Published in final edited form as:

Med Biol Eng Comput. 2008 December ; 46(12): 1239–1251. doi:10.1007/s11517-008-0414-z.

MRI-based anatomical model of the human head for specific absorption rate mapping

Nikos Makris^{1,2,3}, Leonardo Angelone^{2,4}, Seann Tulloch¹, Scott Sorg¹, Jonathan Kaiser¹, David Kennedy^{1,2}, and Giorgio Bonmassar²

¹ Departments of Psychiatry, Neurology and Radiology Services, Center for Morphometric Analysis, HST Athinoula A. Martinos Center, Harvard Medical School, Massachusetts General Hospital, Boston, MA 02129, USA

² HST Athinoula A. Martinos Center for Biomedical Imaging, Massachusetts General Hospital, 149 13th Street, Charlestown, MA 02129, USA, e-mail: giorgio@nmr.mgh.harvard.edu

³ Department of Anatomy and Neurobiology, Boston University School of Medicine, Boston, MA 02118, USA

⁴ Biomedical Engineering Department, Tufts University, Medford, MA 02155, USA

Abstract

In this study, we present a magnetic resonance imaging (MRI)-based, high-resolution, numerical model of the head of a healthy human subject. In order to formulate the model, we performed quantitative volumetric segmentation on the human head, using T1-weighted MRI. The high spatial resolution used ($1 \times 1 \times 1 \text{ mm}^3$), allowed for the precise computation and visualization of a higher number of anatomical structures than provided by previous models. Furthermore, the high spatial resolution allowed us to study individual thin anatomical structures of clinical relevance not visible by the standard model currently adopted in computational bioelectromagnetics. When we computed the electromagnetic field and specific absorption rate (SAR) at 7 Tesla MRI using this high-resolution model, we were able to obtain a detailed visualization of such fine anatomical structures as the epidermis/dermis, bone structures, bone-marrow, white matter and nasal and eye structures.

Keywords

Head; Morphometry; Segmentation; Volumetry; Specific absorption rate; Bioelectromagnetic computation

1 Introduction

The human head is comprised of a great number of different types of biological tissue which combine to form the individual structures of the face and the cranium, including the brain. Materials such as the vitreous humor within the eye-ball, as well as the air within the mastoid cells and other cavities such as the orbital sinus, must also be taken into account when attempting a precise representation of the head's structure. The spatial distribution and topographic relationships of the head structures and tissues make the head a non-homogeneous structure with a complex overall topology. Anatomical details provide important structural and spatial information integral to answering physical and geometrical-topological questions

Correspondence to: Giorgio Bonmassar.

N. Makris and L. Angelone contributed equally to this work.

having to do with the formulation of a head model. Human head models are commonly used for radio-frequency (RF) dosimetry in various areas of bioelectromagnetic safety research, including mobile phones [1], and MRI [2–4]. Currently, head models used in bioelectromagnetic computation have been designed primarily from an engineering perspective [1] and have lacked detailed information of histology, anatomical variability, and diverse topographical organization of the various head tissues. A precise anatomical modeling of the head allows for more accurate visualization of the RF power (i.e., RF energy per unit time) deposition in thin and clinically relevant structures inside the human head. The number of these structures is relevant given that the electro-magnetic (EM) field depends on the electrical properties of the head structures [5,6], especially in conditions requiring modeling of full-wave Maxwell equations [7] where the wavelength of the RF-field becomes comparable with the dimensions of the human head. Given the geometrical complexity of the human head, in computational electromagnetic the estimation of the local distribution of the EM field generated by an external RF source as well as the specific absorption rate (SAR) is a great challenge [8,9]. SAR is the value used in MRI safety guidelines by the Food and Drug Administration [10,11].

A comprehensive quantitative morphometric analysis of a healthy adult human head (i.e., including brain and non-brain structures) was carried out using a T1-weighted MRI. From this anatomical analysis, 21 brain structural entities were distinguished, as well as 28 non-brain structural entities; volume measurements were computed for each. With the help of this analysis, a novel high-resolution head model was constructed, using the finite difference time domain (FDTD) algorithm [12,13] to estimate the EM field and the SAR distribution in a human head at 7 T MRI. We believe that use of the model obtained with this method of morphometric analysis will improve the sensitivity of the computation and mapping of SAR and can also be used as an atlas for automated head segmentation [14].

2 Materials and methods

Subjects

Our volunteer for this study was one healthy, 37-year-old, right-handed Caucasian male, weighing 75 kg and measuring 175 cm in height. Informed consent was obtained in accordance with Massachusetts General Hospital policies.

2.1 MRI protocol

High-resolution anatomical MRI data were acquired. The MRI was performed with a quadrature birdcage transmit/receive head coil on a 1.5 T scanner (General Electric, Milwaukee, WI). A whole-head acquisition was collected using a T1-weighted 3D-SPGR sequence (TR/TE = 24/8 ms) for 124 slices, each 1.3 mm thick (matrix size 256×192 , FOV 256 mm).

Imaging data processing—The volume data were resampled using trilinear interpolation to isotropic voxels with dimensions of $1 \times 1 \times 1 \text{ mm}^3$. The overall head dimensions were 170 mm in width, 217 mm in depth, and 238 mm in height. Segmentation was then applied on this dataset volume in the native space for both brain and non-brain structures (see below).

Overview of the regional anatomy of the head—The general shape of the head is that of an ellipsoid or an ovoid, and its average height is 18–20 cm. This measurement is usually relatively constant as 13% of a person's total body height, although it does vary somewhat with ethnicity, sex, and age. The head is comprised of two subdivisions, the cranium and the face [15]. The cranium contains the brain and its covers (the meninges), and the face hosts the

proximal parts of the respiratory and digestive conduits. Both the cranium and the face contain sensory organs for vision, hearing, olfaction, gustation, and somatic sensation.

2.1.1 Morphometric head segmentation—We divided the process for morphometric head segmentation into ‘brain’ and ‘non-brain’ procedures.

