

Occupational Exposure Assessment on an FM Mast: Electric Field and SAR Values

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Electric field strengths normally exceed the reference levels for occupational exposure in close vicinity to large frequency modulation (FM) transmitters. Thus, a detailed investigation on compliance with basic restrictions is needed before any administrative protection measures are applied. We prepared a detailed numerical model of a 20-kW FM transmitter on a 32-m mast. An electrically isolated anatomical human model was placed in 3 different positions inside the mast in the region where the values of the electric field were highest. The electric field strengths in this region were up to 700 V/m. The highest calculated whole-body specific absorption rate (SAR) was 0.48 W/kg, whereas the maximum 10-g average SAR in the head and trunk was 1.66 W/kg. The results show that the reference levels in the FM frequency range are very conservative for near field exposure. SAR values are not exceeded even for fields 10 times stronger than the reference levels.

occupational exposure exposure assessment measurements numerical calculation
SAR FM radio tower FDTD

1. INTRODUCTION

Beside radars, radio and TV transmitters are among the most powerful, high-frequency sources of electromagnetic fields (EMF). As their power can be up to a few hundred kilowatts, close human exposure to such transmitters can be high and can easily exceed reference levels as defined in the International Commission on Non-Ionizing Radiation Protection (ICNIRP) guidelines [1] and in Directive 2004/40/EC [2]. Both documents have very similar requirements but use different terminology. For high-frequency exposure to EMF, the most important parameter is the specific absorp-

tion rate (SAR). SAR is the measure of absorbed power per mass of tissue; it is monitored to prevent excessive tissue heating. This limit is called basic restrictions in the ICNIRP guidelines and exposure limit values in Directive 2004/40/EC. Limits defining the values of the electric and magnetic field strengths in an unperturbed situation, i.e., no human present, are more conservative but easier to use in practice. These limits are called reference levels in the ICNIRP guidelines and action values in Directive 2004/40/EC. In this paper, we will use the terms basic restrictions and reference levels. The reference levels are frequency dependent; for the electric field strength, they are

61 V/m for frequency modulation (FM) radio (87–108 MHz) and very high frequency (VHF) TV broadcasting (174–223 MHz), whereas for ultra-high frequency (UHF) TV broadcasting (470–830 MHz) they vary from 65.0 to 86.4 V/m.

To prevent excessive heating of the whole body, the value of SAR is limited for the whole body to an average value of 0.4 W/kg for occupational exposure. The localized value of SAR intended to prevent excessive heating of a highly exposed tissue or organ can be higher. The value has to be averaged over 10 g of tissue because of tissue heat conductivity and heat capacitance. It is limited to 10 W/kg in the head and trunk, and 20 W/kg in the limbs.

As it is not possible or practical to directly measure the value of SAR, reference levels are more practical and easier to use [3]. These levels limit unperturbed values of the electric or magnetic field or the equivalent plane-wave power density. The reference levels are conservative, meaning that compliance with them ensures compliance with the relevant basic restrictions. If they are exceeded, however, this does not necessarily mean that the basic restrictions are also exceeded. It is necessary to test compliance with the relevant basic restrictions and determine whether the workplace fulfils these criteria, otherwise additional protective measures are necessary to guarantee that workers are not exposed above the basic restrictions. Therefore, the first step when analysing workers' exposure is to measure or calculate the electromagnetic fields. The results of the measurement and calculation allow a comparison of the measured values with the reference levels which, in turn, can lead to a potential and simple method to test the site if it complies with the ICNIRP guidelines [1] and Directive 2004/40/EC [2].

During maintenance and repair work, workers have to climb transmitters to perform their tasks. However, turning the transmitters off during maintenance and repair is not a viable option for broadcasting companies [4, 5]. As employers are responsible for workers' health and safety, risk assessment should be done to determine whether it is safe to work in a specific location under normal operating conditions or if it is necessary to reduce the output power.

There are studies on occupational exposure to EMF of broadcasting workers, but very few include calculations of SAR values. The European Broadcast Union (EBU) [4] estimated the values of electric field strength and SAR for workers working on FM, VHF and UHF towers. It found that for a typical FM transmitter (output power of 5 kW), the values of the electric field on the tower are 25–80 V/m. Jokela [6] and Bolte [7] suggested similar or even higher values of the electric field reaching several hundreds of volts per metre. It is evident that reference levels are exceeded on a number of broadcasting towers; therefore, it is necessary to further analyse SAR values. However, there are few studies on those values in near field exposure near FM or VHF transmitters. Remkes presented results of measuring and calculating electric field strength and SAR values on an FM tower [8]. There was a large safety factor between the value of the reference levels and the basic restrictions. He also reported that during maintenance work on the FM transmitter, the basic restrictions were exceeded when the value of the unperturbed electric field exceeded the reference levels over 6 times. Due to this high safety factor, it is possible that workers could still be allowed to work close to FM transmitters in many cases; however, this must first be proven by demonstrating compliance with basic restrictions.

