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Brief Communication

Induced Electric Fields in Workers Near Low-Frequency Induction Heating Machines

Bor Kos,[1,2] Blaž Valič,[1] Tadej Kotnik,[2] and Peter Gajšek[1]*

[1]INIS – Institute of Non-Ionizing Radiation, Ljubljana, Slovenia
[2]Faculty of Electrical Engineering, University of Ljubljana, Slovenia

Published data on occupational exposure to induction heating equipment are scarce, particularly in terms of induced quantities in the human body. This article provides some additional information by investigating exposure to two such machines—an induction furnace and an induction hardening machine. Additionally, a spatial averaging algorithm for measured fields we developed in a previous publication is tested on new data. The human model was positioned at distances where measured values of magnetic flux density were above the reference levels. All human exposure was below the basic restriction—the lower bound of the 0.1 top percentile induced electric field in the body of a worker was 0.193 V/m at 30 cm from the induction furnace. Bioelectromagnetics 35:222–226, 2014. © 2013 Wiley Periodicals, Inc.

Key words: occupational exposure; induction heaters; induced electric fields

Induction heating machinery is very prevalent in metalworking industries, as it is used for melting, hardening, tempering, and other processes. The benefits of using induction heating over other heat sources include the more precise control over heating profiles and higher power efficiency. Induction heating devices require very high working powers since they involve heating large pieces to high temperatures in a short time span. They feature powers up to several MW and operate at frequencies of up to 8 MHz [Floderus et al., 2002]. The strong magnetic fields generated by these devices result in considerable exposure to workers near such machinery. In all cases, the occupational reference levels and basic restrictions were taken into account, as we assumed that workers operating near such machinery would receive appropriate awareness training regarding occupational exposure to electromagnetic fields.

Despite the high powers and strong magnetic fields reported in the literature, there is a lack of dosimetric data on human exposure to such sources. We previously reported measurements and simulations of induced electric fields in workers exposed to an induction tempering furnace operating at 10 kHz [Kos et al., 2012]. In the same publication, we also investigated different methods of averaging measured fields in free space to ensure that spatial averaging allows for a reasonable relaxation of reference levels without compromising safety. Spatial averaging is proposed in the International Commission for Non-Ionizing Radiation Protection (ICNIRP) guidelines [ICNIRP, 2010] based on earlier published work [Jokela, 2007]. Other data on induced electric fields and/or currents resulting from exposure to industrial induction heating equipment are currently, to the best of our knowledge, not available in the literature, although other sources of exposure to non-homogeneous magnetic fields have been previously studied [Stuchly and Dawson, 2000].

Here we report the measurements of magnetic flux density in free space, and computationally determined induced electric fields in the workers' body for two large-scale industrial induction heating machines. The first machine investigated was an induction furnace operating at 50 Hz, while the second was a dual-frequency induction hardening machine operating at 67 and 520 Hz. The induction furnace consists of a step-down transformer that uses induction to maintain the temperature of molten metal for casting. The maximum working power of the furnace is 200 kVA. The induction hardening machine consists of a yoke for suspending the steel rollers and axles with two

*Correspondence to: Peter Gajšek, INIS, Pohorskega bataljona 215, SI-1000 Ljubljana, Slovenia. E-mail: peter.gajsek@inis.si

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adjustable inductors. The power and frequency of each inductor can be adjusted according to the needs of the process, with the maximum available power of 1 MVA. Both machines can be seen in Figure 1.

Models of the devices were built using the 3D full-wave electromagnetic and thermal simulation platform SEMCAD X 14.8 (Schmid & Partner Engineering AG, Zurich, Switzerland) and the magnetic fields and induced electric fields in the human models were determined using the low-frequency magneto quasi-static solver. In the case of the induction hardening device, separate simulations were performed for each frequency in the investigation. Since phase information was not available, the induced electric fields were added conservatively considering only the maximum values. However, since the two frequencies are not part of the same harmonic progression, this simplification should not have an effect on the results. In the case of the induction furnace, the melted metal acts as the secondary winding of the step-down transformer. Since the current in the secondary winding is at least two orders of magnitude larger than the primary current, the source was modeled as a single circular winding with a radius of 250 mm. In the case of the induction hardening machine, the inductors have a single winding as well, with the step-down transformers and the power supply farther away than the inductors and work piece. Therefore, only the two vertically displaced single windings contribute significantly to the exposure.