Brain segmentation: Images were positioned within the original three-dimensional coordinate system of the scanner. Gray matter/white matter segmentation overlays were constructed for the full series of coronally reconstructed images [16]. The neuroanatomical subdivisions delineated by this semi-automated general segmentation procedure corresponded generally, but not exclusively, to the natural gray matter boundaries distinguished by differential signal intensities in T1 weighted images [16]. The definition of the 21 brain structural entities and the procedures used for their segmentation are reported in Filipek et al. [16]. Specifically, the following structures were labeled within the grey matter: amygdala, amygdala anterior, accumbens area, brain stem, cerebral cortex, caudate, hippocampus, pallidum, putamen, thalamus proper, ventral diencephalon (DC). Cerebral White matter and optic chiasm were segmented in the white matter. Finally, the following structures filled with cerebro-spinal fluid were segmented and labeled: cavum vergi, lateral ventricle, inferior lateral ventricle, third ventricle, fourth ventricle, cerebro spinal fluid.

Non-brain segmentation: Progressing in the rostrocaudal dimension, the different structures of the face and the cranium were segmented in the 256 consecutive coronal sections. Twenty-eight different structural entities were segmented as listed in Table 1 and shown in Fig. 1. The following paragraphs describe the anatomical–histological definitions used to segment the principal anatomical structural entities (ASEs).

The “**cerebrospinal fluid/subarachnoid**”, or “**CSF/SA**” ASE, refers to the space between the dura and the pia mater. This space is filled with cerebrospinal fluid, which is a clear, very low-protein liquid similar to blood plasma but with a different electrolyte concentration. The “**epidermis/dermis**” ASE is histologically a tissue covering the head surface composed primarily of a keratinized squamous epithelium. The “**ear**” ASE is composed mainly of cartilage. It also contains small amounts of fat, connective tissue, muscle, and skin (epidermis, dermis, subcutaneous tissue, blood vessels, nerve fibers, and lymphatics). The “**nasal structures**” ASE is mainly cartilage, and also contains small amounts of fat, connective tissue, muscle, and skin (epidermis, dermis, subcutaneous tissue, blood vessels, nerve fibers, and lymphatics). The “**soft tissue**” ASE includes structures that are too small and complicated to segment in this type of imaging resolution. The “**subcutaneous tissue**” ASE is a loose connective tissue in which bundles of collagen fibers are mostly oriented parallel to the skin surface. The “**connective tissue**” ASE is composed of cells and fibers of fibroblasts and fibers such as collagen or elastin, which are embedded in a gel-type extracellular matrix. This connective tissue has structural-mechanical properties such as keeping different tissues together; it also has defensive properties such as wound repair.

Eye region: The “**cornea**” ASE is the anterior transparent part of the eye, which refracts most of the light entering the eye and is made-up of epithelial tissue, three layers of collagen fibrils, and an internal layer of endothelium. The “**lens/iris**” ASE contains the lens and the iris, two structures that divide the eyeball into an anterior and a posterior chamber. The lens is composed of elongated, prismatic cells, called lens fibers. These cells are highly organized and contain granular material as well as large quantities of longitudinal microtubule and actin filaments, which give the lens its refractile and elastic properties. The iris is composed mainly of muscular tissue, allowing for dilation and restriction of the pupillae; it also has small quantities of other tissues such as connective and nervous tissue. The “**aqueous humor**” ASE is composed of fluid contained in the anterior chamber of the eye. The fluid consists principally of water as

well as a small quantity of glucose, amino acids and respiratory gases. The “**vitreous humor**” ASE is composed of a liquid that fills the posterior chamber of the eye. This liquid is composed mainly of water within which is a sparse, organized cellular and fibrous content made-up mostly of long glycosaminoglycan chains of sodium-hyaluronate. The “**retina/choroid/sclera**” or “**R/C/S**” ASE comprises the retina, choroid, and sclera. The retina is the neural sensory layer of the eyeball and is in contact with the vitreous humor. The choroid is located between the retina and the sclera and is a highly vascular tissue. The sclera is a hard dense layer surrounding the choroid.

Bone: The “**bone**” ASE is a dynamically changing connective tissue, mineralized and richly vascularized. It is composed mainly of cells (the osteocytes, osteoblasts and osteoclasts as well as osteoprogenitor cells), which are embedded within an intercellular matrix, or ground substance, containing crystals of hydroxyapatite. In the flat bones of the skull, the bone is made up of two layers of compact bone tissue, the outer table (“**outer table**” ASE) and the inner table (“**inner table**” ASE), between which is situated a layer of spongy tissue called the diploe (“**diploe**” ASE). The diploe corresponds to the medullary cavity of a long bone [17,18]. The “**dura**” ASE refers to the cranial dura mater, which is the most external of the meninges. It is a thick, strong, non-elastic sheet that contains and mechanically protects the brain. The “**teeth**” ASE includes the structure of the teeth, which is composed of a crown, made of dentine (ivory) covered by translucent enamel, and of a root covered by bone like cement. The dentine contains a central pulp cavity which enlarges in the root to become a pulp chamber and narrows in the proximal part of the root and apex where it is called pulp canal. The pulp consists mainly of blood vessels, nerves, and connective tissue.

The “**air**” ASE refers to the air content of the upper respiratory and digestive systems such as the pharyngeal and oral cavities and the trachea, as well as to the air content of the orbital sinus. The “**mastoid air cells**” ASE refers to the air content within the mastoid process of the temporal bone. The “**adipose**”, or fat ASE is associated with body heat preservation and production and is composed of adipose cells. It can be distributed in defined areas of the body as adipose tissue. The “**orbital fat**” ASE is located in the caudal part of the orbit, behind the eye. The “**muscle**” ASE is composed of assemblies of muscle cells which contract by converting chemical energy into mechanical work, allowing the body and its individual parts to move. The “**tongue**” ASE is composed almost entirely of muscle fibers although it contains other connective and epithelial tissues as well. The “**nerve**” ASE refers to cranial nerves and is composed principally of axonal fibers and their surrounding myelin sheets. The “**spinal cord**” ASE corresponds to a part of the central nervous system, i.e., the spinal cord, which is contained within the spinal canal of the vertebral column. The “**blood**” ASE is composed of the vessels (arteries and veins) as well as the circulating blood or haemolymphoid tissue.

