SOFTWARE TOOL FOR ANALYSIS OF VOXEL HUMAN BODY MODELS

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Abstract

The paper describes a software tool created to inspect the anatomical structures of any segmented voxel model of the human body for use in numerical analyses of the interaction of non-ionizing electromagnetic radiation with a metallic implant. A voxel model is a three-dimensional representation of the human body model in the form of a numerical array of indices that identify each element as belonging to a particular tissue, organ, or anatomical part. The process of virtual implant placement within these models while maintaining their anatomical limitations is complex and time-consuming. We have created a software tool in the MATLAB environment to simplify and speed up this process. As a representative case, we used the developed tool to identify three implantation sites of pacing electrodes within the cardiovascular system of the available AustinMan and AustinWoman models.

Keywords

anatomical features, implant, pacemaker, virtual insertion, voxel model

Introduction

In recent decades, the assessment of the human body's radiation dose has been a widespread issue in ionizing and non-ionizing radiation protection, medical imaging, and radiation therapy. Radiation dose assessment determines the health risks of electromagnetic field (EMF) exposure and establishes limit values to avoid deterministic harm. As the quantities of an EMF, these limit values are not directly measurable within the human body. Thus, the preferred approach is using computational human body phantoms in combination with numerical modelling tools, such as electromagnetic simulation software capable of modelling various exposure scenarios. Various computational phantoms have been developed and used to study the biological effects of thermal and non-thermal effects caused by EMF emitting devices since the 1960s. Individual organ masses agree with reference values defined by the International Commission on Radiological Protection [1]. At the same time, the anatomy of these phantoms is represented by elementary geometrical elements (such as spheres, cones, and cylinders). These phantoms are anatomical schematics rather than realistic human body models due to their limitations in simple organ shapes.

Computational phantoms have significantly improved and become widely adopted since the introduction of personal computers and medical imaging techniques [2–4]. Medical imaging techniques like computed tomography (CT) and magnetic resonance imaging (MRI) create virtual voxel models of real people with high anatomical resolution. Due to their anatomical superiority, these anthropomorphic phantoms offer a clear advantage over the previous models. Individual anatomical features encoded by Hounsfield units or Relaxation time are included in voxel models created from CT or MRI cross-sectional grayscale images of live subjects. To create a voxel model, the process of segmentation must be used to differentiate greyscale image areas into anatomical structures such as tissues or organs. This is a cumbersome process requiring considerable manual labor and a comprehensive understanding of human anatomy [5]. However, semi-automatic algorithms such as BRISKit exist to accomplish this [6]. Following that, cross-sectional segmented images of the entire body are linked together to form a three-dimensional array of volume elements known as voxels (3D pixels). These cuboid elements are defined by a uniform medium assigned by an index that identifies them as belonging to a specific tissue or organ.

In recent decades, significant efforts have been made to create virtual human body models. Xu and Eckerman describe 121 computational phantoms that have been used in ionizing and non-ionizing radiation studies [7]. Because of the growing interest in the health risks associated with radio and high-frequency EMF exposure, non-ionizing radiation has become a popular research topic. Mobile phones, digital cordless phones, Bluetooth devices, Wi-Fi equipment, microwave ovens,

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home appliances, electronic article surveillance devices, and other technologies or devices produce these fields. Unfortunately, their increased use over the last decade has resulted in a significant increase in human exposure to electromagnetic radiation. Furthermore, previous research has shown that metallic implants (such as pins, rods, screws, leads, and catheters) can alter the spatial distribution of EMF inside the human body, affecting the absorption of electromagnetic energy around them due to the scattering of incident electromagnetic waves [8–13]. As a result, not only anatomically precise virtual human body models are demanded, but also a method for virtually inserting generic implants into these models. However, the voxel models have the disadvantage of being inflexible in general. In addition, the fixed resolution and challenging model variations in the anatomy limit them [14]. In theory, a voxel model can be edited by substituting the material properties (e.g., dielectric and magnetic parameters) of a specific body segment, organ, or tissue, effectively inserting a general implant. However, inserting and adjusting a specific implant (specific volume or shape) in the desired location within a voxel model is a complex and time-consuming procedure. Therefore, a semi-automatic tool based on image processing methods had to be developed.