In this study, electric field measurements were made on an FM mast with 20 kW total transmitted power. A detailed numerical model of the whole mast with the FM antennas was constructed and the values of the electric field strength and SAR values were calculated for three different positions of the human model inside the mast. The results were compared with the basic restrictions and workers' exposure was evaluated.

2. MATERIALS AND METHODS

We analysed workers' exposure to EMF while they climbed the FM mast both with measurements and with numerical calculations. We investigated a real broadcasting facility consisting of a VHF and UHF TV transmitter tower and the FM mast (40 m high). FM antennas transmitting

four different FM programs at 88.6, 92.9, 95.3 and 105.7 MHz were located from the 10th to the 32th metre, whereas the top 8 m were occupied by an additional UHF system transmitting at 791.25 MHz. The power on the FM system located on the FM mast (at the connector of the main cable on the combiner) was 25 kW (10 kW at 95.3 MHz, 5 kW at each of the other frequencies) and 5 kW in the UHF system.

The facility was highly exposed environmentally (gusts of winds up to 60 m/s, lightning, ice). As it was an important telecommunication and broadcasting hub, a two-person crew was always present there. Their main task was to oversee the working conditions in the facility and, if necessary, to perform unscheduled maintenance and repairs, including those on the towers.

2.1. Measurements

Spot measurements were done at fixed locations on the mast with a broadband detector and a spectrum analyser. The maximum root-mean-square (RMS) value of the electric field strength was recorded at each measurement point. Using broadband measurements, the value of the electric field was measured in the regions where the frequency of the field was well known and there was no need to distinguish between contributions of different systems. In total, 16 measurement points were evaluated on the FM mast. Measurements were selective only on two points due to problems with placing the equipment. On the mast, it was possible to do measurements only on two platforms; it was not possible to securely position the tripod supporting the antenna elsewhere. However, one platform was located between the FM and UHF systems, which made it possible to analyse and evaluate the contributions of each system.

For broadband measurements, the measurement system consisted of W&G EMR 300 and Narda type 8.2 E field probes (both from Narda, Germany). The extended uncertainty of the measurement system was ± 3.38 dB in the frequency range from 0.2 to 3000 MHz. During the meas-

urements, the broadband probe/instrument was held in an extended arm as far as possible away from the body to minimize the effect of the human body on the electric field distribution. Six-minute averaging was not done, since the output power of the system was constant and the measured values were stable during the measurements. Instead, the maximum value in one minute was taken as the result of the measurement.

An Anritsu MS 2711 spectrum analyser (Anritsu, USA) with a Clampco EMSAP2000 biconical antenna (Clampco, Italy) was used for frequency selective measurements. The extended measurement uncertainty of the complete system was ± 4.5 dB. During the measurements, the antenna was placed on a wooden tripod to minimize the effect of the human body on the electric field distribution.

Only electric field strength was measured, since in the near field of dielectric sources (which FM, VHF and UHF sources are), the electric field dominates over the magnetic one [9].

2.2. Numerical Calculations

For numerical modelling, we used the finite-difference time-domain (FDTD) method, as implemented in the SEMCAD version 14¹ (Speag, Switzerland) program package. The simulation was first performed in an empty space to find the areas with the highest electric fields. In section 3, we report the RMS values of the local electric field strength, i.e., without any spatial averaging. Since the area of interest was the inside the mast structure, the simulation was padded with λ of empty space around all the radiating elements. The simulation domain was terminated with a uniaxial perfectly matched layer (U-PML) boundary condition.

We included the whole FM mast (without the top 8 m with the UHF transmitters) in the model. The steel lattice mast was 32.20 m high. The FM transmission system consisted of 28 four-dipole antenna arrays (Figure 1).