2.2 Classification of ASEs at radio-frequency by their electrical properties

The classification of ASEs in terms of their electrical properties is necessary in order to precisely compute the EM field and SAR in the human head during an MRI experiment. The electrical properties of ASEs, such as conductivity and permittivity, vary depending on the structural composition of each ASE. For this study, we classified the ASEs using the radiofrequency of 300 MHz, a frequency which is used to elicit the signal at 7 Tesla MRI. Specifically, the electrical properties of the human head structures were considered as: (a) linear with an electric field, (b) isotropic, (c) dispersive (i.e., variable with frequency), and (d) heterogeneous in space. In these conditions, the complex permittivity ε^* is defined as [19]:

$$\varepsilon^*(\omega) = \varepsilon'(\omega) - j\varepsilon''(\omega) = \varepsilon_r(\omega) - j \frac{\sigma_{\text{tot}}(\omega)}{\omega \varepsilon_0} \quad (1)$$

where ε_r is the relative permittivity and $\varepsilon''(\omega) = \frac{\sigma_{\text{tot}}(\omega)}{\omega \varepsilon_0}$ is the frequency dependent loss factor (a-dimensional), with $\omega = 2\pi f$ (s^{-1}) the angular frequency, $\varepsilon_0 = 8.85 \times 10^{-12}$ (Farad m^{-1}) the permittivity of empty space and $\sigma_{\text{tot}}(\omega)$ (Siemens m^{-1}) the total conductivity including a frequency independent ionic conductivity and the frequency dependent losses due to dielectric polarization [6].

The anatomical classification for each structural entity, as well as their density [20–23] and electrical properties at 300 MHz, are shown in Table 1 and mapped in Fig. 2. Electrical properties were assigned to each ASE based on its histological definition and on a comprehensive published database of the electrical properties of biological tissues [6,20,24].

Specifically, the 21 brain structures were paired with the corresponding electrical properties of grey matter, white matter, cerebellum, and cerebrospinal fluid [6] (Table 1). For the non-brain ASEs there was an overall direct correspondence between the anatomical definition and the corresponding dielectric values found in Gabriel et al. [6]. With regard to the structures without a direct equivalence, the ASE “SC-Fat/Muscle” was assigned electrical properties obtained averaging those of fat and muscle. Furthermore, the ASEs “Subcutaneous Tissue,” “Connective Tissue,” and “Soft tissue” were associated with weighted average values of the electrical properties of muscle, cartilage and fat (see “limitations” in discussion).

Finite-difference-time-domain (FDTD) model of the head—The numerical head model was used for simulations based on the FDTD algorithm [12,13] with 30,000 timesteps. The total number of Yee cells [25] for the anatomical segmentation was 4,648,070, and the total volume, including the free space around the model, was $323 \times 373 \times 323 \text{ mm}^3$. A total of seven layers of perfectly matching layer boundary conditions [26] were introduced in the geometry which included a detailed model of a volume RF coil [4,27]. This coil was modeled with 16 perfect electrically conductive rods of 295 mm in length and arranged around the head in circular symmetry (diameter 260 mm). A circular excitation was modeled placing on the center of each rod 300 MHz sinusoidal current generators of 1A peak-to-peak amplitude, 50 Ω load, and a 22.5° phase shift between any two adjacent generators. A Dual core Xeon processor 5110 1.60 GHz, 4 MB l2 cache, 1,066 MHz 4 Gb RAM was used for the simulations.

3 Results

Segmentation

Manual segmentation showed 21 distinct brain and 28 distinct non-brain structural entities in the human head (Fig. 3). The volumetric results for each of these anatomical structural entities are shown in Table 2. High spatial resolution of the imaging data made it easier to segment thin ASEs such as the epidermis/dermis, the outer and inner table, the dura, and the diploe.

Visualization

Fine-grained head model segmentation allowed for 3-D reconstruction and precise visualization of the different ASEs (Fig. 4). Moreover, the intrinsic numerical structure and the spatial detail given by these processes allow for precise and easily manageable anatomical 3D rendering.

A very bright region in the center of the field of view of the human head has been observed at 7 Tesla MRI, using volume coils: the central brightening effect (CBE) [28]. The CBE observed in the present study using FDTD simulations with the proposed model at 7 T, is shown in Fig. 5.

The precise 3D-rendering we were able to obtain makes this model an ideal tool for anatomical visualization (Fig. 6). Such accurate 3D-rendering could be very useful as an educational tool for training surgeons and anatomy students.

4 Discussion

In this study, we used T1-weighted MRI to obtain the semi-automated segmentation and volumetry of one healthy, adult, human head. Using this anatomical analysis, we were able to distinguish 21 brain structural entities as well as 28 non-brain structural entities in the human head; we were able to provide volume measurements for each structural entity distinguished. This level of analysis provides increased anatomical resolution relative to previous models and is able to generate complex anatomical surfaces, which allow for SAR visualization (Fig. 3). Thus, semi-automated fine-grained MRI-based volumetric segmentation used herein provided a versatile and flexible tool to perform volumetric analysis and 3D SAR mapping.

Volumetric anatomical segmentation

Several autopsy studies on humans have included measurements of the size of head compartments [29–35]. With the advent of MRI, morphometric studies have provided a wealth of information on brain and head structure volumetry (see e.g., [16,36–39]), but available information regarding non-brain head structure volumetry is currently limited. Among the few studies reporting results on segmentation and volumetry for non-brain head structures is the “Visible Human” study. In this investigation, one postmortem human body was cryo-sectioned and the sections were photographed. Segmentation was then performed on the individual sections and 3D reconstructions and volumetric data were derived for the different parts of the human body including the head [40]. Another widely used head model is the digital brain phantom [41,42]. In this model, the human head was segmented semi-automatically using T1-weighted MRI. This segmentation facilitated the identification and volumetric analysis of five non-brain (head) structural entities. Recently, Kruggel et al. [39] reported normative results on global head volumes using a reference population of healthy subjects. Our findings are in agreement with Kruggel’s measurements regarding the total head and the principal brain structures.

Comparison of our model with other sources of human head data

Two different types of comparison were conducted. First, we compared our segmentation results with the results of a postmortem human head by direct inspection [43]. The latter head atlas was interpolated to match the scale of the CMA head. This comparison provided the following correspondence between the CMA versus the Head Atlas: 84% mean overlap between the 26 non-brain SE; 95% and higher overlap between half of SEs. Second, we compared the volumetric results of our model with an anatomical digital brain phantom model by Montreal Neurological Institute (MNI) [42]. The volumes of the structural entities studied in our model and those studied using the MNI model showed an average volume concordance of 99% for the entire head; the overall weighted average of percentage difference across all the ASEs was 8.94%, ranging from 1 to 20%. Given that there was some mismatching in the definition of ASEs and the fact that the two head datasets were segmented using different segmentation procedures, these differences were to be expected.

