertical cross-section of the ultra-high frequency (UHF) mast. *Notes*. A—no human model, B—human model at 32.1 m, C—human model at 33.5 m, D—human model at 35 m. The results are normalized to 1 kV/m and are shown in logarithmic scale.

(cf. the values at the back of the human model in panels B, C and D in Figure 5), but the influence of the human body was limited only to a very small area and not as far as for the FM transmitters [8].

As the reference levels were not exceeded when the worker was climbing in the vicinity of the UHF antennas, we also analysed the situation when the workers were climbing directly over the UHF antennas. Such a situation is quite common for UHF transmitters, since in most cases UHF antennas are mounted in all directions to allow uniform broadcasting of the transmitter. In front of the UHF antennas, the electric field was much higher compared to the situation analysed previously. The vertical axis in Figure 6 shows the calculated value of the electric field in front of the UHF antennas at 0 and 0.16 m. Values exceeded reference levels ~10 times.

3.2. SAR

The results for the electric field show that reference levels are exceeded when worker have to climb over UHF antennas, but not when they are not climbing in the main beam of the antennas. Although reference levels are not exceeded then, we calculated SAR values in the human model for all kinds of exposure: a human model at 32.1, 33.5, 34.4 and 35 m above the ground, climbing the ladder near antennas, and the human model climbing the mast directly over antennas. Table 2 presents the results; the values of the average SAR_{wb} and the maximum 10-g averaged SAR_{10g} with the position of this maximum are given separately. Besides the results for exposure caused by the UHF transmitter, we also calculated SAR caused by the FM transmitter below the UHF one. As the human model in those situations was always at least 2 m above the top antennas of the FM transmitter, SAR was low at 32.1 and 35 m above the ground and could be neglected in further analysis. However, the situation was quite different when the human model was closer to the FM transmitter (see p. 149 in this issue of *JOSE*).

The values of SAR show that where the values of the electric field are below the reference levels, the basic restrictions are not exceeded either. When the worker was climbing the mast on the ladder, he was situated less than 1 m from the UHF antennas, but he was not in their main beam. In this case, SAR_{wb} was ~0.05 W/kg, i.e., ~10 times lower than the basic restrictions (0.4 W/kg). Depending on the height above the ground, the maximum value of SAR_{10g} was 1.38–2.52 W/kg, which was below the basic restrictions (10 W/kg for the head and trunk, 20 W/kg for the limbs) for the isolated model. The results showed that when the model was grounded (touched the metallic construction of the mast), the maximum value of SAR_{10g} was higher compared to the results of the isolated model: the value increased from 2.52 to

TABLE 2. Values of SAR Calculated for the Exposure of a Human Climbing a Ladder at 32.1, 33.5, 34.4 and 35 m Above the Ground for an Isolated Human Model, and at 33.5 m for a Grounded[1] Human Model; Exposure in Front of UHF Antennas

Position of Model	SAR_{wb} (W/kg)[2]	max SAR_{10g} (W/kg)	Location of max SAR_{10g} in Model, Basic Restriction Value (W/kg)
UHF, 32.1 m	0.050	1.570	foot, 20
FM, 32.1 m	0.004	0.040	testicles, 10
UHF, 33.5 m	0.050	2.520	foot, 20
UHF, 33.5 m grounded	0.050	3.860	foot, 20
UHF, 34.4 m	0.050	2.140	foot, 20
UHF, 35.0 m	0.050	1.380	penis, 10
FM, 35.0 m	0.005	0.097	shoulder, 10
In front of UHF antenna	1.130	37.000	foot, 20

Notes. SAR—specific absorption rate, SAR_{wb}—whole-body value of SAR, max SAR_{10g}—maximum 10-g averaged SAR_{10g}, UHF—ultra-high frequency, FM—frequency modulation; 1—touching the metallic structure of the mast, 2—basic restriction value: 0.4 W/kg. The results are presented for all 6 exposure scenarios for the UHF transmitter and for 2 exposure scenarios for the FM transmitter located below the UHF transmitter (below 30 m).

