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Application of postured human model for SAR measurements

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Abstract. In the last two decades, the increasing number of electronic devices used in day-to-day life led to a growing interest in the study of the electromagnetic field interaction with biological tissues. The design of medical devices and wireless communication devices such as mobile phones benefits a lot from the bio-electromagnetic simulations in which digital human models are used.

The digital human models currently available have an upright position which limits the research activities in realistic scenarios, where postured human bodies must be considered. For this reason, a software application called “BodyFlex for CST STUDIO SUITE” was developed. In its current version, this application can deform the voxel-based human model named HUGO (Dipp GmbH, 2010) to allow the generation of common postures that people use in normal life, ensuring the continuity of tissues and conserving the mass to an acceptable level. This paper describes the enhancement of the “BodyFlex” application, which is related to the movements of the forearm and the wrist of a digital human model.

One of the electromagnetic applications in which the forearm and the wrist movement of a voxel based human model has a significant meaning is the measurement of the specific absorption rate (SAR) when a model is exposed to a radio frequency electromagnetic field produced by a mobile phone. Current SAR measurements of the exposure from mobile phones are performed with the SAM (Specific Anthropomorphic Mannequin) phantom which is filled with a dispersive but homogeneous material. We are interested what happens with the SAR values if a realistic inhomogeneous human model is used. To this aim, two human models, a homogeneous and an inhomogeneous one, in two simulation scenarios are used, in order to examine and observe the differences in the results for the SAR values.

1 Introduction

Bioelectromagnetics as an interdisciplinary science that investigates the interaction between the biological systems and the electromagnetic fields offers new and important opportunities for development of medical devices for diagnosis and therapeutic purposes. This science is very attractive and interesting nowadays, as electromagnetic devices, in particular mobile phones, play an increasing role in everyday life. During the development of the electromagnetic devices it is very important to understand the field distribution inside the human body, since direct measurement of the electromagnetic field inside the tissues and organs of the living organisms is almost impossible. As a result of the rapid development of computer science, measurements can be replaced by simulations on the human body models to predict the electromagnetic radiation effects and the macroscopic effects such as heating and specific absorption rate (SAR) distribution.

The upright position of all of the digital human models is a limiting factor in the electromagnetic research activities for realistic situations, and imposes the need for the generation of postured human models. Some deformed human models already exist (Allen et al. 2003, 2005; Findlay and Dimbylow et al., 2005, 2006; Dawson et al., 1999, 2002; Nagaoka and Watanabe, 2008), but the posing techniques are often very time consuming, and the positions of the models are limited. One approach for generation of a postured human model where continuity of the tissues and mass conservation are considered was proposed by Gao (2011), and was implemented within the software tool “BodyFlex”. The software is based on an improved version of the well known free form deformation technique (FFD) introduced by Sederberg and Perry (1986), combined with the marching cubes algorithm (MC) introduced by Lorensen and Cline (1987). The “BodyFlex” application deforms and postures the voxel-based human model named “HUGO” (Dipp GmbH, 2010) which is built from the Visual Human Project

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data (Ackerman, 1998). However, some parts of HUGO's body such as wrist and the fingers cannot be moved with the current version of the software application.

In this paper, we describe the enhancement of the "BodyFlex" application in order to allow a proper movement of the forearm and the wrist, which is necessary for evaluation of the electromagnetic effects from mobile phones. To this aim, non-axis aligned control lattices and a special treatment for the forearm and hand deformation were introduced, for coping with the non-standard position of these body parts, which are bent over the lower part of the abdomen in the original model. Additionally, we analyze and compare the SAR values obtained by electromagnetic simulations, in which the inhomogeneous HUGO model in original and deformed position and the homogeneous model SAM are exposed to the electromagnetic field produced by a mobile phone.

2 "BodyFlex" application overview and enhancement

2.1 "BodyFlex" application overview

The powerful and quick application "BodyFlex" developed by Gao (2011) can generate common postures that people use in normal life, by deforming the voxel-based human model named HUGO. The combination of the free form deformation technique (FFD) for 3-D solid geometric models deformation introduced by Sederberg and Perry (1986) and the marching cubes (MC) algorithm introduced by Lorensen and Cline (1987) allow the generation of different positions for the HUGO model, while ensuring continuity of the tissues and conservation of the mass to an acceptable level.

