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Numerical Dosimetry of Induced Phenomena in the Human Body by a Three-Phase Power Line

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We computed by finite element the fields induced in an heterogeneous model of the human body by both the electric and magnetic field generated by a three-phase power line. Results were partially validated and analyzed by comparison with existing data with uniform magnetic field. Induced currents due to both E and B were developed inside the body in an asymmetrical manner.

Index Terms—Dosimetry, extremely low frequency (ELF), finite-element method, human body.

I. HUMAN EXPOSURE TO ELF ELECTROMAGNETIC FIELDS

THE human body is increasingly exposed to “electrosmog” due to an increasing use of electricity. The accurate association between exposure to extremely low frequency (ELF) electromagnetic fields (EMF) and health hazard is an open question. Previous studies can be roughly classified in behavioral, biological and epidemiological studies. The most obvious effect of ELF EMF on the human body is the transitory stimulation of the nervous system. Such an effect, called “magneto-phosphene,” was first remarked by d’Arsonval in 1896 [1]; more recently, brain stimulation through strong magnetic pulses (TMS) are being used as therapy against some types of mental diseases [2]. However, the main concern with EMF exposure is cancer. Exposure to ELF EMF probably does not produce *by itself* any physical or chemical damage to DNA. Unfortunately, this is not enough to ensure that such an exposure has no effect (positive or negative) at all. The current research trend is to look for “second order” effects of EMF on sensitive biological phenomena, and notably on the immune system, cell signal pathways and DNA replication. For instance, Miyakoshi *et al.* [3] found that exposure to 50-Hz EMF induced mutations in cell cultures where the tumor suppressor gene *p53* was damaged (which is the case for nearly 50% of cancers), but this same exposure had no effect when the wild type gene was present. In short, such a result suggests that EMF exposure could enhance a preexisting pathological situation, but is unlikely to induce cancer. Nevertheless, epidemiological studies indicate an association between EMF exposure and cancer with a relative risk of about 2 for childhood leukemia [4]. A detailed discussion on interactions between EMF and biology is out of the scope of this work (interested readers can find a review in [1]). The key point is that this topic is a challenge for molecular biology, and that even the question concerning which electrical quantity (E, B, or J) plays a biological role is still open. This lack of knowledge about the effects of long-term exposure on human health is a source of concern for the general public. Some international organizations have provided guidelines for limiting human EMF

exposure, based upon well established health effects. At low frequencies, there is no consensus about the relevant physical quantity for defining the maximum “dose”; ICNIRP guidelines [5] are based on the current density J induced into the human body, whereas the IEEE committee [6] has adopted the induced electric field E. Both of these quantities are difficult to measure [7], [8], therefore numerical dosimetry is mandatory.

In this paper, we present a computation by finite element (FE) of J and E induced by both the electric and magnetic fields generated by a three-phase power line. We first present the method and formulation used (Section II) and a partial validation based upon existing literature (Section III). The computation of J and E induced in the human body in proximity to a power line is presented in Section IV as a case study. Finally, some conclusions are presented in Section V.

II. FORMULATION AND NUMERICAL METHODS

Our goal is to compute the E and J induced in the human body by the simultaneous exposure to a magnetic and electric fields. At power frequencies, the human body is very small compared to the wavelength of the EMF. Therefore, the computation can be performed under the quasi-static approximation—that is, wave propagation phenomena can be neglected. Moreover, due to the particular electrical feature of living matter, some assumptions can be made.

- 1) The conductivity σ of the tissues is weak enough to assume that the induced currents do not modify the source magnetic flux density \mathbf{B} .
- 2) The average conductivity σ and permittivity ε of the human body are big enough, to assume that the external surface of the human body is nearly equipotential.
- 3) Due to the low ratio $\varepsilon\omega/\sigma$, displacement currents can be neglected in the human body (but not in the air).

These approximations are widely accepted [9]–[13] up to about 1 MHz. As displacement currents can be neglected, the current density can be expressed by

$$\mathbf{J} = \sigma \mathbf{E}. \quad (1)$$

Assume to know a magnetic vector potential corresponding to the flux density (no matter the gauge)

$$\mathbf{B} = \text{curl } \mathbf{A}. \quad (2)$$

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By Faraday equation, the electric field \mathbf{E} inside the body can be expressed as

$$\mathbf{E} = -\partial_t \mathbf{A} - \text{grad } \phi \quad (3)$$

where ϕ is a continuous unknown scalar electric potential. By substituting (1) and (2) into the continuity equation $\text{div curl } \mathbf{H} = \text{div } \mathbf{J} = 0$ one obtains

$$-\text{div} [\sigma(\partial_t \mathbf{A} + \text{grad } \phi)] = 0. \quad (4)$$