The scope of this study was to develop a software tool that could visualize human models while also tracking user-defined anatomical features like the cardiovascular system. The cardiovascular system has been chosen as a representative example of an anatomical feature for a specific implant; a pacemaker's lead, which must maintain anatomical constraints as it travels through the human body.

Materials and Methods

Numerical Models

The open-source models, namely AustinMan and AustinWoman, were used as numerical human body models [15]. Those models, created at The University of Texas, are voxel-based models for electromagnetic simulations based on the Visible Human Project dataset from the National Library of Medicine [16]. AustinMan is a 38-year-old adult male cadaver, and AustinWoman is a 59-year-old adult female cadaver which have been used to create an anatomically realistic human phantoms using digitized photographic images from cryosectioning, CT, and MRI images. There are 80 anatomical entities, which are mapped by 47 different tissues. We use the model's highest spatial model resolution (1×1×1 mm) to track anatomical features as precise as possible. The spatial resolutions of 2, 4, and 8 mm^3 are also available. Fig. 1 shows voxel-based models with one quadrant removed to emphasize the internal anatomical complexity and the cardiovascular system as a point of interest.

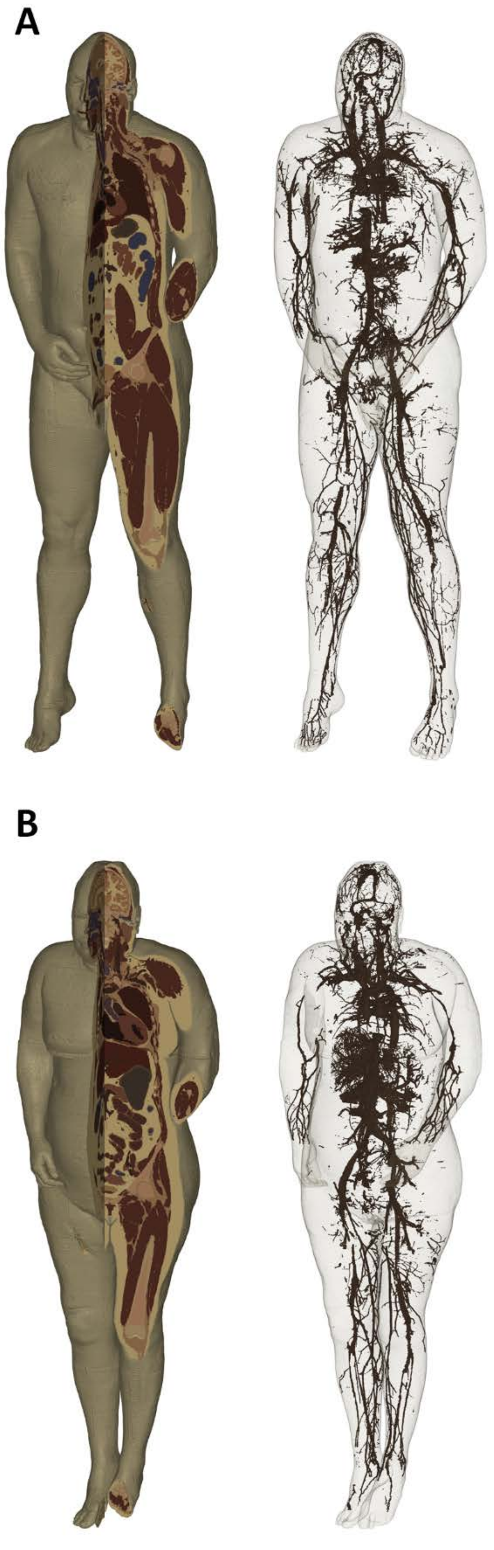


Fig. 1: The perspective visualization of the AustinMan (A) and AustinWoman (B) models, with one quadrant removed to emphasize internal anatomical structures (left) and cardiovascular system (right).