Antennas were distributed over eight floors at 3-m intervals. In three horizontal directions,

¹ <http://www.speag.com/>



Figure 1. Model of a 4-dipole antenna (one of 28).

there were eight antennas, whereas in one there were only four, giving a total of 28. The whole FM transmission system was fed with a 120-m 3-1/8" cable and through three step power splitters located on the mast so that the power was distributed to each dipole separately. The attenuation of the whole system of cables and power splitters was 1.1 dB, i.e., the 25 kW power on the connector of the main cable to the combiner was reduced to ~20 kW on all 112 dipoles. The system had a circular polarization, with one third of the power fed to the vertical dipoles and two thirds to the horizontal ones. Beside the differences in the power between the vertical and horizontal dipoles, there was also variability of the power between the antennas at different heights and azimuths. The power on each dipole ranged from 0.37 to 2.2% of the total power. Moreover, the lengths of the cables also varied, so there was a phase shift between different antennas. The radiation pattern of the whole antenna system was defined with the power distribution and phase shift between the dipoles. The power splitters and the cables were not included in the simulation; instead, the excitation of each of the 112 dipoles was individually set to the corresponding power level and phase as determined by the power

splitter system and cable lengths. The excitation frequency was set to 98 MHz.

Once the location of the highest electric field intensity was known, an anatomical human model was inserted into the simulation [10]. The model used was a 34-year-old male, 1.74 m tall with a weight of 70 kg. The model was placed in the centre of the mast at three different heights; at the location of the highest field (23.7 m above the ground), and 1.3 m above and below this point (middle, upper and lower positions, respectively). The lower position was located between the fifth and the sixth floors, where the power fed to the surrounding antennas was highest; the antennas in the fifth and sixth floors were fed 40% of the total power. Figure 2 shows the human model in the middle position. The human model was isolated, i.e., not in contact with the metallic structure of the mast.

The simulation with the human model was done in two steps. First, the dielectric properties of the model were homogeneous with conductivity 0.47 S/m and relative permittivity 44 (two thirds of the relative permittivity of the muscle). The maximum spatial resolution of the model was kept under $\lambda/14$ (~0.2 m in free space) throughout the whole simulation domain to ensure stability of the FDTD simulation; it

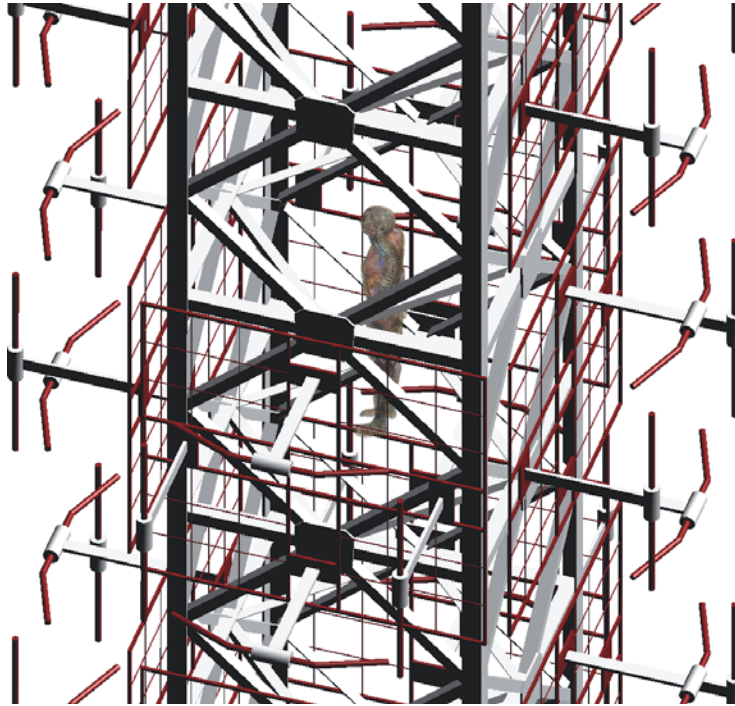


Figure 2. The human model inside the steel lattice mast with antennas in the middle position at the height of 23.7 m.

was finer in the homogeneous human model and structures of the mast (minimum size of the voxel $0.005 \times 0.005 \times 0.008$ m). The incident field was recorded and used in the second simulation via Huygens box excitation [11] with the size of $1.5 \times 1.5 \times 3.25$ m. In the second simulation, only the human model was considered, but this time the spatial discretization was much finer; voxels of $3 \times 3 \times 3$ mm were used in the model and tissue properties was set to inhomogeneous evaluated from the well-known parametric model [12, 13] for the centre frequency used in the simulations (98 MHz). This approach allowed a good resolution of the anatomy and a better precision of the SAR computation without causing a gratuitous increase in computational cost.