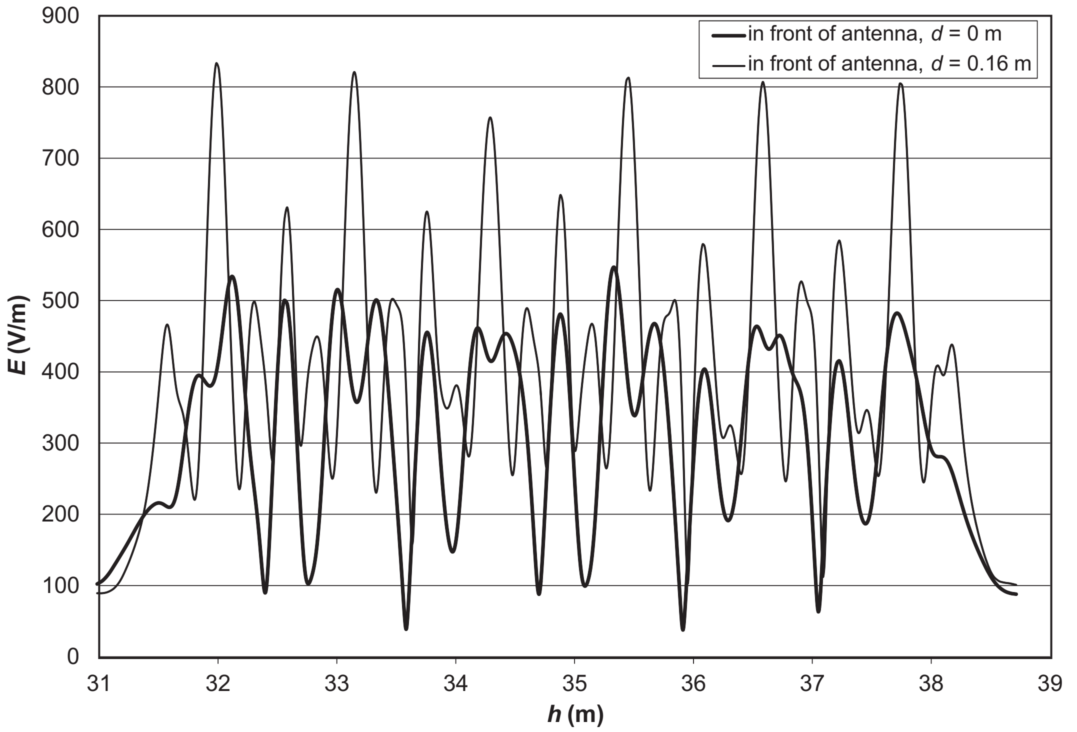

Figure 6. Electric field in front of ultra-high frequency (UHF) antennas at 0 and 0.16 m from their front covers.

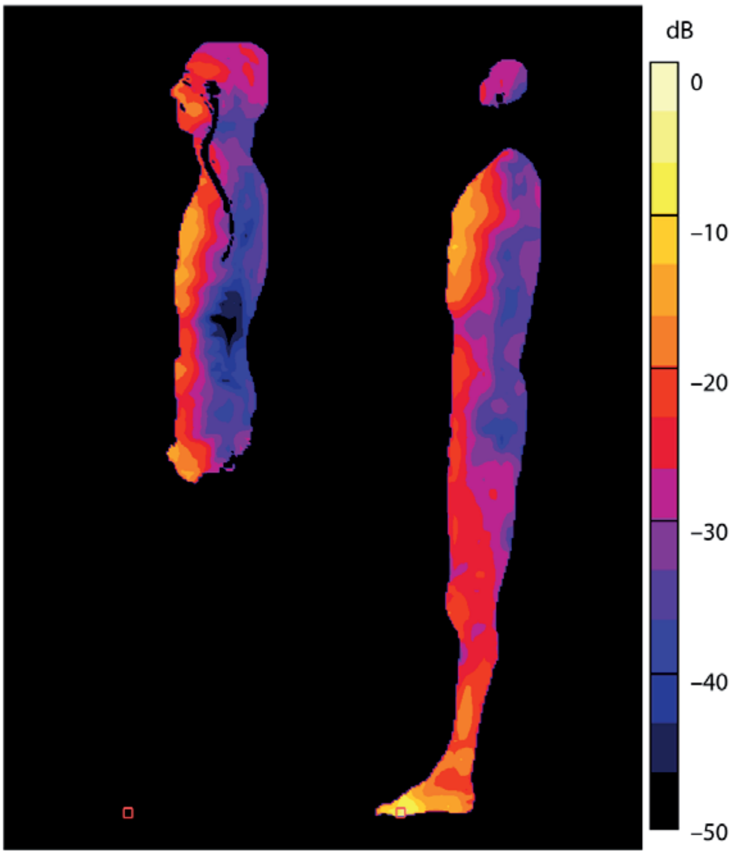

Figure 7. Specific absorption rate (SAR) values in a vertical cross-section in the middle of the human model (left) and in the centre of the foot (right) for the grounded exposure scenario. *Notes*. The scale is normalized to 20 W/kg. The square indicates the highest value of SAR (37 W/kg), which is located in the foot.