In order to generate a new position of the HUGO model, the "BodyFlex" application imports a voxel dataset file with a specific resolution which can be chosen by the user. After this step, the user can choose to see the model and its tissues by a rendering technique based on the MC algorithm. The movement of particular body part is defined on a simplified human model in which only the joints of the model and their positions are considered. In this step, control FFD lattices around all parts of the body are created with the improved version of the FFD technique. Next, after the definition of the movement for one or few body parts has been completed, the posturing of the model is performed. The last step is the export of the deformed model in a new voxel dataset file with the same model resolution as the original imported model. Finally, the mass conservation for both the individual tissues and the entire deformed model can be checked.

Within the first version of the "BodyFlex" application, deformations of almost all parts of the body are possible. Exceptions are the wrist and fingers movements which require a change in the current algorithm because of the position of the forearm and the hand of the HUGO model which are bent on the lower part of the abdomen. This enhancement of the "BodyFlex" application is described in the next section.

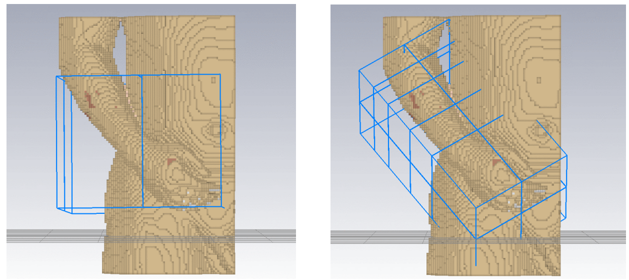

Fig. 1. Old version (on the left side) and new version (on the right side) of the FFD lattices for the forearm and the wrist.

2.2 Enhancement of the "BodyFlex" application

In order to allow an evaluation of the electromagnetic radiation from mobile phones, a movement of the forearm and wrist joint needs to be considered. The first version of the "BodyFlex" application does not deal with the wrist movements. As shown in Fig. 1 left, the FFD control lattices which embed the forearm and the wrist part do not treat these parts separately. Furthermore, the FFD control lattices are aligned to the global coordinate system axes, while the forearm has a tilted position in the original HUGO model.

In the new version of the "BodyFlex" application, as shown in Fig. 1 right, the FFD control lattices in which the forearm and the wrist are embedded for deformation have a rotated starting position. To determine a position of a control point or a voxel data point in the rotated lattice set in local coordinates, the cosine matrix was used. The direction cosine matrix is widely used in computer graphics for a transformation from one to another coordinate system and is defined by the following formula:

$$\mathbf{R} = \begin{bmatrix} \cos\theta_{x'x} & \cos\theta_{x'y} & \cos\theta_{x'z} \\ \cos\theta_{y'x} & \cos\theta_{y'y} & \cos\theta_{y'z} \\ \cos\theta_{z'x} & \cos\theta_{z'y} & \cos\theta_{z'z} \end{bmatrix}. \tag{1}$$

In Eq. (1), θ is the angle between the global coordinate system axis x, y or z and the axis x', y' or z' of the rotated coordinate system, respectively. To explain the determination of a point in the translated and rotated local coordinate system, we take the following example. We consider two coordinate systems, such that the first coordinate system is the Cartesian coordinate system and the second one is attached to the FFD control lattice set on the wrist. The second coordinate system has axes aligned to the FFD control lattices and center in point *O (a,b,c)*. We want to determine the local coordinates x_2, y_2, z_2 of a point M in the second coordinate system, with respect to its coordinates x_1, y_1, z_1 in the first coordinate system. The dimensions of the FFD lattice set is *len_x,len_y* and *len_z*. To this aim, we use the direction cosine matrix and the position of the point M in the second coordinate system can

