OTOVIRT: An Image-Guided Workflow for Individualized Surgical Planning and Multiphysics Simulation in Cochlear Implant Patients

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Abstract. In this work, we present a workflow aimed to help ear, nose, and throat (ENT) surgeons in the planning and analysis of inner ear and cochlear implant (CI) surgical interventions. The proposed workflow, OTOVIRT, is based on a multi-modal image registration process with both computer tomography (CT) and magnetic resonance images (MRI) of the patient, followed by the segmentation of anatomical relevant structures. The volumetric images and the 3D anatomic models developed are then used to create virtual surgical simulations of the CI intervention. OTOVIRT modelling workflow proves to be an efficient pipeline to improve surgical outcomes and train surgeons' capabilities. Further advances in OTOVIRT workflow will hopefully allow multimodal data extraction and multiphysics simulation to be systematically conducted in daily clinical practice.

Keywords: 3D models · segmentation · multiphysic simulation

1 Introduction

Last few decades have seen significant improvements in the development of cochlear implants (CI). These devices are capable of converting acoustic stimuli into electrical signals by stimulating auditory nerve fibres through electrodes surgically inserted in the cochlea. CIs allow people with severe hearing loss to develop or regain hearing sensation [1,2].

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Regarding CI surgeries, specialists face high inter-subject variability due to the complex anatomical structures embedded within the temporal bone, such as the cochlea, the carotid or the facial nerve [1]. This makes CI surgery a difficult procedure that demands high levels of knowledge and training from ENT specialists [1–3]. The use of modern tools such as virtual reality, haptic feedback, robotics and high-fidelity simulators may prove useful tools to improve surgical performance while preserving patient safety [4–6].

CI virtual surgical simulators have increasingly gained the attention of researchers and ENT surgeons, with different proposals being published in the literature [3,4,7,8]. Most of these simulators are based on the manipulation of expensive synthetic tissues or corpses. Recent proposals also include computer-based solutions relying on virtual reality, haptic feedback, and 3D printing. However, new surgical simulation strategies that can be easily adapted to the clinical practice and systematically used by ENT surgeons are still needed [4].

In this work, a harmonized 3D modeling workflow for realistic virtual simulation of CI surgeries (OTOVIRT) has been designed and implemented. The objective is to provide both novel and specialized surgeons with a modelling and simulation workflow to train and improve surgical capabilities and outcomes while preserving patient safety. We are focused on developing a cost-effective, open and easy-to-use modeling tool to help ENT surgeons in the training and execution of CI surgeries. In this sense, an open-access plugin developed in 3D Slicer will be made available for the community, which can also be used as a part of a more complete multiphysics modeling framework to predict electric field and current distribution in the cochlea and head tissues due to CI stimulation.

The paper is organized as follows: Sect. 2 describes the methods followed for the design and implementation of the OTOVIRT modelling worfklow. Section 3 presents the results obatined for different anatomical models derived from patients medical data using OTOVIRT. Section 4 discusses the results and highlights future improvements of the OTOVIRT pipeline.

2 Material and Methods

Figure 1 shows the OTOVIRT modelling workflow designed. First, a multimodal 3D image registration process is performed based on a CT image of the temporal bone and a full-head MRI. The Landmark Registration module of the open-source 3D-Slicer (https://www.slicer.org/) platform is used to align both images. Subsequently, realistic 3D-anatomical models are obtained using a customized 3D-Slicer module specifically designed for the semi-automatic segmentation of the cochlea and other internal ear structures, including the semicircular canals, carotid artery, sigmoid sinus, internal jugular vein, and facial nerve. Finally, a virtual surgery simulation is carried out in Blender software (https://www.blender.org/) and integrated into the OTOVIRT modelling workflow in order to provide ENT surgeons with more realistic surgical scenarios. In addition, a full-head volume mesh suitable for finite-element-method (FEM), with all internal structures embedded, can be generated for multiphysics simulation.