Equation (4) holds everywhere inside the human body. At the surface of the body, the following continuity condition holds

$$[[\mathbf{n} \cdot (\mathbf{J} + \varepsilon_0 \partial_t \mathbf{E})]] = 0 \quad (5)$$

where \mathbf{n} is the outer unitary normal vector. Thus, one obtains the following non uniform boundary condition:

$$\mathbf{n} \cdot \mathbf{J}|_{\text{body}} = -\mathbf{n} \cdot \varepsilon_0 \partial_t \mathbf{E}|_{\text{air}}. \quad (6)$$

Equations (4) and (6) can be expressed in the following weak form by using Galerkin method [14]:

$$\langle \tau, w \rangle_{\partial\Omega} - (\sigma(\partial_t \mathbf{A} + \text{grad } \phi), \text{grad } w) = 0 \quad \forall w \in H^1(\Omega) \quad (7)$$

where the surface source term τ is defined as

$$\tau = \mathbf{n} \cdot \varepsilon_0 \partial_t \mathbf{E}|_{\text{air}} \quad (8)$$

and $w \in H^1(\Omega)$ are continuous grad-conform test functions. In these equations, the domain Ω is the human body.

In practice, owing to the assumptions (1)–(3), the original “induced current”-like problem has been transformed into a simpler “conduction” problem, which is ruled by a simple Poisson equation. This now classical formulation was originally developed by Bossavit [15]. Compared to some general purpose formulations like $\mathbf{T} - \omega$ and $\mathbf{A} - V$, this formulation allows to save memory and computation time, as only the resolution domain is bound to the human body, and only one unknown per node is required. One observes that when no external electric field is present, the surface source term τ is zero, and therefore (7) reduces to the well known “magnetic exposure” $\phi - \mathbf{A}$ formulation, whose details and validation can be found in [16].

We implemented this formulation by using first-order, nodal finite elements, in the harmonic regime. The source magnetic vector potential \mathbf{A} is continuous inside the human body, and therefore is approximated by using nodal elements. In practice, three problems have to be solved.

- Step 1: Compute a vector potential \mathbf{A} such that $\mathbf{B} = \text{curl } \mathbf{A}$ (no matter the gauge of this potential). This potential can be computed in absence of the human body by using Biot–Savart, or numerical methods [17], or analytical model (for instance a multipolar expansion) based on experimental data [18].
- Step 2: Compute the electric field \mathbf{E} outside the human body by the classical electrostatic formulation; this allows calculating the surface source-term (8). In this paper, this is done by using the finite-element method (FE).
- Step 3: Compute \mathbf{E} and \mathbf{J} by using (7).

In all cases, symmetrical positive definite sparse matrixes are obtained. All the problems are solved by using conjugate

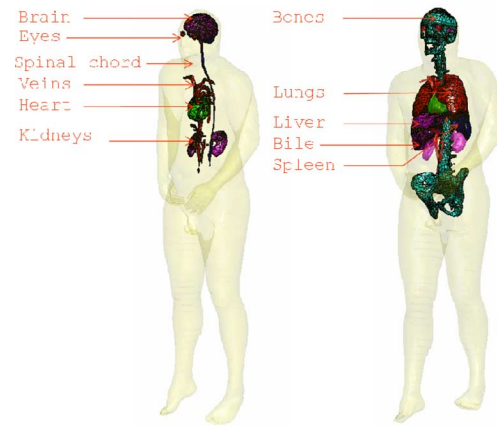


Fig. 1. The ZOL model of the human body: it is composed of 17 different tissues (not all represented here), 84 293 nodes and 475 159 first-order tetrahedral elements.

TABLE I
CONDUCTIVITIES OF TISSUES (S/m, $f = 50$ Hz)

Tissue	Conductivity
Muscle	0.2333
Brain	0.0533
Cerebellum	0.0753
Eyes	1.5000
Spinal marrow	0.0274
Lungs	0.0684
Heart	0.0827
Veins	0.7000
Liver	0.0367
Stomach	0.5210
Kidneys	0.0892
Spleen	0.0857
Bile	0.9000
Colon	0.0545
Intestine	0.5220
Duodenum	0.5220
Bones	0.0504

gradient, preconditioned by incomplete Cholesky factorization. Computational time are of order of 5 to 10 minutes for 84 293 degrees of freedom with a generic PC.