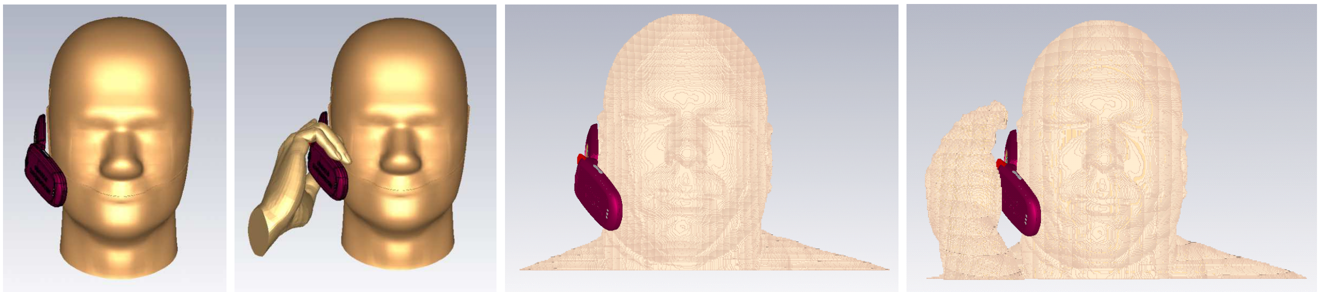

Fig. 2. SAM (on the left side) and HUGO (on the right side) models used for simulations.

be obtained by solving the Eq (2):

$$\begin{pmatrix} x_2 \\ y_2 \\ z_2 \end{pmatrix} = \begin{pmatrix} x_1 - a \\ y_1 - b \\ z_1 - c \end{pmatrix} * \mathbf{R} * \begin{pmatrix} len\_x^{-1} \\ len\_y^{-1} \\ len\_z^{-1} \end{pmatrix}. \quad (2)$$

After the voxels of the HUGO model are placed into the desired position by applying the trivariate tensor product Bernstein polynomial, the local coordinates of the voxels are transformed back to global coordinates by the following formula:

$$\begin{pmatrix} x_1 \\ y_1 \\ z_1 \end{pmatrix} = \begin{pmatrix} a \\ b \\ c \end{pmatrix} + \mathbf{R}^{-1} * \begin{pmatrix} x_2 * len\_x \\ y_2 * len\_y \\ z_2 * len\_z \end{pmatrix}. \quad (3)$$

Another problem which arises is the proper rotation of the wrist. Because the hand of the HUGO model is bent on the lower part of the abdomen, the rotation of the wrist cannot be performed around the axes aligned with the global coordinate system. Therefore, an algorithm for a rotation around arbitrary axes, which in this case are the axes of the local coordinate system, should be implemented. The calculation of a new position of a point described by Brouke (1992) makes series of transformations and rotations on the original position of the point, which are defined by the following formula:

$$\begin{pmatrix} x' \\ y' \\ z' \\ 1 \end{pmatrix} = \mathbf{T}^{-1}\mathbf{R}_x^{-1}\mathbf{R}_y^{-1}\mathbf{R}_z\mathbf{R}_y\mathbf{R}_x\mathbf{T} \begin{pmatrix} x \\ y \\ z \\ 1 \end{pmatrix}. \quad (4)$$

In Eq. 4), x, y, z and x', y', z' are the coordinates of the original and the new position of the point respectively. The translation of the point is performed by using the translation matrix $\mathbf{T}$ and its inverse $\mathbf{T}^{-1}$, while the rotations and the inverse rotations around the x, y and z axes are denoted by $\mathbf{R}_x, \mathbf{R}_y, \mathbf{R}_z$ and $\mathbf{R}_x^{-1}, \mathbf{R}_y^{-1}$ respectively.

3 Application: Analysis of the SAR distribution in simulations with mobile phones

3.1 Specific Absorption Rate (SAR)

Two international bodies ICNIRP (2009) and IEEE (2005) have developed guidelines in which the radiofrequency exposure limits for mobile phone users are expressed in terms of specific absorption rate (SAR). The SAR is defined as a measure of the rate at which energy is absorbed by the body which is exposed to a radio frequency electromagnetic field. Usually it is averaged either over the whole body or over a small sample volume (typically 1 g or 10 g of tissue) and can be expressed by the following formula:

$$\mathrm{SAR} = \frac{\iiint \frac{\sigma(r)|E(r)|^2 dV}{\rho(r)}}{V} \left[\frac{W}{kg}\right]. \quad (5)$$

In Eq. (5), σ represents the electrical conductivity and ρ is the mass density of the sample tissue. The electric field strength E magnitude is given in terms of the root mean square value.