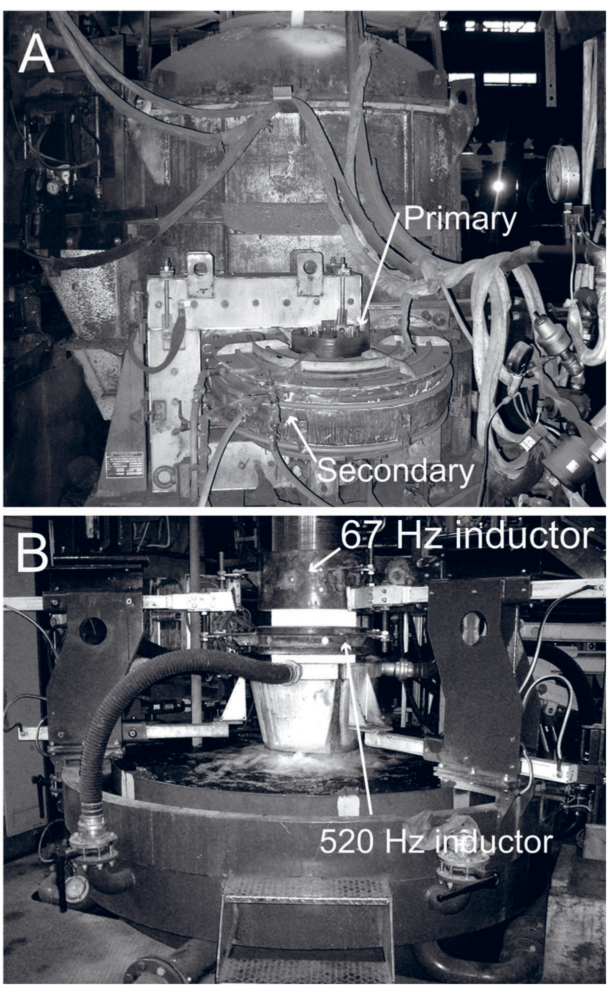

Fig. 1. **A**: induction furnace operating at 50 Hz. In the foreground, the step-down transformer is visible, with the secondary winding clad in heat-resistant material. **B**: The induction hardening machine with two single-winding inductors.

To validate the model, we first performed spot measurements of magnetic flux density around the device. For measurements of the induction furnace, a calibrated Narda ELT-400 (Narda Safety Test Solutions GmbH, Pfullingen, Germany) instrument with a 100 cm^2 B-field probe was used. The combined extended ($k = 2$) uncertainty for the measurement was 2.32 dB (−23%/+31%). For measurements of the induction hardening machine, a calibrated EFA-3 (Wandel & Goltermann, Reutlingen, Germany, now Narda-STS) instrument with a 100 cm^2 B-field probe was used. The combined extended ($k = 2$) uncertainty of the measurement setup was 2.56 dB (−26%/+34%).

In order to compare the measured and the computed values of the magnetic flux density, we averaged the magnetic field over three mutually perpendicular planes with 100 cm^2 cross-sections. The averages of each field component were then added to determine the field magnitude that would be detected by the measurement probe.

The Duke (34-year-old male) model from the Virtual Family set of fully-body anatomic human models (IT'IS Foundation, Zurich, Switzerland) was used for the dosimetric computation [Christ et al., 2010]. The model was positioned at those distances accessible to workers where the measurements were performed. In all cases, the positioning was such that the model was facing the source. The distance was measured from the front of the chest to the closest point on the surface of the inductor model as represented in the numeric model used in the simulations (the size of the current loop was adjusted to match the geometrical center of the single-winding inductors), with the human positioned in an upright (standing) position.

At 0, 20, and 60 cm distance, the measured valued for the induction furnace were 4.2 mT, 2.2 mT, and 480 μT, respectively. The computed values of magnetic flux density at the same probe locations were 7.9 mT, 2.3 mT, and 420 μT, respectively. Although the error at the closest point is rather large, the results align much better at the larger distances and are also inside the uncertainty boundaries as defined in the literature [Kuster et al., 2006]. The numerical model was used to determine the in situ electric field in the male model of the Virtual Family set of models [Christ et al., 2010].