To determine the 10-g averaged value of SAR (SAR_{10g}), the efficient averaging algorithm was used (based on Standard No. IEEE C95.3:2002 [14]), which is included in the SEMCAD package. In comparison to the more general requirement that the tissue over which SAR is averaged has to be contiguous only, the averaging volume in that standard is more precisely defined, a cube, and thus widely comparable.

3. RESULTS

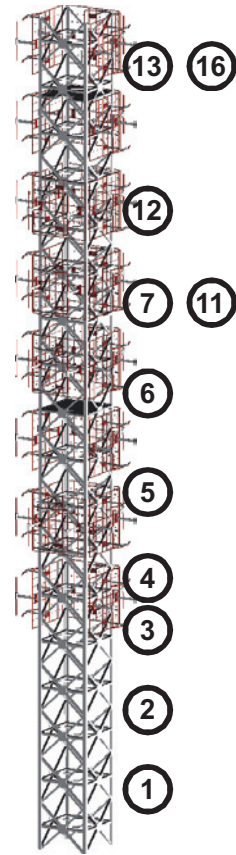
3.1. Electric Field

We measured the values of the electric field strength at 16 measurement points on the FM mast (Table 1). The measurements were made at nine different heights in the middle of the mast, where the distance to the metallic structure of the mast was ~ 1 m. Measurements were also made at different distances from the splitter system at 21 and 30 m.

On the lower part of the mast below the antennas, the values of the electric field strength in the centre of the mast varied between 30 and 75 V/m, whereas on the upper part of the mast, they were 100–200 V/m. Close to the splitter system located in the upper 10 m of the mast, the electric field was higher and could reach 600 V/m on the surface of the splitter elements, but it decreased rapidly with distance and 0.5 m away the values were not elevated any more. Table 1 shows that the electric field strength exceeded the reference levels on the FM mast in the whole area where the FM and UHF system antennas were located.

TABLE 1. Results of Broadband Measurements on the FM Mast

Measurement Point	h (m)	E (V/m)	Description
1	2.5	30	in the middle
2*	5.5	51	in the middle
3*	8.5	75	in the middle
4*	10.5	146	in the middle
5*	14.0	140	in the middle
6*	17.5	100	in the middle of 1st platform
7*	21.0	150	in the middle
8*	21.0	400	0 m from splitter
9*	21.0	350	0.2 m from splitter
10*	21.0	200	0.5 m from splitter
11*	21.0	140	1 m from splitter
12*	24.5	200	in the middle
13*	30.0	175	in the middle of top platform
14*	30.0	600	0 m from splitter
15*	30.0	222	0.2 m from splitter
16*	30.0	200	0.5 m from splitter



Notes. FM—frequency modulation, E —electric field. The horizontal locations of the measurement points are given in the table and vertical locations in the figure on the right. For measurement points marked with an asterisk, it was not possible to guarantee compliance with the reference levels as the measured values of the E field together with the extended measurement uncertainty exceeded the reference level (61 V/m).

The results of the selective measurements were used to evaluate the contribution of the FM and UHF system to total exposure (Table 2). The results clearly demonstrated that the highest exposures were found in close proximity to the FM antennas. The measurements at measurement point 13 on the FM mast were taken between the FM and UHF systems. The power of one FM frequency (88.6, 92.9 or 105.7 MHz) and of the UHF system at 791.8 MHz was similar but the measured values of the electric field strength were higher for the FM system than for the UHF system at the same power. The reason is that each panel of the UHF antenna was more directional and, therefore, had higher gain compared to the FM panel of the antennas. Thus, the electric fields of the UHF antennas decreased faster when we moved vertically away from them compared to the FM antennas.

Figures 3–4 compare measured and calculated values of the electric field strength. First,

TABLE 2. Results of Selective Measurements on the FM Mast on the Ground and on the Platform at the Top (Measurement Point 13)

Measurement	System	Frequency (MHz)	E (V/m)
At the top	FM	88.6	13.3
$h = 30$ m	FM	92.9	28.4
Broadband result:	FM*	95.3	83.4
75 V/m	FM*	105.7	46.3
	UHF	631.4	5.4
	UHF	791.8	17.5
	UHF	796.82	4.7
On the ground	FM	88.6	5.7
$h = 1$ m	FM	92.9	6.0
Broadband result:	FM	95.3	8.0
13.4 V/m	FM	105.7	5.6
	UHF	631.4	4.0

Notes. FM—frequency modulation, E —electric field, UHF—ultra-high frequency. For measurements marked with an asterisk, it was not possible to guarantee compliance with the reference levels as the measured values of the electric field together with the extended measurement uncertainty exceeded the reference level (61 V/m). Values under 2 V/m are not shown.