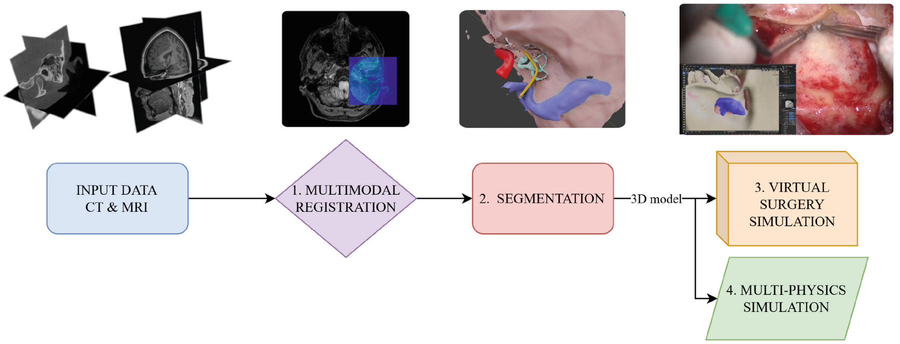


Fig. 1. OTOVIRT modelling workflow. The input data for the OTOVIRT pipeline is an inner-ear CT scan and a full-head MRI. 1) Both CT and MR images are registered and subsequently aligned. 2) A customized 3D-Slicer plugin is used to segment different tissues and create a realistic 3D anatomical model of the inner ear structures. Head tissues are automatically segmented based on SimNIBS software 3) A virtual surgery simulation is conducted in Blender. 4) Finally, a volume mesh suitable for FEM multiphysics analysis can also be obtained from the models.

2.1 Multi-modal Image Registration

Combining structures obtained from different medical images requires a multi-modal registration and co-alignment [9]. In addition, notice that different field of views are supported in our case, with a full-head MRI and a CT scan that only covers the temporal bone. To align both images, the Landmark Registration module of 3D-Slicer is used in the OTOVIRT pipeline. In this module, the user manually places a series of landmarks that are subsequently overlapped using a rigid transformation. The landmarks used in this study were the superior and inferior sections of the cochlea and the semicircular canals, which can be clearly seen in both CT and MR images.

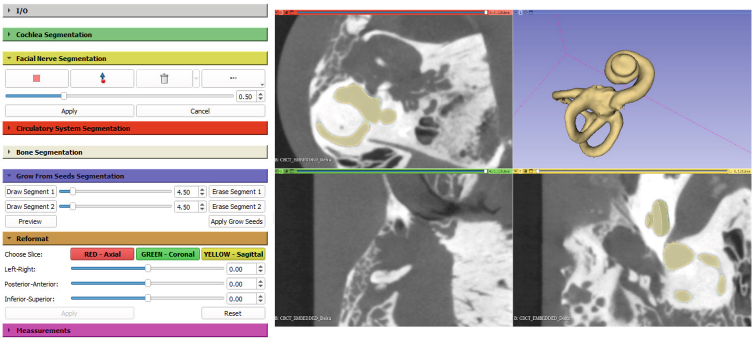
2.2 Segmentation

Semi-automatic Segmentation of the Inner Ear: The segmentation of the inner ear is carried out through a customized plugin coded in 3D Slicer (Fig. 2). It contains a main view with separated sections or tabs to segment each relevant anatomical structure.

The module has been designed to contain the following sections:

- Cochlea segmentation: A simple algorithm is used to segment the cochlea with the use of a bounding box placed by the user in the region of interest (ROI). First, a threshold-based simulation is performed to retain the cochlear bony structures. Second, a morphological opening operation is used to disconnect the cochlea from other spurious elements. Finally, a connectivity-based segmentation is applied to remove these elements.

- Facial nerve segmentation: this tool requires the definition of a series of landmarks, within which a tubular model is interpolated, thus emulating the anatomical profile of the facial nerve.
- Circulatory system segmentation: Similar to the facial nerve simulation tool, the tubular segments are created based on carotid size.
- Bone segmentation: this section uses a two-step threshold segmentation. The first threshold is used to segment the outer contour. With the second threshold, the inner trabeculae is limited to the outer volume.



0.50

Draw Segment 1: 4.50

Draw Segment 2: 4.50

Choose Slice:

Left-Right: 0.00

Posterior-Anterior: 0.00

Inferior-Superior: 0.00

Fig. 2. View of the 3D-Slicer segmentation plugin implemented for the semi-automatic segmentation of inner ear structures.