The adult male model was positioned at distances of 30, 40, and 60 cm from the inductor and the maximum in situ E fields in a single 2 mm × 2 mm × 2 mm voxel in the whole body were 1.82, 1.68, and 0.62 V/m at 30, 40, and 60 cm, respectively. ICNIRP guidelines recommend averaging computationally determined fields in a cubic volume with dimensions of 2 mm × 2 mm × 2 mm. Since this is the same size as the voxels used in the simulation, such averaging cannot be performed. In order to do so, simulations would need to be performed with a grid smaller than 2 mm. Instead we are reporting the E_{999} field, defined as the value below which 99.9% of the computed E field values (i.e., voxels of the simulation) occur. The values of E_{999} were 0.193, 0.124, and 0.062 V/m at 30, 40, and 60 cm, respectively. All these values are below the basic restriction of 0.8 V/m at 50 Hz. Additionally, the contiguous tissue 99th percentile—the E_{99}—was checked for all tissues, which is most relevant for the tissues of the central nervous system, that have a lower basic restriction. The highest values are reported in Table 1. The results of the current work confirm that the torso-averaged value of magnetic flux density in free space over 9 averaging points reduces the measured free-space values (thus offering a "relaxation" when comparing them with the reference levels) [Kos et al., 2012], while keeping the real exposure below the basic restrictions.

The second case studied was the dual-frequency induction hardening device operating at 67 and 520 Hz. Using the same methods described above, we compared measured values of magnetic flux density to computed values at the same locations. The measured values at 67 Hz were 710, 150, and 85 μT at 1, 1.5, and 3 m distance, respectively, while the measured values at 520 Hz were 200, 34, and 17 μT at 1, 1.5, and 3 m, respectively. Computed values in corresponding locations at 67 Hz were 625, 165, and 54 μT at 1, 1.5 and 3 m, respectively, while at 520 Hz, they were 151, 36, and 12 μT at 1, 1.5, and 3 m, respectively.

Similar to the first case considered, numerical simulations were used to determine the in situ induced electric field in the adult male model from the Virtual Family at three different distances from the source. At 67 Hz, the maximum values of the electric field were 2.71, 1.71, and 0.95 V/m at 0.5, 0.7, and 1 m, respectively. At the same distances, the respective E_{999} values were 0.27, 0.17, and 0.09 V/m. The exposure at 520 Hz is higher, even though the external fields are lower, with the maximum values of electric field being 4.82, 2.78, and 1.39 V/m, and the corresponding E_{999} values being 0.51, 0.28, and 0.14 V/m. Since the exposure to these two frequencies is independent (they are not on the same harmonic scale, and therefore not phase-coherent), the combined exposure can be easily and accurately checked using the formula from the ICNIRP guidelines:

TABLE 1. Values of Induced Electric Field in the Worker Exposed to Induction Heating Equipment at Different Frequencies

	50 Hz induction furnace[a]			Hardening machine 67 Hz[b]			Hardening machine 520 Hz[c]			Hardening machine exposure index[d]		
Distance	30 cm	40 cm	60 cm	0.5 m	0.7 m	1 m	0.5 m	0.7 m	1 m	0.5 m	0.7 m	1 m
E_{max} (voxel) (V/m)	1.82	1.68	0.62	2.71	1.71	0.95	4.82	2.78	1.39	9.41	5.60	2.93
E_{999} (V/m)	0.19	0.124	0.062	0.27	0.17	0.09	0.51	0.28	0.14	0.98	0.57	0.29
Highest tissue E_{99} (V/m)	0.13	0.094	0.042	0.22	0.12	0.06	0.35	0.19	0.10	0.54	0.32	0.17
Tissue with highest E_{99}	Bone	Bone	Bone	Mucosa	Penis	Penis	Bone	Bone	Bone	Bone	Bone	Bone
Highest IEEE-averaged E (V/m)	0.86	0.57	0.26	0.18	0.10	0.052	2.39	1.35	0.67	3.54	2.03	1.03
Tissue with highest IEEE E	Skin	Skin	Skin	Gray matter	Gray matter	Gray matter	Skin	Skin	Skin	Gray matter	Gray matter	Gray matter

The highest voxel E field, the E_{999} field of the whole body, the highest E_{99} field, and the highest IEEE line-averaged E field of a contiguous tissue are shown.

[a]ICNIRP basic restriction at 50 Hz is 0.1 V/m for tissues of the CNS and 0.8 V/m for other tissues. IEEE basic restrictions at 50 Hz are 0.0442 V/m for tissues of the brain, 0.943 V/m for the heart and 2.1 V/m for other tissues.

[b]ICNIRP basic restriction at 67 Hz is 0.134 V/m for tissues of the CNS and 0.8 V/m for other tissues. IEEE basic restrictions at 67 Hz are 0.0593 V/m for tissues of the brain, 0.943 V/m for the heart and 2.1 V/m for other tissues.