Computational models

Several numerical models based on volumetric segmentation for EM field estimation have been presented in literature. In these studies, each structure instead was considered as an entity combining both anatomical and electrical properties using the condensed term of “tissue”. For instance, the study led by the FDA presented fourteen different numerical head models [1] including the one based on the Visible Human Project. The Visible Human model has an

interpolated spatial resolution of 1 mm^3 isotropic with 24 tissues segmented for the head [44]. Every other model, based on MRI and computerized tomography (CT) images, had either lower resolution (2 mm^3) or a lower number of tissues. A recent study showed that a resolution of $2 \times 2 \times 2.5\text{ mm}^3$ is quite accurate when evaluating whole-head SAR in MRI [45]. On the other hand, in cases such as parallel transmission at ultra high-field MRI or MRI recording in human subjects with conductive leads, the interactions between the RF field and the load (i.e., human head) are expected to generate local peaks of electric field, hence SAR [46]. In these cases, the use of the whole-head SAR as the exclusive dosimetric parameter for safety profile may be potentially inaccurate [9,47] and the estimation of local SAR, e.g., 10 g averaged [11], could be more appropriate.

In this study we used instead the term “anatomical structural entity” to define a structure in terms of its anatomical and histological properties. This analytical process allowed the achievement of a detailed anatomical definition of the head and a precise modeling of its electrical heterogeneity. Overall, compared to other existing models, our model provides both the highest spatial resolution, i.e., 1 mm^3 isotropic, and the highest number of anatomical structures ASEs, i.e., 49 (21 brain and 28 non-brain).

Novelty and significance

The present study was different from previous *in vivo* investigations mainly in two ways: (a) in the detail of anatomical description and fine-grained subdivision of the human head, and (b) in the spatial resolution of the head model. The previous works of Kruggel and MNI provided the volumetric segmentation of only a few tissues (head and brain for Kruggel, ten tissues for the MNI). The Visible Human Project has the same numerical resolution (1 mm^3 isotropic) of the present model, however the data used for this model were derived from post-mortem data. The high spatial resolution (1 mm^3) and large number of anatomical structures segmented in our model allow for an improved detailing of the geometrical precision and spatial distribution of discrete tissue and electrical classes. More specifically, the increased number of structures examined allowed for ease in the geometrical characterization of further anatomical details such as nasal cavities or the ventricular system. The high spatial resolution also allowed us to distinguish contiguous but anatomically and electrically [6] distinct structures such as the outer table, the diploe, and the inner table. The ability to distinguish these types of structures may directly affect the estimation of EM field [48].

Other potential applications

The computational model derived from the anatomical segmentation can be used for EM field and SAR estimation, both of which are useful for MRI–RF coil design as well as for general studies of RF-absorption during MRI. Moreover, the model can be used to estimate B_0 susceptibility because it allows for identification of the spatial configuration of regions of high magnetic susceptibility differences, such as at the various air-bone-soft tissue interfaces. Algorithms have been designed to compensate for MRI artifacts, which distort the signal in certain brain regions [49,50].

Limitations

This study was based on one healthy subject, whereas other volumetric analyses such as in Kruggel [39], used large datasets. The purpose of the present study, however, was to develop a method for obtaining a fine-grained anatomical analysis of the human head. Future studies should address the question of creating databases in healthy and diseased conditions. Also, our model does not include the shoulders, and this may negatively affect the estimation of the EM field for the volume of the full-head coil [51]. The labeling of the segmentation results is voxel-based, therefore its transformation to the surface domain requires additional processing steps that need to be considered in terms of topology, surface continuity, and smoothness.

A highly precise anatomical segmentation may not necessarily correspond to improved accuracy in electrical modeling or in estimating RF-heating. In this study, the anatomical segmentation did not always correspond to the definitions for electrical properties provided by the literature [6], and some anatomical structures were assigned averaged electrical properties. For example, subcutaneous tissues, connective tissues, and soft-tissues were assigned properties equivalent to a weighted average of muscle, fat, and cartilage which are the main components of these structures.

The accuracy in dosimetric analysis obtained with the head model may be affected by the limited degree of precision for which electrical properties are provided [53,57–59]. The total absorbed RF power (i.e., RF energy per unit time) was strongly affected by few structures with high volume and conductivity, such as muscle, grey and white matter (Fig. 7) whereas other structures with low conductivity had a relatively low power absorbed. Further simulations were conducted by separately increasing by 20% the electrical conductivity of the five SEs with highest volume (Table 2), namely muscle, grey matter, white matter, epidermis/dermis and subcutaneous fat/muscle. The estimated SAR was then compared to the SAR estimated using the values of electrical properties shown in Table 1. Results, presented in Table 3, showed that the maximum difference for SAR estimated in each 1 mm³ voxel using the head model with modified conductivity with respect to the reference one was 33%. There was no significant difference in the estimate of the peak 10 g averaged SAR (i.e., maximum change of 4.4%), as well as peak unaveraged 1 mm³ and 1 g averaged SAR.

Moreover, the values found in literature were often derived from in vitro or post-mortem measurements in animals [20,52]; electrical properties in vivo for human subjects may be different and may vary with factors such as temperature or age [52–55]. The anatomical segmentation obtained for this model can be seen as a first step for a more complex biophysical characterization of the human head. Direct measurements of the electrical properties in vivo using an electrical impedance approach offer an interesting and novel perspective to provide anatomically specific electrical properties [56].

5 Conclusions

This study combines a semi-automated comprehensive fine-grained MRI-based anatomical volumetric segmentation with EM field estimation. We carried out a quantitative morphometric analysis on a healthy adult human head using a fine-grained anatomical method on a high resolution MRI dataset. The resulting novel high-resolution head model has been evaluated for EM field computation, providing accurate estimation of the central brightening effect at 7 T. The high degree of precision in this model may allow improvement in the sensitivity of computation and in the accuracy of SAR visualization in 3D of thin anatomical structures with clinical significance. This model also has potential applications in the visualization of thermal distribution in hyperthermia and ablation therapy [60], surgery simulation [61], computational modeling used for pharmacokinetic/pharmacodynamic studies in cancer research [62], as well as in more general geometrical, biophysical, and physiological modeling of the human head [63,64].