The pacemaker (PM) is an implantable medical device that detects and stimulates the heart's electrical activity when it becomes insufficient. The PM is made up of a metallic case with electronic circuits and a battery inside, and it uses its leads to perform electro-stimulation or detection in the heart. The two stimulation/detection poles—ring and tip—are separated by insulation and terminate the PM's lead (Fig. 2). Using an active or passive fixation mechanism, these poles directly contact blood and myocardium in a specific heart section. The PM is usually surgically implanted in the left pectoral region, but the exact implant pocket location and depth are determined by physician preference and cannot be predicted. The right pectoral region and the abdomen are the two remaining PM implantation sites. On the other hand, the cardiovascular system determines the PM's lead's implantation path. The PM's lead enters the subclavian vein through a small incision below the collar bone in the left pectoral implantation region, descends through the superior vena cava, and terminates in the right heart atrium or ventricle depending on the PM's operating mode [17].

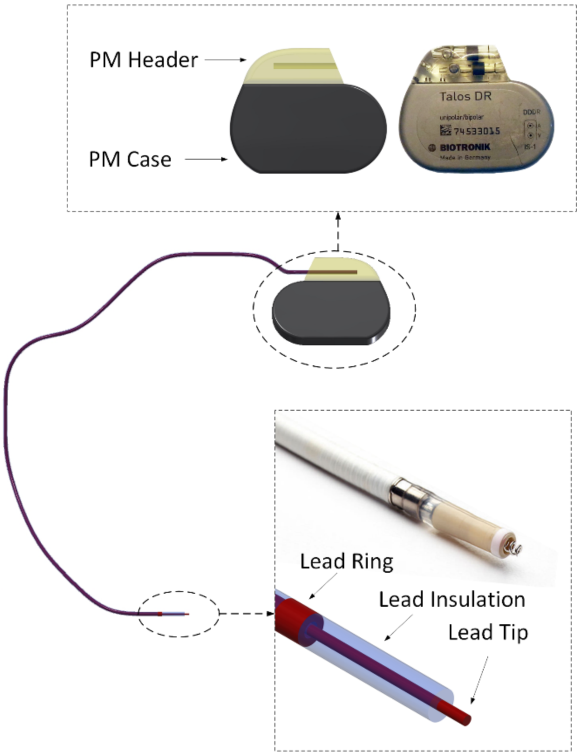


Fig. 2: The created numerical model of implantable pacemaker with pacing electrode in bipolar mode with active fixation in Autodesk Inventor.

The precise location of particular veins for lead routing must be known with respect to the phantom global reference frame to create and virtually insert PM's lead model within the numerical phantom. The proposed software tool's primary goal is to achieve this.