[c]ICNIRP basic restriction at 520 Hz is 0.8 V/m for all tissues of the body. IEEE basic restrictions at 520 Hz are 0.4602 V/m for tissues of the brain, and 2.1 V/m for other tissues.

[d]Values for exposure index are given in dimensionless units. Overexposure is indicated by a value greater than 1.

$$\sum_{j=1\,\text{Hz}}^{10\,\text{MHz}} \frac{E_{i,j}}{E_{L,j}} \leq 1$$

The values of the formula are shown in Table 1. In this case, the spatially averaged values of magnetic fields have been shown to be good predictors of actual exposure.

All values of induced electric fields are summarized in Table 1, with the corresponding maximum values and averaged values of the magnetic flux density shown in Table 2. Figure 2 shows the central cross-section of induced E field in the body. In the classification of exposure based on the tissue E_{99} values, the appropriate basic restriction values were taken into account for each tissue (the tissues of the central nervous system having lower basic restrictions). From the cross-comparison of the two tables, it can be seen that the spatial averaging did not introduce any false negatives (locations where the averaged magnetic flux density is below the reference level, yet the corresponding values of induced in situ electric fields is above the corresponding basic restriction). Additionally, the data for induced in situ electric field was also compared to the relevant IEEE standard [IEEE, 2002] using the line averaging algorithm implemented in SEMCAD X in each tissue of the model. The values were found to be above the basic restriction in several cases, most notably for the hardening machine considering combined exposure at all distances in the brain. Although the values are high, it is possible that the values were pushed a bit higher by extracting fields in each separate tissue, rather than grouping tissues with the same basic restrictions together. Additionally, Chen et al. [2013] also reported that reference levels of the IEEE [2002] standard were in contradiction with the basic restrictions by a factor of more than 5. Due to these results, the authors have even recommended a revision of the exposure limits.

As was found in previous work [Kos et al., 2012], the averaging is best applied at shorter distances from the source, since farther away the fields vary so slowly that averaging does not reduce the values by a significant amount. Averaging has a larger effect when more averaging points are used, or if an arithmetic average is used, but that introduces a higher possibility of false negatives (locations where the actual exposure is above the basic restriction, but the averaged field is below the reference level).

Although the devices under investigation produce very strong magnetic fields, the induced values in the body did not exceed the ICNIRP basic restrictions. This corroborates our previous findings that the reference levels are conservative for inhomo-

TABLE 2. Maximum and Averaged Values of Magnetic Flux Density in Measurement Planes at Equivalent Distances to the Body Positions in Table 1

	Induction furnace at 50 Hz[a,b]	
Distance [cm]	Spatial average (mT)	Max field (mT)
30	1.43	1.93
40	0.95	1.18
60	0.48	0.54

	Induction hardening machine			
	67 Hz[a,b]		520 Hz[b,c]	
Distance [cm]	Spatial average (mT)	Max field (mT)	Spatial average (mT)	Max field (mT)
50	1.98	2.29	0.44	0.50
70	1.15	1.26	0.25	0.27
100	0.59	0.62	0.13	0.14

	Exposure index (combined exposure)			
Distance [cm]	Spatial average (D.U.)[d]	Max field (D.U.)[d]	Spatial average (IEEE MPE)	Max field (IEEE MPE)
50	2.42	2.78	0.89	1.03
70	1.40	1.54	0.52	0.57
100	0.72	0.76	0.27	0.28

[a]ICNIRP reference levels at 50 Hz and 67 are 1 mT.
[b]IEEE maximum permissible exposure for controlled environment is 2.71 mT at all investigates frequencies.
[c]ICNIRP reference level at 520 Hz is 577 μT.
[d]Value given in dimensionless units. Overexposure is indicated by a value larger than one.

