

A novel electric current simulator in the human brain

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Dr. Shoji Hamada is an Associate Professor and a research scientist interested in studying and developing computational tools for the analysis of electromagnetic fields in anisotropic conductive media, with wide implications in biomedical engineering applications.

Can you provide our readers some background and an outline of your research?

My specialty is the development and conceptual design of numerical calculation methods for fields in the human body. The voxel-based indirect boundary element method (IBEM) and the voxel-based method of moments (MoM) are examples of such numerical field calculation methods.

Biological neural activities generate electric currents in the body, voltage differences on the skin surface, and magnetic fields around the body. By quantitatively calculating the quantities caused by each unit of neural activity at every possible position, for example, we can noninvasively estimate the distribution of brain neural activities by analysing a measured brainwave and magnetic encephalographic signal with inverse calculation techniques. Note that an inverse calculation needs preliminary forward calculations like these.

On the other hand, when electric, magnetic, and electromagnetic fields are applied to a patient, they induce electric fields and currents in the body. For example, transcranial magnetic stimulation applies external magnetic fields to the human head to induce electric currents in the brain for symptomatic treatment, and a defibrillator is used to apply contact currents to the human body to stimulate the heart and re-establish effective rhythms. By quantitatively calculating the actual current distribution, we can improve the performance and effectiveness of these devices.

In order to improve calculation accuracy and reliability, it is important to consider the following key techniques: [i] using “tailor-made” numerical human models derived from personal MR images, [ii] considering anisotropic conductive properties of biological tissues such as nerve fibre bundles, and [iii] developing or improving a field calculation method suitable for [i] and [ii].

How do you use data from magnetic resonance

imaging (MRI) in your research?

The MRI technique noninvasively provides internal structural information of organs, and the numerical human models developed from the MR images are very good replicas. In particular, an accurate personal model can be produced from MR images, which are most accurate for an individual.

The diffusion tensor imaging (DTI) technique available lately is a variant of MRI. The diffusion tensor can be approximately converted to an electric conductivity tensor that represents the anisotropic conductivity of the biological tissue. Therefore, by using MRI and DTI, we can develop numerical human models that have both the structural and conductive information derived from the body.

MR images are provided as a stack of pixel pictures, which are called voxel data, and are equivalent to a three-dimensional, equal-interval, orthogonal coordinate grid. Thus, by using voxel models and field-calculation methods suitable for voxel model analyses, we can efficiently perform numerical field analyses.

Can you provide us more detail on voxel-based static MoM and related method voxel-based IBEM?

The voxel-based static MoM and voxel-based IBEM are low-frequency electric-field calculation methods designed to be suitable for voxel model analyses. The voxel-based IBEM can analyse large-scale voxel models having structural information derived from MRI. In comparison the voxel-based static MoM can analyse voxel models having both structural and conductive information derived from MRI and DTI, respectively.

Standard IBEM is designed to calculate the currents through isotropic tissues. The voxel-based MoM technique enables us to numerically calculate electric currents flowing through anisotropic conductive tissues such as nerve fibre bundles. By visualising the calculated

current distribution, we can observe them.

My recent conference paper describes how we developed and verified the voxel-based static MoM.

What alternative numerical calculation techniques are there for analysing electric current flowing through anisotropic tissues such as nerve fibre bundles?

Numerical field calculation methods that can also address anisotropy are finite difference methods (FDM) and finite element methods (FEM). In comparison the advantage of the combined use of the voxel-based static MoM and voxel-based IBEM is as follows:

Let us assume the voxel model to be analysed is composed of $D \times D \times D$ voxels, for simplicity. A simple estimation of calculation time and computer memory indicates a D^2 dependency for the voxel-based IBEM using the fast multipole method (FMM). This dependency comes from IBEM using surface elements. On the other hand, the dependency of the FDM, FEM, and voxel-based static MoM is D^3 , because these methods are practically based on volume elements. These dependencies suggest that the voxel-based IBEM is suitable for large-scale model analyses. Because voxel-based static MoM is suitable for use with the voxel-based IBEM, their combined use would be the best choice.

What applications except for electro/magnetoencephalography can your method be useful for?

The numerical calculation technique can help us to improve electric devices directly affecting the body, like defibrillators and electro-surgical knives, because design parameters of these devices could be effectively optimised by running well-organized numerical simulations. The parameters that could be optimized are, for example, shape, size, position, and the number of electrodes and coils; intensity, frequency, and wave form of electric power sources.