Acknowledgments

Preparation of this article was supported in part by grants from: The National Association for Research in Schizophrenia and Depression (NARSAD) and the National Institutes of Health National Center for Complementary and Alternative Medicine NCAM (NM); the Fairway Trust and NIH grants NS34189 & EB005149 (DK); R01 EB002459 and P41 RR014075 (GB), and the MIND institute. The authors would like to thank the many people that kindly contributed to this project with discussions and useful insights, including Franz Schmitt, Franz Hebrank and Andreas Potthast (Siemens Medical Systems), CK Chou and Goga Bit Babik (Motorola Corporate EME), Chris Collins (Penn State), David Kaplan, Sergio Fantini, Peter Wong, and Mark Cronin-Golomb (Tufts University). We would like also to thank the colleagues at the A. Martinos Center, including Martijn Cloos, Graham Wiggins, Mary Foley, and Larry Wald for

their help with the MRI images, and Mr. George Papadimitriou and Mr. James Howard and for their contributions to this study.

References

1. Kainz W, et al. Dosimetric comparison of the specific anthropomorphic mannequin (SAM) to 14 anatomical head models using a novel definition for the mobile phone positioning. *PhysMed Biol* 2005;50(14):3423–3445.10.1088/0031-9155/50/14/016
2. Gandhi OP, Chen XB. Specific absorption rates and induced current densities for an anatomy-based model of the human for exposure to time-varying magnetic fields of MRI. *Magn Reson Med* 1999;41(4):816–823.10.1002/(SICI)1522-2594(199904)41:4<816::AID-MRM22>3.0.CO;2-5 [PubMed: 10332859]
3. Ibrahim TS, et al. Electromagnetic perspective on the operation of RF coils at 1.5–11.7 Tesla. *Magn Reson Med* 2005;54(3):683–690.10.1002/mrm.20596 [PubMed: 16088934]
4. Collins CM, Smith MB. Calculations of B(1) distribution, SNR, and SAR for a surface coil adjacent to an anatomically-accurate human body model. *Magn Reson Med* 2001;45(4):692–699.10.1002/mrm.1092 [PubMed: 11283998]
5. Christ A, et al. Characterization of the electromagnetic near-field absorption in layered biological tissue in the frequency range from 30 MHz to 6, 000 MHz. *Phys Med Biol* 2006;51(19):4951–4965.10.1088/0031-9155/51/19/014 [PubMed: 16985280]
6. Gabriel C, Gabriel S, Corthout E. The dielectric properties of biological tissues: II. Measurements in the frequency range 10 Hz to 20 GHz. *Phys Med Biol* 1996;41:2251–2269.10.1088/0031-9155/41/11/002 [PubMed: 8938025]
7. Ibrahim TS, et al. In-depth study of the electromagnetics of ultrahigh-field MRI. *NMR Biomed* 2007;20(1):58–68.10.1002/nbm.1094 [PubMed: 17006885]
8. Chou CK, et al. Radio frequency electromagnetic exposure: tutorial review on experimental dosimetry. *Bioelectromagnetics* 1996;17(3):195–208.10.1002/(SICI)1521-186X(1996)17:3<195::AID-BEM5>3.0.CO;2-Z [PubMed: 8809359]
9. Nitz WR, et al. Specific absorption rate as a poor indicator of magnetic resonance-related implant heating. *Invest Radiol* 2005;40(12):773–776.10.1097/01.rli.0000185898.59140.91 [PubMed: 16304480]
10. FDA. Criteria for significant risk investigations of magnetic resonance diagnostic devices. Center for Devices and Radiological Health; 2003.
11. IEC. International Standard, medical equipment, part 2–33: particular requirements for the safety of the magnetic resonance equipment for medical diagnosis, 2nd revision. International Electrotechnical Commission 601-2-33; Geneva. 2002. p. 29-31.
12. Kunz, KS.; Luebbers, RJ. The finite difference time domain method for electromagnetics. CRC Press; Boca Raton: 1993. p. 448
13. Taflove, A.; Hagness, SC. Computational electrodynamics: the finite-difference time-domain method. Artech House; Boston: 2000.
14. Fischl B, et al. Whole brain segmentation: automated labeling of neuroanatomical structures in the human brain. *Neuron* 2002;33(3):341–355.10.1016/S0896-6273(02)00569-X [PubMed: 11832223]
15. Testut, L.; Jacob, O. UTET. Turin; Italy: 1974. Trattato di Anatomia Topografica con applicazioni medico-chirurgiche.
16. Filipek PA, et al. The young adult human brain: an MRI-based morphometric analysis. *Cereb Cortex* 1994;4(4):344–360.10.1093/cercor/4.4.344 [PubMed: 7950308]
17. Fawcett, D.; Jensch, R. Bloom and Fawcett's concise histology. 2. H. Arnold; London: 2002.
18. Gray, H.; Williams, PL.; Bannister, LH. Gray's anatomy: the anatomical basis of medicine and surgery. 38. Churchill Livingstone; New York: 1995. p. 20922092
19. v Vorst, AA.; Rosen Kotsuka, Y. Wiley series in microwave and optical engineering. Vol. xiii. Wiley; Hoboken: 2006. RF/microwave interaction with biological tissues; p. 330
20. Gabriel, C.; Gabriel, S.; Corthout, E. The dielectric properties of biological tissues: I. Literature survey; *Phys Med Biol*. 1996. p. 2231-2249.FCC, <http://www.fcc.gov/fcc-bin/dielec.sh>