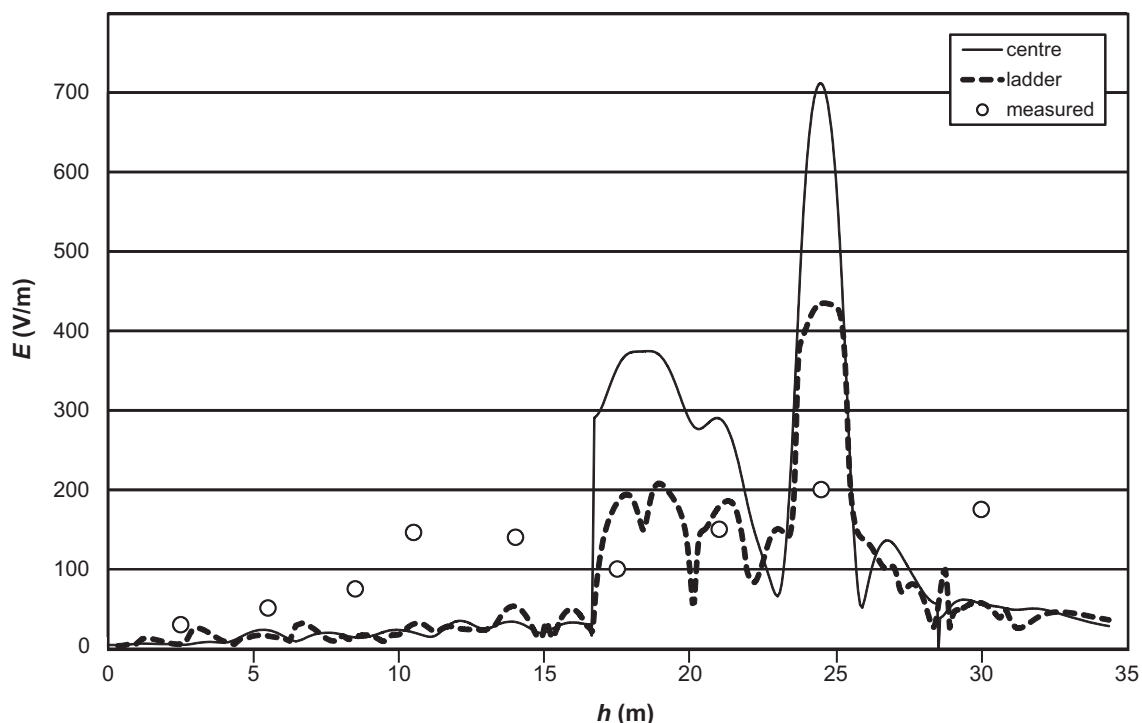


Figure 3. Measured and calculated values of the electric field E inside the frequency modulation (FM) mast over the height h . Notes. The values of the electric field are shown for the centre of the mast (centre) and close to the ladder (ladder). The human body was not included in the calculation; empty space situation.

