Computers in Biology and Medicine 101 (2018) 33–38

Contents lists available at ScienceDirect

Computers in Biology and Medicine

journal homepage: www.elsevier.com/locate/compbiomed

New method for establishing a 3D subject-specific numerical electromagnetic model using hybrid imaging modalities

Can Hu[a,1], Jie Feng[b,1], Sherman Xuegang Xin[c,*]

[a] Department of Radiation Oncology, Changhai Hospital Affiliated to the Second Military Medical University, Changhai Road 168, Yangpu District, Shanghai, 200433, China

[b] Medical Imaging Centre of Nanfang Hospital, Southern Medical University, Guangzhou city, Guangdong, China

[c] School of Medicine, South China University of Technology, Guangzhou city, Guangdong Province, 510005, China

ARTICLE INFO

Keywords:
Subject-specific numerical electromagnetic model
Hybrid modality
Dosimetry-related study
Bio-electromagnetics

ABSTRACT

Numerical electromagnetic models that can mimic the dielectric properties of human tissues have been widely used for dosimetry-related studies in bio-electromagnetics, particularly for the calculation of electromagnetic field distribution inside the human body, which is subject specific. Reports indicated that considerable electromagnetic field variations may occur inside different human subjects even when existing differences in the geometrical dimensions of these subjects are minimal. Therefore, a subject-specific three-dimensional (3D) electromagnetic model is crucially required to calculate the electromagnetic field distribution accurately. However, the manner in which a precise subject-specific 3D electromagnetic model is established has not been fully explored in the literature yet. In this study, a new method was proposed for the establishment of a subject-specific 3D electromagnetic model using hybrid imaging modalities, with computed tomography (CT) and magnetic resonance (MR) images as sources. The exemplary application was provided by using the established subject-specific model to calculate the local specific absorption rates in MR imaging. Comparison studies indicated that detailed information was obtained using the proposed model.

1. Introduction

Numerical electromagnetic models that can mimic the dielectric properties of the human body have been widely used for dosimetry-related studies and/or electromagnetic field–tissue interaction research in bio-electromagnetics [1]. Various three-dimensional (3D) electromagnetic models characterized by different model resolutions and numbers of segmented tissue types have been introduced in the literature [2–17]. For example, virtual families [2], which comprise four anatomical whole-body models (34-year-old male, 26-year-old female, 11-year-old female, and 6-year-old male), have been widely used in simulation studies [18–20]. Dimbylow introduced the NORMAN, which consists of approximately 9 million voxels with a resolution of 2 mm; the NORMAN models the adult human body with 37 tissue categories [3]. Such models have been widely used to calculate the electromagnetic field energy deposited inside the human body, such as the values of local specific absorption rate (SAR) [13,14,21–23]. Calculation accuracy is largely determined by the quality of the electromagnetic models [13,14,21–23].

The aforementioned models represent the human body for general and not for a specific human subject. However, when exposed to a definite electromagnetic source, the electromagnetic field distribution inside different subjects may vary severely, even when only slight differences of geographical dimensions exist among these subjects [24]. This phenomenon suggests that the electromagnetic field distribution inside the human body is subject specific. Thus, a precise subject-specific model is required when accurate electromagnetic field distribution inside the human body is needed. For example, in non-invasive tumor therapy that uses focused high-energy electromagnetic fields, accurate electromagnetic distribution inside the human body is required to decide the deposited energy.

Jin [24] first reported the establishment of a subject-specific electromagnetic model, where a library of magnetic resonance (MR) images and tissue volumes were used as foundation. Viable metrics were established to evaluate the models' similarity, which was used as guidance for the selection of matched model. Image registration techniques were used to adjust the corresponding property of the library of MR images and tissue volumes to obtain the determined subject-specific

* Corresponding author.
E-mail address: xinxg@scut.edu.cn (S.X. Xin).

[1] These authors contribute equally to this paper.

https://doi.org/10.1016/j.compbiomed.2018.07.015
Received 19 January 2018; Received in revised form 23 July 2018; Accepted 24 July 2018

voxel model. This method considerably improved the accuracy of the electromagnetic model. However, limitations, such as insufficient number of meshes and shapes of human tissues, still exist in the established library of MR images. A method for establishing a subject-specific electromagnetic model using X-ray computed tomography (CT) imaging data for the analysis of the radio frequency (RF) field deposited inside the human subject was reported in Ref. [25]. However, only X-ray CT image data were used to establish the subject-specific model, thereby resulting in coarse numerical model due to the poor resolution of soft tissues in the X-ray CT images.

In the present study, we proposed a new method for the establishment of a subject-specific numerical electromagnetic model using hybrid imaging data, that is, the data of CT and MR images obtained from the same human subject. The established subject-specific model fully utilizes the complementary merits of CT and MR imaging (MRI). A comparison study was implemented using the established subject-specific model against a previously reported model [25] to verify the efficacy of the proposed method. The results demonstrated that detailed information can be obtained further using our method.

2. Materials and methods

The tomographic imaging data obtained from X-ray CT and MR scanners were used as source data. Manual segmentation and volume rendering were implemented to build the 3D anatomical models separately from CT and MRI. The two-dimensional (2D) anatomical models were then meshed in triangle cells using the finite element method. The meshed models were merged, optimized, and assigned with density, conductivity, and dielectric constants to form the 3D electromagnetic model.