21. Collins CM, Liu W, Wang J, Gruetter R, Vaughan JT, Ugurbil K, Smith MB. Temperature and SAR calculations for a human head within volume and surface coils at 64 and 300 MHz. *J Magn Reson Imaging* 2004;19:650–656. [PubMed: 15112317]
22. DeMarco SC, Lazzi G, Liu W, Weiland JD, Humayun MS. Computed SAR and thermal elevation in a 0.25 mm 2-D model of the human eye and head in response to an implanted retinal stimulator—part I: models and methods. *Antennas and propagation. IEEE Trans* 2003;51:2274–2285.
23. Li QX, Gandhi OP. Thermal implications of the new relaxed IEEE RF safety standard for head exposures to cellular telephones at 835 and 1,900 MHz. *IEEE Trans Microw Theory Tech* 2006;54:3146–3154.
24. Gabriel C, Gabriel S, Corthout E. The dielectric properties of biological tissues: I. Literature survey. *Phys Med Biol* 1996;41:2231–2249.10.1088/0031-9155/41/11/001 [PubMed: 8938024]
25. Yee KS. Numerical solution of initial boundary value problems involving Maxwell's equations in isotropic media. *IEEE Trans Antenn Propag* 1966;14(3):302–307.10.1109/TAP.1966.1138693
26. Berenger JP. A perfectly matched layer for the absorption of electromagnetic waves. *Comput Phys* 1994;114:185–200.10.1006/jcph.1994.1159
27. Jin, J-M. Biomedical engineering series. Vol. xiv. CRC Press; Boca Raton: 1999. Electromagnetic analysis and design in magnetic resonance imaging; p. 282
28. Collins CM, et al. Central brightening due to constructive interference with, without, and despite dielectric resonance. *J Magn Reson Imaging* 2005;21(2):192–196.10.1002/jmri.20245 [PubMed: 15666397]
29. Blinkov, SM.; Glezer, IëI. Vol. xxxii. Basic Books; New York: 1968. The human brain in figures and tables; a quantitative handbook; p. 482
30. Chrzanowska G, Beben A. Weight of the brain and body height in man between the ages of 20 and 89 years. *Folia Morphol (Warsz)* 1973;32(4):391–406. [PubMed: 4543876]
31. Debakan A, Sadowsky D. Changes in brain weight during the span of human life: relation of brain weights and body heights and body weights. *Ann Neurol* 1978;4:345–356.10.1002/ana.410040410 [PubMed: 727739]
32. Hwang YI, et al. Study on the Korean adult cranial capacity. *J Korean Med Sci* 1995;10:239–242. [PubMed: 8593202]
33. Miller A, et al. Spectral analysis of arterial bruits (phono-angiography): experimental validation. *Circulation* 1980;61(3):515–520. [PubMed: 7353242]
34. Peters M, Jancke L, Zilles K. Comparison of overall brain volume and midsagittal corpus callosum surface area as obtained from NMR scans and direct anatomical measures: a within-subject study on autopsy brains. *Neuropsychologia* 2000;38(10):1375–1381.10.1016/S0028-3932(00)00048-8 [PubMed: 10869580]
35. Svennerholm L, Bostrom K, Jungbjer B. Changes in weight and compositions of major membrane components of human brain during the span of adult human life of Swedes. *Acta Neuropathol* 1997;94(4):345–352.10.1007/s004010050717 [PubMed: 9341935]
36. Caviness VS Jr, et al. Advanced application of magnetic resonance imaging in human brain science. *Brain Dev* 1995;17(6):399–408.10.1016/0387-7604(95)00090-9 [PubMed: 8747418]
37. Kennedy DN, et al. Gyri of the human neocortex: an MRI-based analysis of volume and variance. *Cereb Cortex* 1998;8(4):372–384.10.1093/cercor/8.4.372 [PubMed: 9651132]
38. Makris N, et al. MRI-Based topographic parcellation of human cerebral white matter and nuclei II. Rationale and applications with systematics of cerebral connectivity. *Neuroimage* 1999;9(1):18–45.10.1006/nimg.1998.0384 [PubMed: 9918726]
39. Kruggel F. MRI-based volumetry of head compartments: normative values of healthy adults. *Neuroimage* 2006;30(1):1–11.10.1016/j.neuroimage.2005.09.063 [PubMed: 16289929]
40. Visible_Human_Project. The visible human project. US National Library of Medicine; 1996.
41. Aubert-Broche B, Evans AC, Collins L. A new improved version of the realistic digital brain phantom. *Neuroimage* 2006;32(1):138–145.10.1016/j.neuroimage.2006.03.052 [PubMed: 16750398]
42. Collins DL, et al. Design and construction of a realistic digital brain phantom. *IEEE Trans Med Imaging* 1998;17:463–468.10.1109/42.712135 [PubMed: 9735909]