For radiofrequency exposure to mobile phones, governments define the maximal allowed exposure in terms of energy absorbed in the head and the limbs. Namely, FCC in USA requires the phones on the market to have an SAR level of maximum 1.6 W kg^{-1} taken over a volume which contains 1 g of tissue, while CENELEC in Europe requires maximal SAR value of 2 W kg^{-1} averaged over 10 g of tissue. The SAR values mentioned previously refer to the maximal value which may appear in the head, while for the limbs, the maximal SAR value is 4 W kg^{-1}.

3.2 Simulation scenarios and setup

In order to analyse the SAR distribution in the human body resulting from an exposure to radiofrequency electromagnetic fields, simulations were performed with the commercial software CST MICROWAVE STUDIO (CST AG, 2012) on two models: a homogenous one (SAM) and the realistic HUGO model. Two scenarios with mobile phone placed in a talk position were considered. In the first scenario, the mobile

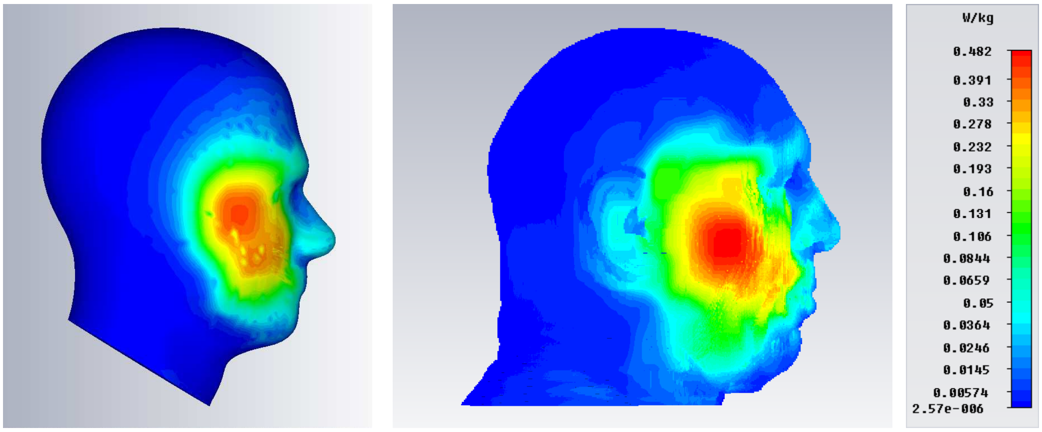

Fig. 3. SAR distribution in SAM (on the left side) and HUGO (on the right side) models on 1.8 GHz when no hand is present.

phone is not held by the hand (there is no hand in the simulation) and in the second scenario, the hand is placed behind the mobile phone as shown in Fig. 2. In the case of the SAM model, the mobile phone is held in the hand, while in the case of the HUGO model the hand is placed behind the mobile phone, since the finger movement is currently still under development.

The simulations were performed on a hexahedral mesh by using the transient solver. For the excitation, a discrete face port with an impedance of 50 Ohm was defined. The frequency range was between 0 and 2.5 GHz and field monitors for farfields, electric fields and power losses at 0.9 and 1.8 GHz were defined. At the frequency of 0.9 GHz the reference power was set to 0.125 W and at the frequency of 1.8 GHz the reference power was set to 0.25 W. As a post processing result, SAR values were obtained according to the IEEE C95.3 standard averaging method: at the frequency of 0.9 GHz the averaging mass was 10 g, while at the frequency of 1.8 GHz, the averaging mass was 1 g. The results for the SAR values for the SAM and the HUGO model, for the two scenarios, are presented in the next section.

3.3 Simulation results

As expected, a difference between the SAR values computed on the SAM and the HUGO model can be noticed.