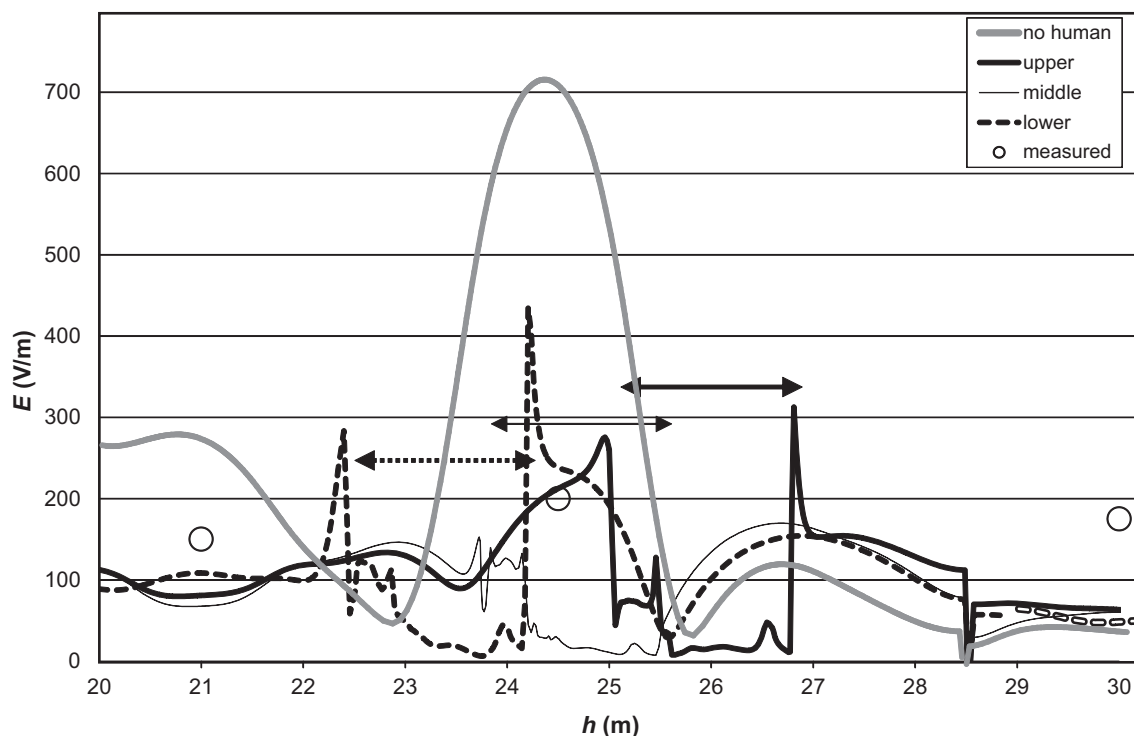


Figure 4. Measured and calculated values of the electric field E inside the frequency modulation (FM) mast over the height h . Notes. The values of the electric field are shown for the centre of the mast for the situation without the human model and for 3 different positions of the human model inside the FM mast at 22.4, 23.7 and 25.0 m. Arrows indicate the position of the human model.

we calculated the electric field in and around the mast without the presence of the human model. Figure 3 shows the values for two locations: in the centre of the mast (like during measurements) and close to the ladder inside the mast (typical exposure when climbing a mast). The measurement points close to the splitter system (8, 9, 10, 11, 14, 15 and 16) were not included since the effect of the splitter system was limited to the distance under 1 m and it was not included in the numerical model.

The calculated values of the electric field in the centre of the mast were under 50 V/m up to the height of 17 m, where the first platform was located. They were lower than the measured values, which exceeded 100 V/m for heights over 10 m. Higher than 17 m, the calculated values of the electric field in the centre of the mast reached

700 V/m, whereas the measured values were under 200 V/m. The calculated values of the electric field strength were lower close to the ladder, since the distance to the well-conducting structures, such as the ladder and the steel lattice mast, was shorter than to the centre of the mast and the electric field distribution was greatly affected. Instead of the values up to 700 V/m, close to the ladder, the highest calculated values of the electric field strength were up to 430 V/m. However, they were still much higher than the reference levels (61 V/m). Figure 4 shows that in addition to parts of the mast structure, also the human body affected the electric field distribution.

Not only is the electric field greatly reduced inside the human model and close to it, but it also exerts influence over the electric field distribution