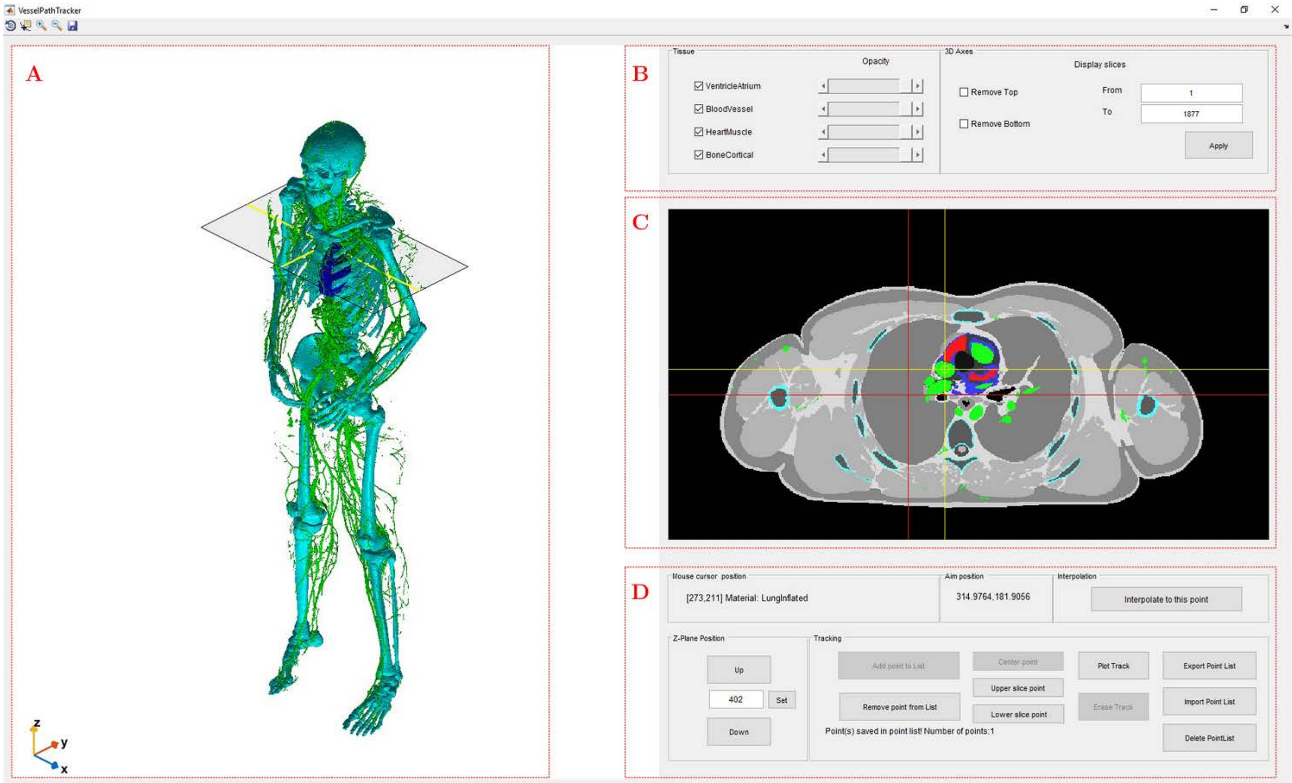
Software Design

Due to the complexity of the human anatomy and the variety of PM's implantation locations, we decided against designing a fully automated software. Instead, the designed software implemented a user-friendly graphical user interface and semi-automatic routines for tracking a desired anatomical feature, such as the cardiovascular system. We used already segmented images provided by The University of Texas [15] as input. Provided a series of 8-bit grey-scale images form a structured grid of the AustinMan and AustinWoman model. AustinMan and AustinWoman are characterized by 1877 and 1730 transverse slices, respectively. These input data are used to visualize the human body model in the transverse plane as a three-dimensional and two-dimensional representation. The proposed software tool's working principle is to manually select at least two desired points within the human body model. The spatial coordinates of selected points are then used to calculate a trajectory that connects them while maintaining anatomical constraints. For example, the spatial borders of individual parts of the cardiovascular system represent anatomical constraints for PM's lead trajectory. Interconnected points representing the vein lumen center points in the transverse plane define the trajectory.

Results

The proposed software tool was developed in the MATLAB environment. Fig. 3 depicts the main graphical user interface. The application displays the input model as a three-dimensional rotatable representation that can be zoomed and a two-dimensional transverse plane representation.

A pre-processing routine computes isosurface data from a Cartesian, axis-aligned structured grid for the three-dimensional visualization (Fig. 3A). Using a semi-transparent cutting plane, the two-dimensional view of input grey-scale images in the transverse plane is linked and depicted within three-dimensional visualization (Fig. 3C). The users can choose the vertical position of the cutting plane in the transverse plane, which allows them to see all segmented anatomical structures of the imported human body model. On the other hand, three-dimensional visualization has a limited number of anatomical structures, such as the skeleton, heart muscle, heart compartments, and blood vessels. It is because we are particularly interested in the cardiovascular system. The visualization of the remaining anatomical structures of an imported model, on the other hand, could be easily changed programmatically. The view editing panel allows the user to hide a specific anatomical structure, adjust its opacity, select the range of displayed human body slices, and remove the top or bottom visualization concerning the selected cutting



☑ VentricleAtrium
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☑ HeartMuscle
☑ BoneCortical
☐ Remove Top
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From 1
To 1877
[273,211] Material: LungInflated
314.9764,181.9056
402
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Fig. 3: The developed application's graphical user interface is as follows: A – a three-dimensional rendering of a human body model with the desired anatomical features, B – visualization editing panel, C – two-dimensional visualization of the human body model in the transverse plane with all anatomical features, D – control panel for tracking anatomical features of interest.