Our model (named “ZOL” in the following—Fig. 1) of the human body has been built by using the software AMIRA, starting from the segmented data of the Visible Human Project, formerly available from <http://www.brooks.af.mil> (named “AF” model in [11]). It is composed of 17 different tissues, whose conductivities are based on the classical works of Gabriel *et al.* [19] (see Table I). So as to obtain the mesh for the electrostatic computation (external to the body) of step 2, we have exported the external surface of the body to GMSH [20], built and meshed the outer geometry. Due to some technical problems, it has not yet been possible to build a geometry with the human body in contact with the soil (which would have been much more realistic).

III. COMPARISON WITH EXISTING DATA

With respect of more standard numerical problems, when dealing with dosimetry in the human body one is concerned with the problem of obtaining a model of the human body. Therefore, not only the numerical method, but also the model of the body by itself has to be evaluated. In literature there exist many models

TABLE II
AVERAGE ELECTRIC FIELD E_{avg} ($\mu\text{V/m}$)

Tissue	Average electric field			
	ZOL	AF	NORMAN	UVIC
Brain	17.5	10.3	10.0	9.07
Heart	15.9	16.7	16.7	14.5
Kidneys	30.8	20.4	20.3	20.7
Lungs	21.6	20.7	22.8	18.9
Muscle	24.3	18.7	12.8	12.4

TABLE III
MAXIMUM ELECTRIC FIELD E_{max} ($\mu\text{V/m}$)

Tissue	Maximum electric field			
	ZOL	AF	NORMAN	UVIC
Brain	38.8	93.0	84.8	65.5
Heart	36.3	123.0	82.1	56.4
Kidneys	48.3	55.3	79.5	92.5
Lungs	59.7	80.3	140	102
Muscle	252.8	300	176	135

TABLE IV
99 PERCENTILE ELECTRIC FIELD E_{99} ($\mu\text{V/m}$)

Tissue	99 percentile electric field			
	ZOL	AF	NORMAN	UVIC
Brain	25.6	21.4	30.7	26.5
Heart	31.8	34.3	58.1	41.1
Kidneys	45.2	31.7	42.7	50.2
Lungs	47.0	35.8	59.2	46.4
Muscle	67.1	49.5	42.9	42.5

of the human body [21], most of which are based on voxels. Regrettably, only a few data is available on inter-laboratory and inter-model comparison. We compared our results with data found in [11], which have been obtained with different computational methods (Scalar Potential Finite Difference—SPFD) and models (named “AF,” “UVIC,” and “NORMAN”). The exposure conditions are: $E = 0, B = 1 \mu\text{T}$ uniform, oriented in the direction back/front, frequency = 60 Hz. The average, maximum and 99 percentile electric fields induced in several tissues are reported in Tables II–IV, respectively. As a first observation, the orders of magnitudes obtained are the same. A deeper analysis shows large difference in some tissues (brain) as well as close values for other tissues (heart). Some of these differences can be explained by size and shape differences between the models (ZOL and AF are the bigger than NORMAN and UVIC). The most troubling point concerns ZOL and AF models, which in principle derive from the same anatomical data. In author’s opinion, the different methods (FE and SPFD) cannot explain such a difference on average values (Table II): the scattering in data is likely to come from the details of the models. For instance, in ZOL’s brain the gray matter, white matter and CSF are not distinguished, whereas they are in other models, and muscle anisotropy is not taken into account. Moreover, the discretization of the different models is not the same: this parameter has a major impact on maximum values [10].

IV. EXPOSURE TO A POWER LINE

As case study, we considered the exposure to the E and B field generated by a balanced three-phase power line (63 kV, 510 A,

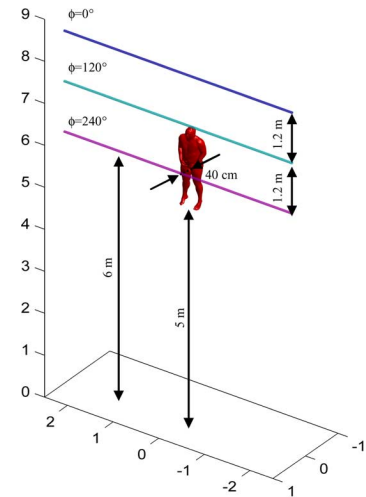


Fig. 2. Three-phase line: the body is at 5 m from the soil. The three phases are at 40 cm from the surface of the body, and at a height of 6, 7.2, and 8.4 m.