- Grow from Seeds Segmentation: this is a multi-purpose segmentation tool for complex and irregular anatomical structures, such as the incus, malleus and staples. This section incorporates a set of macros to define inclusion and exclusion criteria of the seeds for a more intuitive and straightforward delimitation of the ROI.
- Reformat: this section includes sliders to rotate the anatomical axes of the volumetric images. This allows the user to observe structures such as the cochlea in real magnitude.
- Measurements: this tool measures relevant data and metrics such as volume segmentation, centroids, roundness, flatness, elongation, principal axes and moments, among others.

Once the segmentation is performed, voxel volume models of the anatomical structures are obtained, which can be later used for the virtual surgical simulation.

Automatic Segmentation of the Full Head: The software selected to segment brain tissues was SimNIBS 3.2.4. From T1 and T2 MRI scans of a patient's head, SimNIBS can automatically generate a range of head structures [10], with greater accuracy in brain tissues [11]. The tissues generated by SimNIBS are: grey matter (GM), white matter (WM), cerebrospinal fluid (CSF), skull (bone), skin, eyes, sinuses, ventricles, and air cavities. SimNIBS uses SPM12 (https://www.fil.ion.ucl.ac.uk//spm/software/spm12/) and CAT12 software (https://neuro-jena.github.io/cat/) for the segmentation [12]. While SPM12 is responsible for modelling tissues based on voxel intensity, CAT12 uses a full segmentation approach to improve surface models such as GM [13].

The main advantange of using SimNIBS as a part of the OTOVIRT modelling workflow is that it provides the user with cleaned and non-intersecting models of head tissues, which are specially useful when creating a non-manifold assembly and a volume mesh suitable for FEM multiphysics simulations.

2.3 Virtual Surgery Simulation

The virtual surgery simulation tool developed in the OTOVIRT pipeline is based on Blender software, which includes: i) a versatile main view that facilitates precise translation and rotation of generated models in space, ii) a data loading tool which automatically assigns a colour and an identifier to each segmented structure, iii) a set of modelling tools to emulate the procedure as closely as possible to the real intervention.

This way, a simulation of a masteidoctomy based on the milling of the temporal bone is performed in Blender. This can be achieved by using a set of tools that mimic a surgical drill. The interaction with the 3D models can be configured in many ways according to size, shape, strength, stroke delay, stroke jitter, among others.

2.4 Multiphysics Simulation

In addition, once the 3D models are obtained, multiphysics simulations can be performed in order to predict the magnitude and distribution of electric fields and currents flowing through a patient's cochlea, as well as extracochlearly through head tissues, depending on different CI stimulation modes. To do that, a non-manifold assembly based on the 3D surface tissue models obtained with OTOVIRT pipeline is created, from which a tetrahedral volume mesh suitable for FEM analyses is subsequently processed. The volume meshes are finally imported into Comsol Multyphyisics software (https://www.comsol.com/comsol-multiphysics) where the physics of the problem, in this case through Laplace equation, is solved to obtain the voltage distribution across each tissue domain. These models can help us better understand the effect of different stimulation strategies on predicted current distribution, in order to optimize and personalize novel CI stimulation modes.

3 Results

Our results include various 3D anatomical models of the temporal bone and head tissues derived from the OTOVIRT pipeline using patient-specific image data and different CT modalities (see Fig. 3).

Each CT type allows for the visualization of different structures within the cochlea and the temporal bone with varying levels of detail, depending on their spatial resolution. For instance, internal structures of the cochlea such as the *scala timpani* and *scala vestibuli* are only visible in μCT.

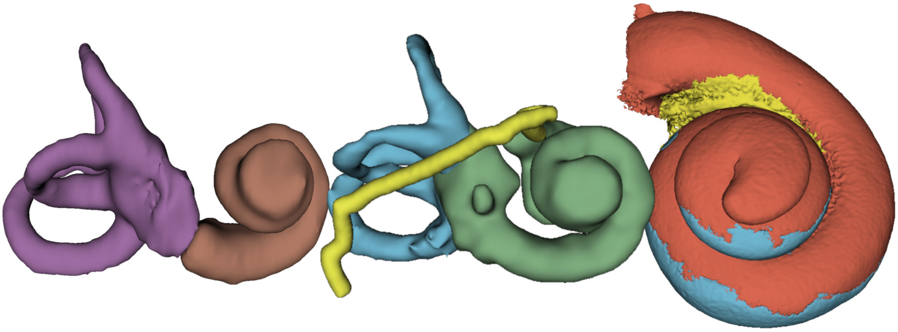


Fig. 3. Comparison of the models obtained from different types of CT scans. Left: cochleovestibular system segmented from a conventional CT scan used in the clinics. Center: CBCT. Right: MicroCT (μCT).