43. Schnitzlein, H.; Murtagh, F. Imaging anatomy of the head and spine: a photographic color Atlas of MRI, CT, gross and microscopic anatomy in axial, coronal and sagittal planes. Urban & Schwarzenberg; Munich: 1985.
44. Bit-Babik G, et al. Simulation of exposure and SAR estimation for adult and child heads exposed to radiofrequency energy from portable communication devices. *Radiat Res* 2005;163(5):580–590.10.1667/RR3353 [PubMed: 15850420]
45. Collins CM, Smith MB. Spatial resolution of numerical models of man and calculated specific absorption rate using the FDTD method: a study at 64 MHz in a magnetic resonance imaging coil. *J Magn Reson Imaging* 2003;18(3):383–388.10.1002/jmri.10359 [PubMed: 12938138]
46. NCRP. Radiofrequency electromagnetic fields: properties, quantities and units, biophysical interaction, and measurement. National Council Radiation Protection and Measurements; Bethesda. 1981.
47. Baker KB, et al. Variability in RF-induced heating of a deep brain stimulation implant across MR systems. *J Magn Reson Imaging* 2006;24(6):1236–1242.10.1002/jmri.20769 [PubMed: 17078088]
48. Kong, JA. Electromagnetic wave theory. 2. Vol. xi. Wiley; New York: 1990. p. 704
49. Collins CM, et al. Numerical calculations of the static magnetic field in three-dimensional multi-tissue models of the human head. *Magn Reson Imaging* 2002;20(5):413–424.10.1016/S0730-725X(02)00507-6 [PubMed: 12206867]
50. Fisel, CR., et al. A general model for susceptibility-based MR contrast. Eighth annual meeting of the society of magnetic resonance in medicine; Amsterdam, The Netherlands. 1989.
51. Ibrahim TS, et al. Dielectric resonances and B(1) field inhomogeneity in UHFMRI: computational analysis and experimental findings. *Magn Reson Imaging* 2001;19(2):219–226.10.1016/S0730-725X(01)00300-9 [PubMed: 11358660]
52. Foster KR, et al. Dielectric properties of brain tissue between 0.01 and 10 GHz. *Phys Med Biol* 1979;24(6):1177–1187.10.1088/0031-9155/24/6/008 [PubMed: 531093]
53. Gabriel C. Dielectric properties of biological tissue: variation with age. *Bioelectromagnetics Suppl* 2005;7:S12–S18.
54. Foster KR, Schwan HP. Dielectric properties of tissues and biological materials: a critical review. *Crit Rev Biomed Eng* 1989;17(1):25–104. [PubMed: 2651001]
55. Peyman A, et al. Dielectric properties of porcine cerebro-spinal tissues at microwave frequencies: in vivo, in vitro and systematic variation with age. *Phys Med Biol* 2007;52(8):2229–2245.10.1088/0031-9155/52/8/013 [PubMed: 17404466]
56. Katscher, U., et al. Electric properties tomography (EPT) via MRI. ISMRM Fourteenth Scientific Meeting; Seattle. 2006.
57. Hurt W, Zirix J, Mason P. Variability in EMF permittivity values: implications for SAR calculations. *IEEE Trans Biomed Eng* 2000;47(3):396–401. [PubMed: 10743782]
58. Mason P, et al. Effects of frequency, permittivity, and voxel size on predicted specific absorption rate values in biological tissue during electromagnetic—field exposure. *IEEE Trans Microw Theory* 2000;48:2050–2058.10.1109/22.884194
59. Kang G, Gandhi OP. Effect of dielectric properties on the peak 1 and 10 g SAR fro 802.11 a/b/g Frequencies 2.45 and 5.15 to 5.85 GHz. *IEEE Trans Electromagn Compat* 2004;46:268–274.10.1109/TEM.2004.826875
60. Van den Berg, CAT. Exploiting their similarities for mutual benefits. Utrecht: 2006. Radiofrequency fields in hyperthermia and MRI.
61. Clatz O, et al. Dynamic model of communicating hydrocephalus for surgery simulation. *IEEE Trans Biomed Eng* 2007;54(4):755–758.10.1109/TBME.2006.890146 [PubMed: 17405384]
62. Greco WR. New practices in computational modeling. *Clin Cancer Res* 2007;13(4):1074–1075.10.1158/1078-0432.CCR-06-2811 [PubMed: 17317813]
63. Ayache, N. Computational models for the human body. In: Ciarlet, P., editor. *Handbook of numerical analysis*. Elsevier; Amsterdam: 2004. p. 670
64. Coatrieux, JL.; Bassingthwaighe, JB., editors. *Proc IEEE*. Vol. 94. 2006. Special issue on the physiome and beyond; p. 671-678.

Fig. 1.

Representative coronal (*left*) and sagittal (*right*) sections comparing the segmentation results of the CMA head with the Schnitzlein and Murtagh (1985) head atlas [43]. Key: 1 epidermis, 2 ear/pinna, 3 nasal structures, 4 SC tissue, 5 connective tissue, 6 soft tissue, 7 aqueous humor, 8 vitreous humor, 9 cornea, 10 lens/iris, 11 R/C/S, 12 outer table, 13 diploe, 14 inner table, 15 dura, 16 bone, 17 teeth, 18 air (resp./diges./sinus), 19 mastoid/air cells, 20 adipose, 21 orbital fat, 22 SC fat/muscle, 23 muscle, 24 tongue, 25 nerve, 26 spinal cord, 27 blood/vessel, 28 CSF-subarachnoid

Fig. 2. Electrical structural entities. Maps of density ρ (kg m^{-3}) (*top*), conductivity σ (S m^{-1}) (*center*), and permittivity ϵ_r (*bottom*), at 300 MHz for the different ASEs segmented. The maximum scale was fixed at $\epsilon_r = 70$ and $\sigma = 1$ for illustrative purposes. These values were used for FDTD simulations at 7 T MRI

Fig. 3. Results of segmentation of the head model in eight representative pairs of coronal sections. In each pair, the segmented image is shown on the *left* and the image with the color-coded structural entities (SEs) is on the *right* (brain SEs are masked in *black*). The complete segmentation can be found at the following URL:
http://www.cma.mgh.harvard.edu/head_model/brain.php

Fig. 4.

3-D view of head model. **a** Epidermis; **b** muscle (*red*), outer table (*white*) and eye regions (lens, cornea and vitreous humor); **c** dura mater (*gold*), blood vessels (*red*), and bone (*white*); **d** dura mater (*gold*), blood vessels (*red*) and eye regions; **e** dura mater (*gold*), blood vessels (*red*), eye regions, tongue (*light red*), ears and nasal structures (*pink*) and bone (*white*); **f** outer table, bone (*white*) and blood vessels (*red*); **g** cerebral cortex (*green*), blood vessels (*red*), and eye regions; **h** cerebral white matter (*offwhite*), blood vessels (*red*) and eye regions

Fig. 5. Results of FDTD simulations. The FDTD simulations implemented with the proposed head model allowed for precise EM computation and mapping. (*Right*) MRI data on the human subject at 7 T showing the characteristic central brightening effect. (*Center*) simulated B field mapped on the numerical model. (*Left*) related SAR distribution in the human head

Fig. 6.

The wealth of anatomical tissue classes make the 3D-rendering of the model an ideal tool for anatomical visualization and SAR mapping (in W/kg), as shown in this 3D view of the epidermis/dermis (a), grey matter (b), bone structures (i.e., outer table, inner-table, bone, teeth (c), blood vessels (d), diploe (e), and eye-region, i.e., vitreous humour, aqueous humour, retina/choroid/sclera, lens, cornea, optical nerve (f). SAR values were normalized to obtain a whole-head SAR equal to 0.46 W/kg. Max SAR in scale equal to 1 W/kg

Fig. 7.