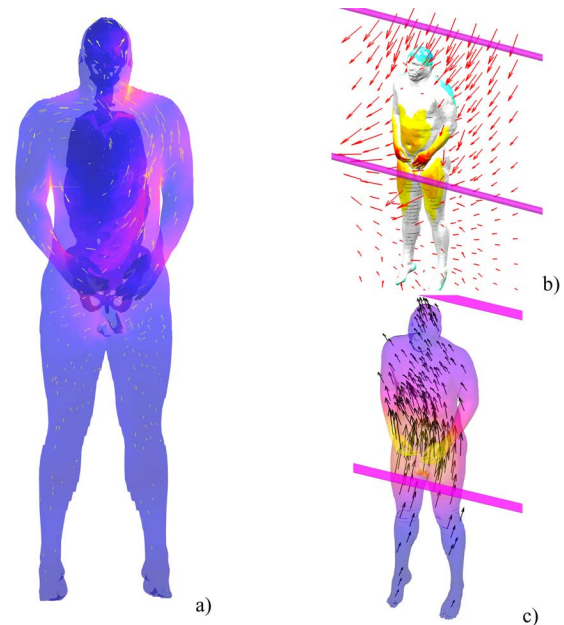


Fig. 3. (a) Induced currents into the human body showing an asymmetrical pattern. The source terms: the surface charge density and the external electric field. (c) Magnetic flux density B into the human body.

50 Hz—see Fig. 2). Fig. 3 shows the induced current inside the human body [Fig. 3(a)], together with the two source terms: the surface charge density τ together with the external electric field [Fig. 3(b)], and the magnetic flux density B [Fig. 3(c)]. One observes that the spatial distribution of the current density is not trivial: with this particular configuration electrically induced currents tend to flow in the back–front direction, whereas magnetically induced current lines form closed loops. The result is that the distribution of induced fields has an asymmetrical pattern. In Table V are reported the average, maximum and 99 percentile values of J and E in the tissues of the body. One observes that the maximum of J and E are not located in the same tissues. It can be observed that (for instance) 99 percentile J_{99} is maximum in the eyes, whereas the maximum of E_{99} is located into the colon. This fact is likely to be due to the different influence of the conductivity: on one hand on J and E , and on the other hand on the electrically and magnetically induced fields. Apart from

TABLE V
INDUCED ELECTRIC FIELD AND CURRENT DENSITY

Tissue	Current density J (mA/m ²)			Electric field E (mV/m)		
	J _{avg}	J _{max}	J ₉₉	E _{avg}	E _{max}	E ₉₉
Muscle	1.11	9.86	3.07	4.76	42.3	13.2
Brain	0.39	0.89	0.62	7.34	16.7	11.6
Cerebellum	0.64	1.27	1.04	8.51	16.9	13.9
Eyes	3.80	8.62	8.28	2.53	5.75	5.52
Spinal marrow	0.16	0.37	0.32	5.68	13.6	11.5
Lungs	0.36	1.19	0.99	5.33	17.3	14.4
Heart	0.53	1.10	1.00	6.40	13.2	12.0
Veins	0.77	8.69	5.79	2.53	12.4	8.27
Liver	0.16	0.54	0.44	4.49	14.6	11.9
Stomach	2.00	5.16	3.67	3.84	9.90	7.04
Kidneys	0.49	1.14	1.07	5.55	12.7	12.0
Spleen	0.82	1.48	1.35	9.55	17.3	15.8
Bile	1.19	4.34	3.66	1.33	4.82	4.06
Colon	0.36	0.99	0.88	6.69	18.2	16.1
Intestine	2.81	5.89	4.88	5.39	11.3	9.36
Duodenum	1.65	4.87	3.93	3.16	9.32	7.52
Bones	0.63	0.93	0.65	5.68	18.4	12.9

the numerical values reported in Table V (which anyway overestimate a real situation, because workers are generally protected from electric field exposure by special suits), the most important point which has to be stressed is that constraints imposed by the regulation is likely to not be the same if the electric field or the induced current density is taken as quantity for computing the maximum dose.

V. CONCLUSION

In this paper, we present a formulation and a geometrical model of the human body, which together allow computing electrical field and current density induced into the human body by a low-frequency electric and magnetic field by using FE. The comparison of our results with existing data found in literature provided a partial validation of our modeling. In particular, the obtained values are reasonably close with existing data (differences rarely exceed 50%), and the largest differences can be at least partly explained by known features of the models, like size effects. However, this analysis put in evidence the difficulties in comparing different models and methods: not only the morphological differences, but also discretization and postprocessing are likely to play a not negligible role. The development of adapted method to handle this complexity is a major challenge in numerical dosimetry. As a case study, we computed E and J induced by a three-phase power line. The obtained result showed an asymmetrical pattern in the fields distributions inside the body, which is due to the different phase and orientation between electrically and magnetically induced fields. Most importantly, the localization of maximum fields is not the same for E and J: therefore E and J are not equivalent from the point of view of the constraints imposed for limiting exposure for EMF. Future works are oriented toward validating electrically induced currents by comparison with existing data, and improving the data processing, the quality of the solution by error estimators, and the resolution and accuracy of our model of the human body.

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