3.86 W/kg in the grounded case. It was still below the basic restrictions in contrast with exposure in front of the UHF antennas. In this case, SAR_{wb} was up to 1.13 W/kg, i.e., nearly 3 times over the basic restrictions; the maximum value of SAR_{10g} was 37 W/kg, i.e., nearly 2 times over the basic restrictions. Figure 7 shows the location of the maximum value; the results are presented in a vertical cross-section in the middle of the human model (left) and through the centre of the foot (right). The results show that, in general, the local values of SAR were higher in the part of the body oriented towards the antennas and lower deeper inside the body. Figure 7 shows that the highest values were in the foot. In the head and torso, the values of SAR_{10g} were ~10 dB lower than in the limbs.

4. DISCUSSION AND CONCLUSION

Our previous study demonstrated that the reference levels were quite conservative compared to basic restrictions in the case of near field exposure close to the FM transmitters (see p. 149 in this issue of *JOSE*). When the human body is present, it has an important influence on the electric field distribution not only close to the human body but also in a range of a few metres. Due to this interaction, we found that even when an unperturbed field exceeded the reference levels up to 10 times, SAR values could still be below the basic restrictions.

In this study, we analysed whether the reference levels are conservative also for near exposure in the UHF range; the wavelength is nearly 10 times shorter and, therefore, the interaction between the body and the transmitter could be different.

As a measure of the conservativeness of the reference levels, we calculated the safety factor *S* as in Remkes [9]:
for all scenarios in Table 3; $E_{calculated}$—calculated

$$S = \left(\frac{\max E_{calculated}}{E_{reference\ levels}} \right)^2 \frac{SAR_{wb\ basic\ restrictions}}{SAR_{wb\ calculated}},$$

value of the electric field, $E_{reference\ levels}$—reference level for the electric field, $SAR_{basic\ restrictions}$—basic restrictions for SAR, $SAR_{calculated}$—calculated value of SAR. Table 3 shows the safety factor *S* calculated for SAR_{wb} and SAR_{10g}.

TABLE 3. Safety Factor *S* Calculated for Different UHF Exposure Scenarios: on the Ladder at 32.1, 33.5, 34.4 and 35 m for an Isolated Human Model and at 33.5 m for a Grounded[1] Human Model; Exposure in Front of UHF Antennas for Basic Restriction for Whole-Body (S_{wb}) and Maximum 10-g Averaged SAR (S_{max10g})

Position of Model	S_{wb}	S_{max10g}
32.1 m	4	5
33.5 m	3	3
33.5 m grounded	3	2
34.4 m	3	4
35.0 m	4	6
in front of UHF antenna	13	19

Notes. UHF—ultra-high frequency, SAR—specific absorption rate; 1—touching the metallic structure of the mast.

Results in Table 3 show that for all the isolated cases, SAR_{wb} was exceeded first, as the safety factor *S* was lower for the whole body in all cases except where the model was grounded. When the human body touched the metallic structure, there were local enhancements of the values of SAR in the area of the body which was grounded and the maximum value of SAR_{10g} was exceeded prior to SAR_{wb}.

If we compare the safety factor *S* for exposure close to the UHF transmitter with *S* for exposure on the FM transmitters from the literature [8, 9], we see that the reference levels are not as conservative for near field exposure in the UHF frequency range as for the FM frequency range. The safety factor *S* for near field FM exposure is reported to be 40–250, always much higher than for UHF exposure.

As the safety factor *S* in this situation is only 2–4 for exposure close to the UHF antennas and not in front of them, the results of the measurements in the empty space are a good prediction of real exposure. However, for exposure immediately in front of the antennas, the safety factor *S* is over 10, i.e., basic restrictions are not exceeded even though the electric field in the empty space is up to 3 times higher than the reference levels. However, as for the UHF transmitter the electric field was over 5 times higher, the values of SAR exceeded the basic restrictions for exposure in front of the antenna. Therefore, workers should be allowed to climb such antennas only if the transmitter is turned off.

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