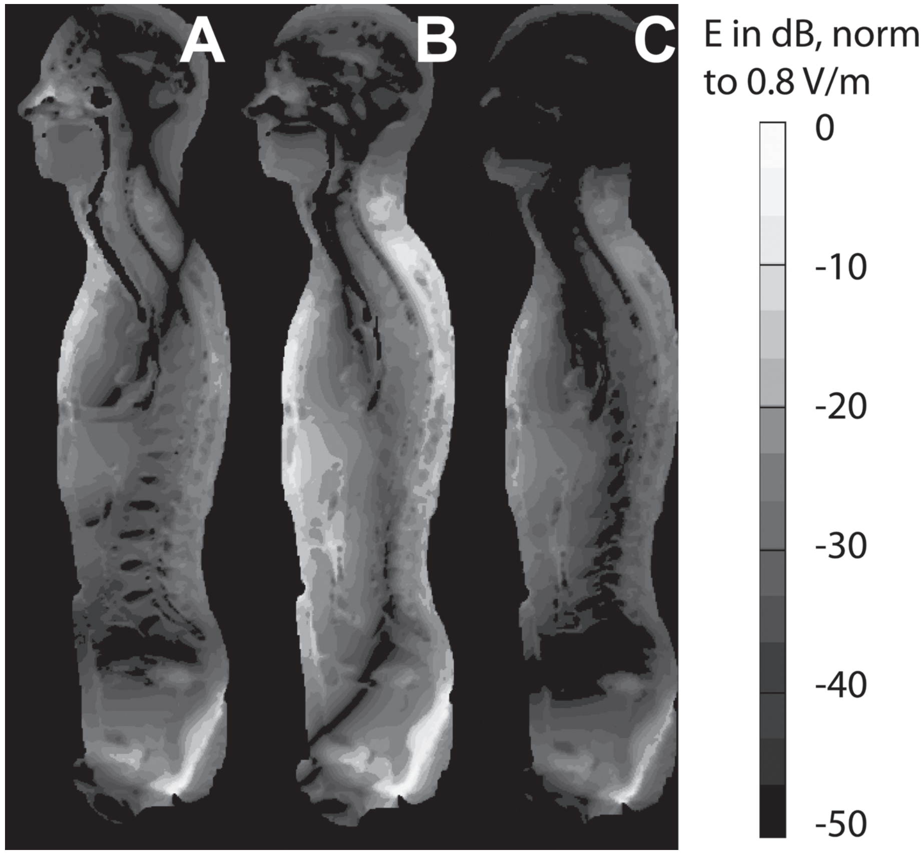

Fig. 2. Induced electric field in dB normalized to 0.8 V/m for the exposure at: (A) 50 cm from the induction hardening machine at 67 Hz, (**B**) at 50 cm from the induction hardening machine at 520 Hz, (**C**) at 30 cm from the induction furnace at 50 Hz.

geneous fields. The limitation of the present study is, however, that the influence of body posture and the issues of body parts forming larger conductive loops between limbs, or with external conductive objects such as metallic parts of machinery, remain to be investigated. Despite the exposure being below the reference levels, the induced in situ E field values exceed the IEEE basic restrictions, and this relation should be further investigated.

REFERENCES

Chen X-L, Benkler S, Chavannes N, De Santis V, Bakker J, van Rhoon G, Mosig J, Kuster N. 2013. Analysis of human brain exposure to low-frequency magnetic fields: A numerical assessment of spatially averaged electric fields and exposure limits. Bioelectromagnetics 34:375–384.

Christ A, Kainz W, Hahn E, Honegger K, Zefferer M, Neufeld E, Rascher W, Janka R, Bautz W, Chen J, Kiefer B, Schmitt P, Hollenbach H, Shen J, Oberle M, Szczerba D, Kam A, Guag J, Kuster N. 2010. The virtual family-development of surface-based anatomical models of two adults and two children for dosimetric simulations. Phys Med Biol 55: N23–N38.

Floderus B, Stenlund C, Carlgren F. 2002. Occupational exposures to high frequency electromagnetic fields in the intermediate range (>300 Hz–10 MHz). Bioelectromagnetics 23:568–577.

International Commission on Non-Ionizing Radiation Protection (ICNIRP). 2010. Guidelines for limiting exposure to time-varying electric and magnetic fields (1 Hz to 100 kHz). Health Phys 99:818–836.

Institute of Electrical and Electronics Engineers (IEEE). 2002. IEEE standard for safety levels with respect to human exposure to electromagnetic fields, 0–3 kHz. New York: IEEE. IEEE Std C95.6-2002.

Jokela K. 2007. Assessment of complex EMF exposure situations including inhomogeneous field distribution. Health Phys 92:531–540.

Kos B, Valič B, Kotnik T, Gajšek P. 2012. Occupational exposure assessment of magnetic fields generated by induction heating equipment-the role of spatial averaging. Phys Med Biol 57:5943–5953.

Kuster N, Torres VB, Nikoloski N, Frauscher M, Kainz W. 2006. Methodology of detailed dosimetry and treatment of uncertainty and variations for in vivo studies. Bioelectromagnetics 27:378–391.

Stuchly MA, Dawson TW. 2000. Interaction of low-frequency electric and magnetic fields with the human body. Proc IEEE 88:643–664.