The pie-chart shows the percentage of RF-power absorbed by each anatomical structure. The absorbed RF power (i.e., RF energy per unit time) was higher for ASEs with high volume and conductivity, such as epidermis/dermis, grey matter, white matter, and muscle, and lower for ASEs with low conductivity, such as bone or outer/inner table

Table 1

List of segmented brain anatomical structural entities in this study and their corresponding electrical structural entities; their densities and electrical properties

ASEs		Density (kg/m ³)	300 MHz ^d	
			σ (S/m)	ϵ_r
Brain				
Grey matter	L/R Accumbens area	1,030 ^a	0.69	60.00
	Amygdala	1,030 ^a	0.69	60.00
	L/R Amygdala anterior	1,030 ^a	0.69	60.00
	L/R Caudate	1,030 ^a	0.69	60.00
	L/R Cerebral cortex	1,030 ^a	0.69	60.00
	L/R Hippocampus	1,030 ^a	0.69	60.00
	L/R Pallidum	1,030 ^a	0.69	60.00
	L/R Putamen	1,030 ^a	0.69	60.00
	L/R Thalamus proper	1,030 ^a	0.69	60.00
	L/R VentralDC	1,030 ^a	0.69	60.00
White matter	L/R Cerebral white matter	1,030 ^a	0.41	43.77
	Optic chiasm	1,030 ^a	0.41	43.77
Cerebellum	L/R Cerebellum cortex	1,030 ^a	0.97	59.70
	L/R Cerebellum white matter	1,030 ^a	0.97	59.70
Brain stem	Brain stem	1,030 ^a	0.69	60.00
CSF	Cerebro spinal fluid	1,010 ^a	2.22	72.73
	Cavum vergi	1,010 ^a	2.22	72.73
	Inferior lateral ventricle	1,010 ^a	2.22	72.73
	Lateral ventricle	1,010 ^a	2.22	72.73
	Third ventricle	1,010 ^a	2.22	72.73
	Fourth ventricle	1,010 ^a	2.22	72.73
Non-brain	Adipose	920 ^a	0.07	11.74
	Air (resp./diges./sinus)	1.3 ^b	0.00	1.00
	Aqueous humor	1,010 ^{a,c}	1.51	69.01
	Blood vessels	1,000 ^a	1.31	65.65
	Bone (facial)	1,850 ^b	0.14	18.30
	Connective tissue	1,020	0.47	39.20
	Cornea	1,076 ^c	1.15	61.37
	CSF_Subarachnoid	1,010 ^a	2.22	72.73
	Diploe	1,080 ^b	0.21	23.16
	Dura	1,030 ^a	0.80	47.95

ASEs	Density (kg/m ³)	300 MHz ^d	
		σ (S/m)	ϵ_r
Epidermis/dermis	1,100 ^a	0.64	49.82
Ear/pinna	1,100 ^a	0.55	46.77
Inner table	1,850 ^b	0.08	13.43
Lens	1,100 ^c	0.64	48.95
Mastoid/air cells	1.3 ^b	0.00	1.00
Muscle	1,040 ^d	0.79	58.97
Nasal structures	1,100 ^a	0.55	46.77
Nerve	1,040 ^a	0.41	36.90
Orbital fat	920 ^a	0.07	11.74
Outer table	1,850 ^b	0.08	13.43
Retina/choroid/sclera	1,170 ^a	0.97	58.90
Soft tissue	1,020	0.47	39.20
Spinal cord	1,040 ^a	0.41	36.90
Subcutaneous tissue	1,020	0.47	39.20
Subcutaneous-fat/muscle	980	0.43	35.35
Tongue	1,040 ^d	0.79	58.97
Teeth	1,850 ^b	0.14	18.30
Vitreous humor	1,010 ^{a,c}	1.51	69.01

Ventral DC, ventral diencephalon

^aRef. [23]

^bRef. [21]

^cRef. [22]

^dRef. [20]

Table 2Volume of each anatomical structure in mm³

Brain		Non-brain	
Anatomical structural entities	Volumes (mm³)	Anatomical structural entities	Volumes (mm³)
L/R Accumbens area	1,265	Adipose	39,607
Amygdala	2,435	Air (resp./diges./sinus)	91,384
L/R Amygdala anterior	81	Aqueous humor	158
L/R Caudate	6,236	Blood vessels	22,804
L/R Cerebral cortex	710,449	Bone (facial)	170,902
L/R Hippocampus	8,004	Connective tissue	25,026
L/R Pallidum	2,959	Cornea	67
L/R Putamen	10,115	CSF_Subarachnoid	16,495
L/R Thalamus proper	15,413	Diploe	137,103
L/R VentralDC	10,712	Dura	119,059
L/R Cerebral white matter	437,874	Epidermis	385,805
Optic chiasm	132	Ear/pinna	40,283
L/R Cerebellum cortex	121,522	Inner table	221,874
L/R Cerebellum white matter	22,880	Lens	421
Brain stem	23,250	Mastoid/air cells	35,467
Cavum vergi	51	Muscle	1,084,287
Cerebro spinal fluid	79,348	Nasal structures	54,668
Inferior lateral ventricle	1,091	Nerve	6,032
Lateral ventricle	17,461	Orbital fat	40,450
Third ventricle	1,109	Outer table	65,506
Fourth ventricle	1,591	Retina/choroid/sclera	5,758
		Soft tissue	130,541
		Spinal cord	6,657
		Subcutaneous tissue	42,897
		Subcutaneous-fat/muscle	382,404
		Tongue	18,978
		Teeth	21,201
		Vitreous humor	8,258

Table 3

Changes of peak SAR values (1 mm³, 1 and 10 g avg.) when the electrical conductivity of each of the five main SEs was increased by 20% with respect to the reference head model (Table 1)

$\Delta\sigma = 20\%$	$\Delta\sigma$ (muscle) % change	$\Delta\sigma$ (grey) % change	$\Delta\sigma$ (white) % change	$\Delta\sigma$ (Epidermis) % change	$\Delta\sigma$ (sc fat/muscle) % change
Δ (Peak 1 mm ³ SAR)	1.2	1.2	-0.9	-1.4	1.0
Δ (Peak 1 g SAR)	0.1	1.2	-0.6	-1.7	-1.2
Δ (Peak 10 g SAR)	2.2	1.6	0.1	4.4	1.5
Peak Δ (1 mm ³ SAR)	30.3	33.8	21.6	23.8	27.7
Peak Δ (1 g SAR)	22.8	25.8	15.6	11.3	19.0
Peak Δ (10 g SAR)	18.0	17.5	11.6	0.6	11.5