plane (Fig. 3B). This is intended to assist even those who are unfamiliar with human anatomy in quickly identifying desired anatomical features within the human body. Fig. 3D shows the main component for semi-automatic identification and tracking of the desired anatomical structure. The spatial coordinates of the center points of vein lumen (the subclavian vein, the superior vena cava), the right heart atrium, and the right heart ventricle, respectively, are desired anatomical features with respect to our goal. In general, the user must identify at least two points: a start point in the subclavian vein and a terminal point in the heart ventricle. Then, these points must be manually selected with a mouse click in 2D visualization while their spatial coordinates are registered in the point list. Red and yellow lines, respectively, highlight the current mouse cursor position and previously selected points (Fig. 3C). Under the 2D visualization, their spatial coordinates are displayed. Following that, the user can use the application to calculate the trajectory between two (start and terminal) or more points while maintaining anatomical constraints. The center points identification of anatomical features in the transverse plane is used to calculate trajectory using spatial interpolation between selected points in all adjacent transverse slices.

Furthermore, the spatial coordinates of the center points are smoothed using a Gaussian-weighted moving average with a 10-sample window. The main application part allows the user to choose the vertical position of the transverse cutting plane, register the user-selected point in the transverse plane visualization by mouse click, center this point within the boundary of the selected anatomical region, add or remove this point from the point list, and project already chosen point from upper or lower slice to select at least two points within the input model.

The calculated trajectory between these points can be plotted within 3D visualization and exported as a text file containing the spatial trajectory coordinates once all desired points have been added to the point list. These data could then be used as input into computer-aided design software tools to create a numerical PM's lead model. The subsequent virtual insertion of the PM's lead model features to be anatomi-cally valid due to the identification and calculation of lead trajectory with respect to the human body model's global reference frame.

Fig. 4 depicts the numerical PM models using trajectory data and computer-aided design software, as well as the calculated PM's lead trajectory using the proposed software tool. These numerical models could then be easily imported into the electromagnetic simulation software of preference [18, 19]. Fig. 5 demonstrates the virtual anatomically valid placement of PM and PM's lead model within the AustinMan model using the CST Microwave Studio software. Such

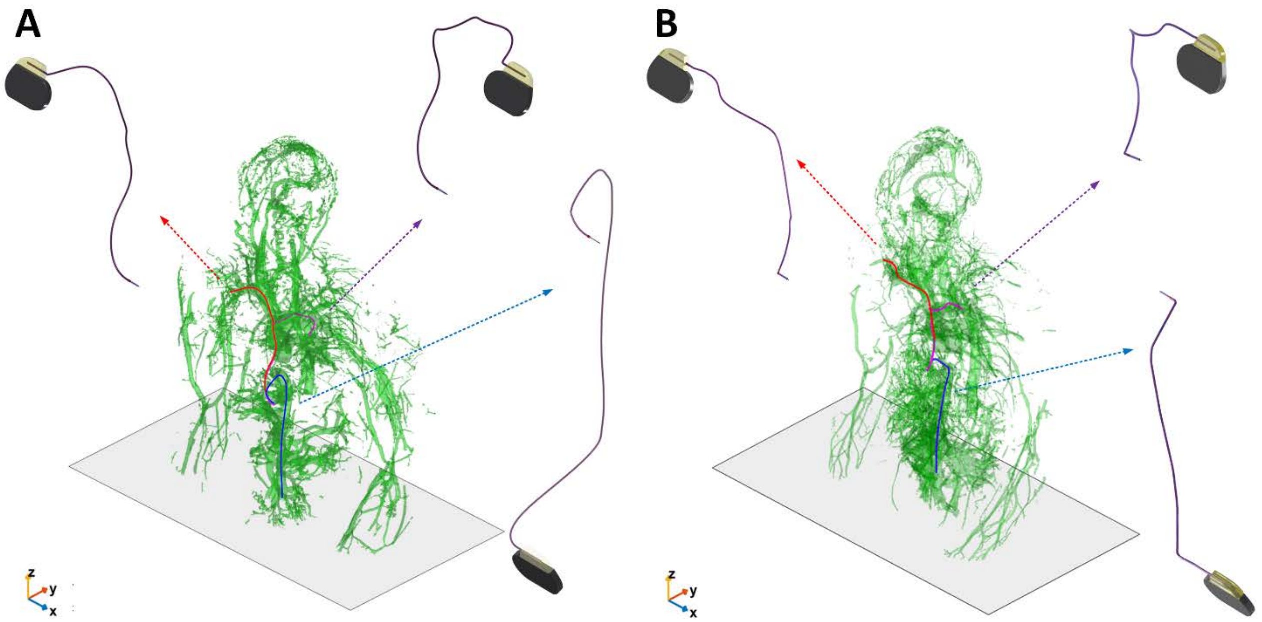

Fig. 4: Calculated trajectories of PM's lead model for right pectoral (red), left pectoral (violet) and abdomen (blue) implantation location of AustinMan (A) and AustinWoman (B) models. To emphasis lead trajectories, only cardiovascular system of the human body model is displayed. The numerical PM models utilizing calculated trajectories is depicted as well.