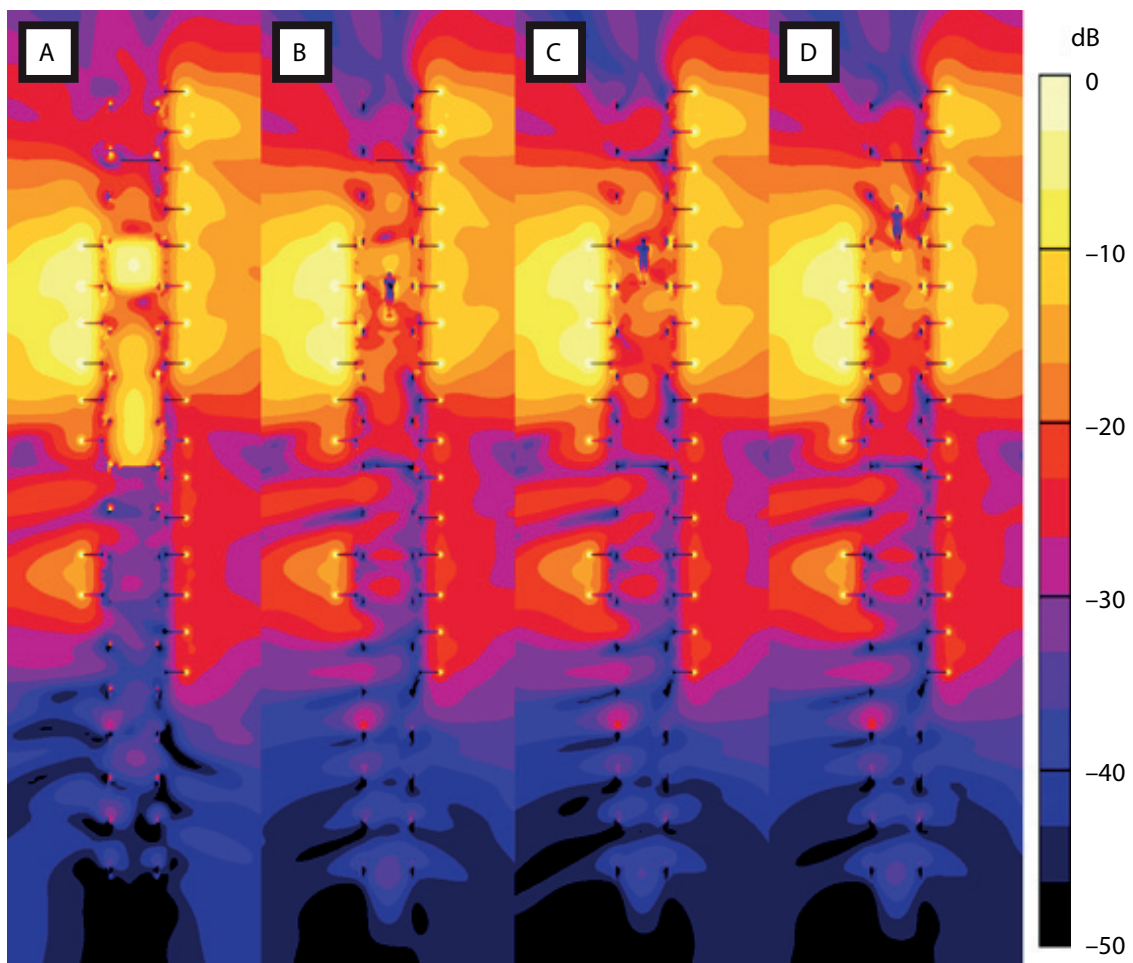


Figure 5. Electric field in a vertical cross-section of the frequency modulation (FM) mast. Notes. A—empty space (without the human model), B—lower position ($h = 22.4$ m), C—middle position ($h = 23.7$ m), D—upper position ($h = 25$ m) of the human model inside the FM mast. The values are normalized to 1 kV/m and are shown in logarithmic scale.

in other locations inside the FM mast in the range of up to a few metres. When there was no human model in the model, the calculated values were higher than the measured ones, but when the human model was included (similar conditions to those during the measurements) the measured values were much closer to the calculated ones. Even in that case, the values of the electric field strength were lower than the reference levels (61 V/m) only in a small region near the torso of the human model and higher elsewhere. Figure 5 shows the effect of the human body on the distribution of the electric field; vertical cross-sections through the centre of the mast indicate an empty space and lower, middle and upper positioning of the human body inside the mast.

3.2. SAR

As the values of the electric field (either measured or calculated) exceeded the reference levels, SAR values in the human model were calculated. Table 3 presents the results; the values of the average whole-body SAR_{wb} , the maximum 10-g averaged SAR_{10g} for the head and trunk and for the limbs are given separately.

TABLE 3. SAR Values Calculated in the Model for the Lower ($h = 22.4$ m), Middle ($h = 23.7$ m) and Upper Position ($h = 25.0$ m) of the Human Model Inside the FM Mast

Position of Model	SAR_{wb} (W/kg)	Head and Trunk Max SAR_{10g} (W/kg)	Limbs Max SAR_{10g} (W/kg)
Lower	0.48	1.66	8.02
Middle	0.17	1.03	1.99
Upper	0.15	1.05	1.96

Notes. SAR—specific absorption rate, FM—frequency modulation, SAR_{wb} —whole-body SAR, SAR_{10g} —10-g averaged value of SAR.

The results show that SAR_{wb} was below the basic restriction (0.4 W/kg) in the middle and upper position of the human model inside the FM mast, but slightly exceeded it in the lower position, where the power on the antennas was the highest. The maximum SAR_{10g} was always below the basic restrictions (10 W/kg for the head and trunk, 20 W/kg for the limbs). Although it was still below the basic restriction, the maximum SAR_{10g} in the limbs was high in the lower posi-

tion of the human model. Figure 6 shows the location of the local maximum. However, the high values were limited to the legs and the arms and were much lower in the torso (Table 3).