Figure 3 shows the SAR distribution in the SAM and the HUGO models at 1.8 GHz, when no hand is present. It can be noticed that the maximal SAR value is higher in the realistic HUGO model than in the SAM model. However, this SAR value does not exceed the maximum allowed SAR value in the head prescribed by FCC and CENELEC. The realistic inhomogeneous human model allows an accurate analysis of the SAR distribution "hot spots" inside the model. As shown in Fig. 4, the parts of the head which absorb the most energy can be identified. The maximum SAR values occur within the skin and fat tissue near the chick, but also some increased SAR values occur in the muscles in the chick and in the mucous membrane in the nose.

In reality, a hand is always present near the head when talking on the phone. The plots of the SAR for this scenario are shown for both SAM and HUGO models in Fig. 5. The results show that in this case the SAR values in the HUGO's head are less than the ones in the SAM's head. Moreover, it is important to emphasize that when using a voxel human model, such as HUGO, the SAR distribution in the hand can be computed and compared to the maximal SAR values allowed in the limbs.

Figure 6 presents a comparison of the SAR values in the HUGO model at 1.8 GHz with and without hand. The maximal SAR value in HUGO's head decreases in case when the hand is present: in this case, a large part of the energy is absorbed by the hand.

4 Conclusions

In this paper we describe the recent advances of the posing program "BodyFlex", which allow the movement of the forearm and wrist of the inhomogeneous voxel human model HUGO. The existing algorithm based on the powerful free form deformation technique was enhanced to allow the definition and use of non-axis aligned control lattices, better fitted to the position of the forearm in the original voxel model. Besides that, an algorithm for the rotation of the wrist around arbitrary axes was implemented in order to enable the anatomically correct movement of this body part.

The presented application was the analysis of the SAR values obtained by electromagnetic simulations, where the inhomogeneous model HUGO in original and deformed positions and the homogeneous model SAM were exposed to the electromagnetic field produced by a mobile phone. As expected, a difference between the SAR values measured on the SAM and the HUGO model was noticed. The SAR values in the head of the realistic model, although larger than in

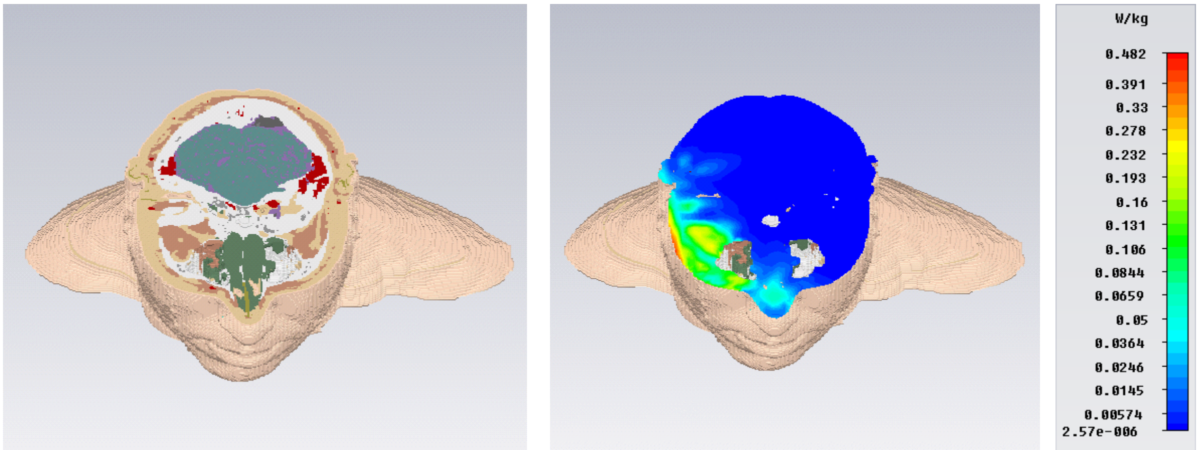

Fig. 4. Cut view of the HUGO model with SAR distribution observed on 1.8 GHz when no hand is present.