2.1. Data acquisition

The study protocol was approved by the ethics committee of Nan Fang Hospital, China. A 45-year-old female volunteer was recruited to follow the study protocol. The X-ray CT and MR images of the pelvic region were obtained from the volunteer. The X-ray source was 541 mm away from the volunteer and 949 mm away from the detector. The parameters for the CT scanning were as follows: collimation of 28.8 mm × 1.2 mm, gantry rotation period of 0.8 s, slice thickness of 5.0 mm, tube voltage of 120 kVp, and tube current of 212 mA. The parameters for MR scanning were as follows: TR = 3733.6 ms, TE = 80.0 ms (proton density weighted), flip angle of 90°, and slice thickness of 5.0 mm. The same slice thickness and geometrical scan regions were used in CT and MR scans for high-quality match and mergence. The pixels size for CT and MR images was 0.8 mm. The matching of the 2D CT and MR images were based on the same slice position (with the same Z value). Examples of the CT and MR images are shown in Fig. 1.

2.2. Reconstruction methodology for the subject-specific 3D electromagnetic model

The first step in reconstructing the 3D electromagnetic model was to segment each organ precisely in the CT and MR images. Segmentation was performed by two invited radiology experts. The contours of different tissues in all images were outlined manually. An intensity-based seeded region grower was used in the segmentation [26]. The results were corrected by drawing free-hand contours of the targeted parts in case of leakage or inaccurate boundaries. In the case of partial enclosure, a binary median filter was used to amend any inconsistencies among the neighboring slices [27]. All results were double-checked slice-by-slice by the two experts to ensure accurate segmentation. Then, the segmented CT and MR images were separately reconstructed into a 3D anatomical model using the graphic processing unit-based volume-rendering method [28]. The 3D anatomical models that were

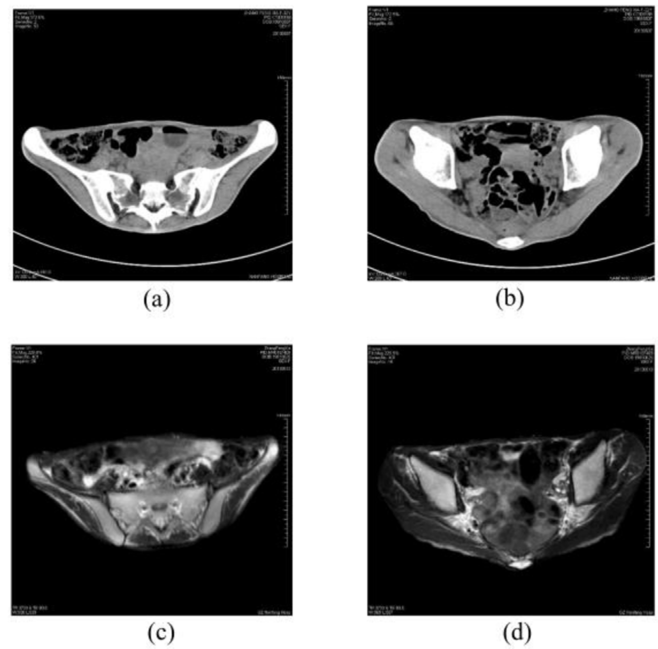

Fig. 1. Examples of slices from CT images [(a) 1st slice; (b) 14th slice] and MR images [(c), 1st slice; (d) 14th slice].

independently built from CT and MR images consisted of different tissues in the stereo lithography format. To meet the requirement of precise mergence, the obtained independent 3D anatomical models of CT and MR were matched using equal-scaling zooming-in and/or zooming-out method to the exact same spatial positions to ensure precise overlap. When merging the CT and MR images, image adjustments were implemented in terms of the position and size to achieve a matched fusion. In the present work, the $x_{i\,\max}$, $x_{i\,\min}$, $y_{i\,\max}$, and $y_{i\,\min}$ of every selected slices were initially determined, and the average of the data collected ($\overline{x_{i\,\max}}$, $\overline{x_{i\,\min}}$, $\overline{y_{i\,\max}}$, and $\overline{y_{i\,\min}}$) was then calculated. Subsequently, the difference of the maximum and minimum averages of the selected slices were calculated as follows: $x_i = \frac{\overline{x_{i\,\max}} - \overline{x_{i\,\min}}}{2}$ and $y_i = \frac{\overline{y_{i\,\max}} - \overline{y_{i\,\min}}}{2}$; and the difference was used as the center position of the selected slices. Thereafter, the factors of equal-scaling zooming-in and/or zooming-out method were calculated correspondingly. The sizes of the mesh and triangle cells were not constant; thus, they were automatically determined by the software that followed an optimized principle. Table 1 lists the details of the volume, number of triangles, surface area, and total number of points of different tissues.

CT and MR images are generally complementary in merits on the basis of their physical principles. For high-quality boundary information of the skin, bone, fat, and muscle, CT images are superior to MR images; however, for high-quality boundary information of the uterus, cervix, ovary, bladder, and body fluid, MR images are superior to CT

Table 1
Mesh parameters for the different tissues in the female pelvic model (model$_{HM}$).

Tissue	Volume (mm^3)	Triangles	Surface (mm^2)	Points
Skin	440500.43	139670	241096.83	69847
Fat	136517.16	103718	121034.05	51815
Bone	641348.26	114384	139288.93	57106
Bladder	24257.18	7866	9665.38	3933
Body fluid	12834.73	3830	4521.35	1917
Muscle	3257839.26	286754	378481.17	143333
Uterus	45162.12	7422	9245.68	3711
Cervix	4154.83	2030	2274.45	1017
Ovary	17920.88	3078	5574.32	1547