an exposure scenario could be subsequently used to assess and analyze the health risks of various non-ionizing EMF sources in terms of the value of the induced electric voltage on the PM's lead sensory part or peak values of the electromagnetic field in the tissue surrounding the implant.

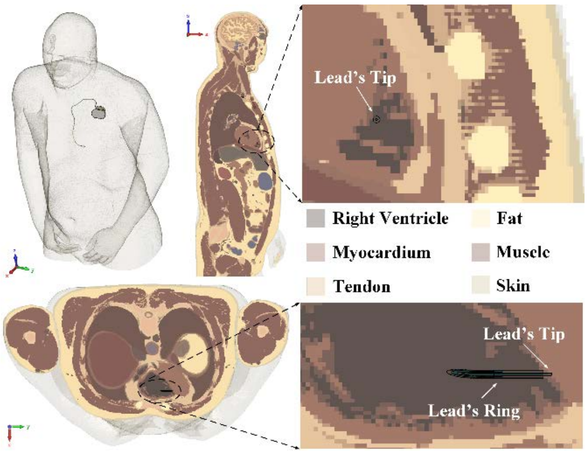

Fig. 5: Anatomically valid placement of the PM and PM's lead models within the numerical model AustinMan while considering the implantation in the right pectoral area.

Discussion

Several works of voxel model analysis and modifications in terms of organs, tissues, or even limbs alteration in volume, shape, or position [20–23]. However, to our knowledge, no work has been published related to the virtual insertion of a specific implant in the desired location within a voxel model. Due to the fact that an implant's virtual model must maintain anatomical constraints, this is a complex and time-consuming task.

The proposed software is a user-friendly, semi-automated, and powerful tool for tracking anatomical features in any segmented voxel model. Using the presented software tool, two human body models were analyzed to detect and register spatial coordinates of particular cardiovascular system parts. Although we used the PM's lead trajectory as an example, the proposed software tool could be used to calculate the trajectory of any leads, catheters, or stents within the cardiovascular system. In addition, it may be applicable for leads of other active medical implants, such as deep brain stimulators, spinal cord stimulators, gastric stimulators, etc. The spatial trajectory coordinates maintain anatomical realism and the voxel model global reference frame, thus eliminating the need for postprocessing alignment.

Because the PM's lead trajectory, typically found in the central veins, was chosen as an example, the implemented method's limitations are that it cannot handle vascular bifurcations or reverse the vessel's direction across vertical slices. However, this could be overcome by using more advanced image processing methods and decision-making techniques. Another shortcoming of the proposed software tool is that it was considered only one tissue type and tested on two available human phantoms.

Since the software tool is developed in the MATLAB environment, which features a wide user base, it could be further improved in terms of analysis of surface-based human body models or functional improvements. In future steps, we would implement methods to consider more tissues or organs to support creating more shape-complex virtual implants such as hip joint or knee joint replacement.

Conclusion

Anatomical human models are now being used to assess the health risks of various non-ionizing EMF sources with exponential growth. The evaluation of the safety of metallic implants, in particular, has become a popular research topic. However, it is time-consuming and challenging to virtually insert implants into these models while maintaining their anatomical constraints. The proposed software is a user-friendly, semi-automated, and powerful tool for tracking anatomical features in any segmented voxel model. The proposed software tool is capable of tracking anatomical features and identifying desired anatomical features within the human body using three and two-dimensional visualization. Any cardiovascular system component's path can be analyzed and processed to calculate implant lead trajectory. The spatial trajectory coordinates maintain anatomical realism and serve as an input for computer-aided design software tools to create numerical implant models concerning the voxel model global reference frame, eliminating the need for any postprocessing alignment.

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