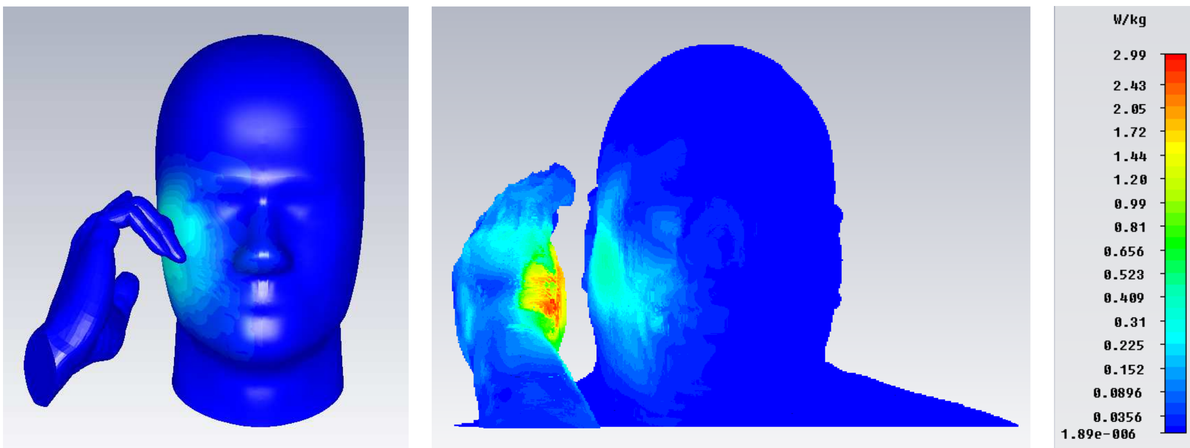

Fig. 5. SAR distribution in SAM (on the left side) and HUGO (on the right side) models on 1.8 GHz when hand is present.

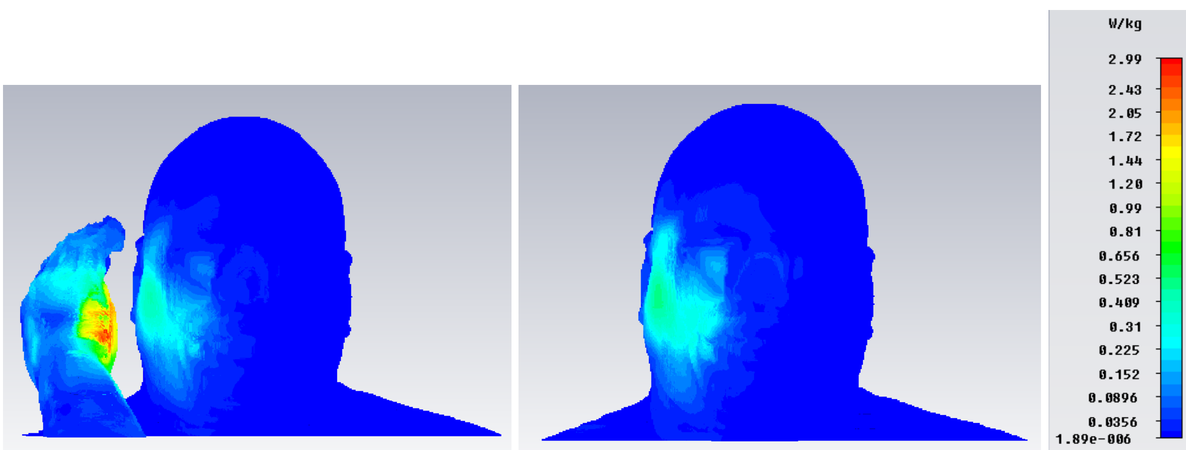

Fig. 6. SAR distribution in HUGO models on 1.8 GHz.

the homogeneous model, did not exceed the limits prescribed in the standards. Additionally, a comparison of the results between two scenarios (with and without hand) on the HUGO model showed that the presence of the hand in the model leads to a decrease of the maximal SAR value in the head. It can be concluded that the hand has a “protective role”, reducing the radio-frequency absorption in the head. Moreover, it is important to emphasize that when using a voxel human model, such as HUGO, the SAR values measured in the hand can be evaluated and compared to the maximal SAR values allowed in the limbs. The analysis of the maximal SAR values obtained by these simulations leads to the conclusion that the prescribed limits for the radiofrequency exposure to mobile phones do not underestimate the SAR values.

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