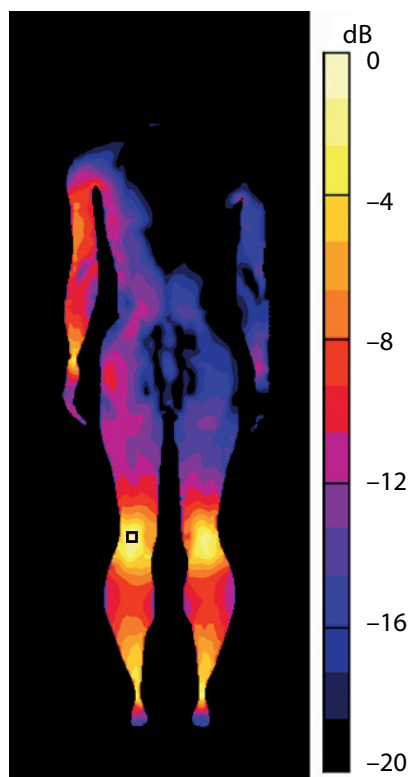


Figure 6. Specific absorption rate (SAR) values in a vertical cross-section in the middle of the human model. Notes. The model is placed in the lower position ($h = 23.4$ m). The scale is normalized to 10 W/kg. The square indicates the highest value of SAR (8.02 W/kg), which is located in the knee.

4. DISCUSSION AND CONCLUSION

The electric field strengths on the locations accessible to maintenance and repair workers inside the 20 kW FM transmitter were determined with measurements and numerical calculations. Since the electric fields in the FM mast exceeded the reference levels by a factor of up to 10, we also numerically calculated SAR values for three different positions of the human body inside the FM mast. For all the analysed cases, the local values of SAR_{10g} were below basic restrictions, but for SAR_{wb} in one position the value was

slightly higher than the basic restrictions. For the analysed situation and the model we used, SAR_{wb} was exceeded before the values of the local SAR_{10g} .

The calculated values of SAR showed that the analysed FM mast did not comply with the ICNIRP guidelines [1] and Directive 2004/40/EC [2] and workers' excessive exposure was highly probable. In addition to exceeded SAR_{wb} for the lower position, the effect of the contact current and the uncertainty of the value of SAR were not analysed, either. Nevertheless, the values of the electric field strength and SAR show that reference levels are conservative compared to the basic restrictions. If we calculate the safety factor S , which is a measure of the conservativeness of the reference levels [8],

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

where $E_{\text{calculated}}$ —calculated value of the electric field, $E_{\text{reference levels}}$ —reference level for the electric field, $SAR_{\text{basic restrictions}}$ —basic restrictions for SAR, $SAR_{\text{calculated}}$ —calculated value of SAR, for all three positions with the highest value of the electric field in the region where the human model is positioned; safety factor $S \approx 100$ for the lower position, $S \approx 230$ for the middle position and $S \approx 250$ for the upper position. In Remkes's study, $S = 42$ [8]. The values we obtained were higher; however, the difference was not unexpected since there were some differences between the models. First, the analysed transmission mast was different albeit similar. Second, the anatomical human models were different. Remkes used the Visible Human Data Set [15] model, whereas we used a 34-year-old male, 1.74-m tall with a weight of 70 kg (a human model from the Virtual Family [10]). Third, the numerical method, discretization and resolution were all different. Nevertheless, both findings agree that in the case of the near field exposure on the FM mast, the reference levels are conservative and based on SAR calculations, it is sometimes possible to safely allow work on the mast without lowering the output power or even turning it off. As the value of the safety factor S varies a lot, it is impor-

tant to be careful and conservative when using these results for risk assessment. However, with additional results for different human models and different exposure situations, we expect the results to become more useful for risk assessment of workers working close to FM transmitters.

The effect of the human body on the electric field distribution is another important finding. Not only does it change close to the human model, but it also significantly affects the field distribution in other parts of the mast (Figures 3–5). This explains the results in Figure 3 with the measured and calculated values of the electric field strengths. We can see that the measured values are lower than the calculated ones. During measurements, the body of the person who carried out the measurements affected the distribution of the electric field; it was reduced close to the body. Figure 4 shows that if the human model is included in the calculations, the resulting electric field levels are lower and closer to the results of the measurements. During the measurements, the person climbing the mast held the instrument. Although the worker performing the measurements tried to hold it as far from the body as possible, clearly this was not enough. To avoid this error it is, therefore, advisable to make measurements remotely, and not by carrying the instrument in the hands.

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