Computing electric currents by considering anisotropies in the brain

A new voxel-based computational method enables the high-speed and large-scale simulation of electric current flowing through anisotropic conductive tissues such as nerve fibre bundles by using biological voxel models derived from medical images.

COMPUTING ELECTROSTATIC FIELDS

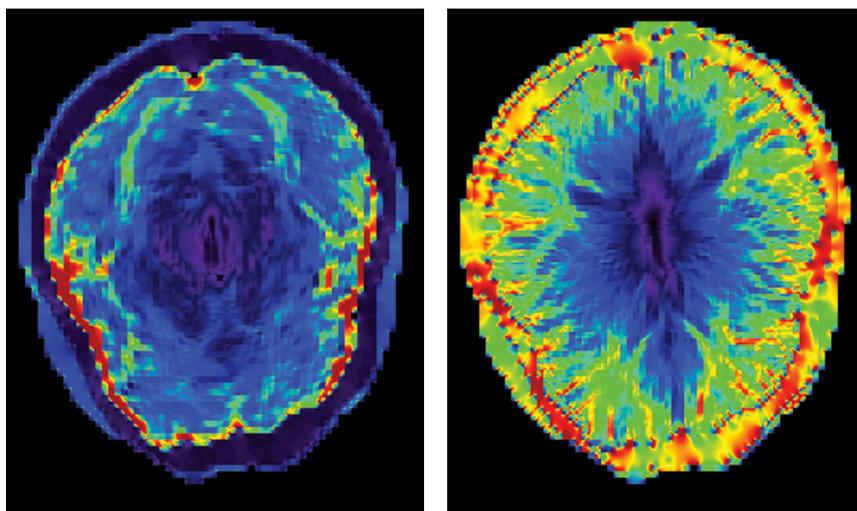
Dr. Shoji Hamada is an associate professor at Kyoto University, Japan, and specialises in computational electromagnetics and electrical engineering. Throughout his career he has developed a range of computational methods and models for the analysis of electromagnetic phenomena in the human body and in dielectric media. We look at his recent work and conference paper “Electrostatic Field Analysis in Anisotropic Conductive Media Using a Voxel-Based Static Method of Moments”.

Hamada has developed a novel computational method that can analyse the electrostatic fields and currents in anisotropic conductive media such as nerve fibre bundles in the human brain. This method is designed to analyse a cubic voxel model that is a stack of two-dimensional pixel arrays (i.e. picture data). The structural information of a voxel model is derived from magnetic resonance imaging (MRI) data, and the anisotropic conductivity tensor of each voxel is derived from diffusion tensor imaging (DTI) data.

Although typical field calculation methods utilize volume elements to address anisotropic conductivities, this method adopts surface elements that emulate volume elements. This choice enables the method to be used concurrently with the voxel-based indirect boundary method (IBEM), which is another field calculation method that uses surface elements. The voxel-based IBEM can perform high-speed analyses of large-scale ‘isotropic’ conductive models. Thus the combined use of this method with the voxel-based IBEM provides improved computing performance in analysing composite media composed of both isotropic and anisotropic conductors.

MAKING REALISTIC VOXEL MODELS FROM MRI AND DTI DATA

MRI is a diagnostic technology widely used in contemporary medicine for its capacity to



Calculated current density J and electric field E .

measure and image minuscule detail. This technology works by using a superconducting magnet to create a strong magnetic field that passes through the patient. The field aligns the spinning hydrogen protons, present in water in the body, along the same direction as the field, thus making the patient virtually transparent for observation. Then a radio wave is pulsed into the target organ to knock the protons out of the regular array. When the radio wave is turned off, the protons re-align with the magnetic field, and as they do so, emit their own radio waves which are detected by instruments inside the machine. These waves carry a signature of the tissue type and injected contrast dye and create the contrast between organs and tissue types.

To obtain reliable calculation results, it is important to make human voxel models as realistic as possible. Thus we utilize MR images to produce a human voxel model. The MRI technique noninvasively and experimentally provides the internal structural information of human organs, and the voxel models derived from MR images are very good replicas of real bodies. The DTI is a variant of the MRI, and

the diffusion tensor can be approximately converted to an electric conductivity tensor that represents the anisotropic conductivity of the biological tissue. By using MRI and DTI data, we can develop voxel models that have both structural and conductive information experimentally derived from an original human body.

In particular, an individual personal model can be produced from personal MRI and DTI data. This is of course the most accurate model of a person. By using such models we can substantially improve the reliability of the calculated electric fields and currents in the model. Such high accuracy is desired for brain-related medical applications in particular.

DETAILS OF DEVELOPED VOXEL-BASED METHOD

In more detail, this new numerical method is a voxel-based static method of moments (MoM). A voxel is a three-dimensional pixel that acts as a small volume element comprising a larger computer model, whereas “static” refers

to the electrostatic and quasi-electrostatic fields which are the targets of the calculation. The method of moments is a widely used tool for solving integral equations to compute electromagnetic fields in numerical models – in this case, voxel human models derived from MRI and DTI data. In his paper, Hamada used his voxel-based MoM to analyse an anatomically exact computer model composed of a three-dimensional array of cubic voxels constructed from imaging data. “Usually, MR images are provided as voxel data and are equivalent to a three-dimensional equal-interval orthogonal coordinate grid”, Hamada said.

The voxel-based IBEM and MoM utilize surface elements, and an element is defined on a square voxel wall between two voxels having different values of conductivity. This definition makes the data structure simple and efficient to handle. In particular, the simple structure enables the IBEM and MoM to straightforwardly utilize both the fast multipole method (FMM) and the fast Fourier transformation (FFT) algorithms. These algorithms dramatically speed up the calculation speed and increase the available number of unknowns.

In addition, using this type of element guarantees a calculation accuracy comparable with that of the finite difference method, which is widely recognized as a practically useful approach. On the other hand, the element definition makes the model shape suffer staircase-shaped errors. The voxel-based IBEM and MoM are designed to address this weak point by using high-resolution and large-scale models that can be handled by using the FMM and FFT. The voxel-based MoM has previously handled up to 284 million unknowns on a personal computer with 64 GB of main memory.

The voxel-based MoM emulates a volume element by using six surface elements defined on six surfaces of a cubic voxel. These six elements represent the distribution of polarization charges in the volume. ‘In a conductive medium, the sum of polarized charges inside any closed region is zero’, Hamada explained. ‘However, the standard IBEM cannot numerically satisfy this relationship in anisotropic conductive media. The voxel-based MoM can numerically satisfy this relationship even in anisotropic conductive media because we designed it to satisfy this relationship by adding a constraint to the basic equations’.

RESEARCH IMPLICATIONS

These computational methods are crucial for researching and developing biomedical engineering applications such as electro/magnetoencephalography, electric/magnetic stimulation, and exposure assessment for electromagnetic fields. A typical application of the field calculation technique is the forward calculation preliminarily required by the inverse calculations for electroencephalography (EEG) and magnetoencephalography (MEG). EEG and MEG reveal the distribution of neural activities in the brain by analysing the measured brainwave and magnetic encephalographic signal using inverse calculation techniques. The improvement in forward calculation accuracy improves the reliability and resolution of analysed neural activities.

Moreover, transcranial magnetic stimulation (TMS) is used for therapeutic reasons and to measure brain activity for diagnostic purposes. The potentially harmful effects of TMS can be avoided because they can be simulated and understood in advance. Electrical devices that directly affect the body, such as defibrillators and electro-surgical knives, can also benefit greatly from this method. Defibrillators are used to impart an electrical current across the heart to return it to normal rhythm, and electro-surgical knives are used to cut tissue during surgery. Hamada informs us that “numerical simulations can be used to optimise design parameters such as shape, size, position, and the number of electrodes and coils; and the intensity, frequency, and waveform of electric power sources”.

This research is important because “Anisotropic conductivity is exhibited by a variety of biological tissues, for example, bones, muscles, and nerve fibres”, said Hamada. The voxel-based IBEM and MoM are designed to suit isotropic and anisotropic media, respectively. Overall, the analysis works best if voxel-based IBEM is used in conjunction with voxel-based static MoM. It is the combination of these methods that results in the greatest advantage. The resulting increase in computing performance will contribute to analyses of finer-resolution and larger-scale models and obtain better accuracy and reliability. ‘Our goal is to prevent harmful effects to the human body caused by electric, magnetic, and electromagnetic fields, and to effectively utilize their beneficial effects’, Hamada said.

Researcher Profile



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Dr. Shoji Hamada is Associate Professor at Kyoto University, Japan, and specialises in computational electromagnetics, electrical engineering, electrical discharges, and electric field calculations, with over 50 published contributions to the field of physics. He received his Ph.D. in electrical engineering from the University of Tokyo 1992. Afterwards he worked with the Tokyo Denki University 1992-1997, and has been a lecturer since 1997 at the Department of Electrical Engineering, Kyoto University, returning to where he completed his B.S. degree. He is a member of IEEE, IEEJ, and JSST.

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