Figure 4 shows an example of a 3D model containing the temporal bone and ear structures. It must be highlighted that this figure emulates a common procedure in CI surgery: a mastoidectomy. It consists in the drilling of the temporal bone in the region beneath the ear pavilion, within the mastoid bone. The surgeon removes irregular bone cells filled with air in order to create the space needed to insert the CI electrode array. Virtual-based simulations were performed in Blender prior to surgery. A virtual mastoidectomy was performed using the sculpting tools in Blender, thus realistically simulating the use of a surgical drill.

To validate the accuracy of the models obtained, various objective volumetric measurements, such as cochlear volume and size, distances A and B, cochlear duct and basal-turn length, were calculated, among others. Table 1 exemplifies a set of relevant morphological data obtained for the pre-operative analysis in a group of patients at different ages, including both adult and children subsets. Through these measures, the required length of the CI electrode array can be estimated based on individual cochlear morphology. This is a relevant clinical parameter which has been reported to be related to clinical post-surgery performance and CI intelligibility measures.

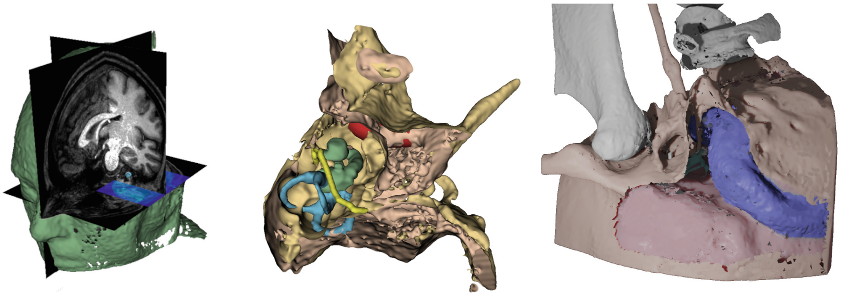


Fig. 4. Left (3DSlicer): 3D model of the head combining a full-head MRI and a CT. Center (3D Slicer) and right (Blender): 3D combined model after a virtual mastoidectomy.

Table 1. A set of features obtained from the 3D models using the Measurements tab of the 3D Slicer plugin developed in this work. A comparison of metrics between young and adult patients is shown. (SD: standard deviation; CDL: cochlear duct length; 2TL: two-turn length; BTL: basal-turn length).

	Adults (> 18 years)		Early Children (< 12 months)	
	mean	SD	mean	SD
Distance A (mm)	9.04	0.37	9.35	0.54
Distance B (mm)	6.70	0.52	7.01	0.43
CDL(lw) (mm)	36.35	1.51	37.59	1.34
2TL(lw) (mm)	33.00	1.38	34.12	1.40
BTL(lw) (mm)	21.97	0.92	22.72	1.07
Cochlear volume (mm^3)	73.57	8.02	69.61	10.45
Temporal volume (mm^3)	45,169.79	1,203.56	10,449.96	456.34

Finally, Fig. 5 shows an example of a multiphyisics simulation in which the 3D models were used to obtain a volume mesh suitable for FEM analysis. Electric field and current spread were computed for two different CI stimulation modes: monopolar and bipolar. This simulation allowed us to predict the different extension of current spread through the complete head for these two stimulation modes. As seen in Fig. 5, while monopolar leads to a higher spread of the current through the scalp and the head, the bipolar mode confines more of the electric current into the region near the cochlea. Therefore, through realistic full head models of the head and inner ear tissues a prediction of both intracochlear and extracochlear voltages and current spread can be obtained in a specific-subject manner, thus paving the way towards the optimization and personalization of CI stimulation strategies and electrode array designs.

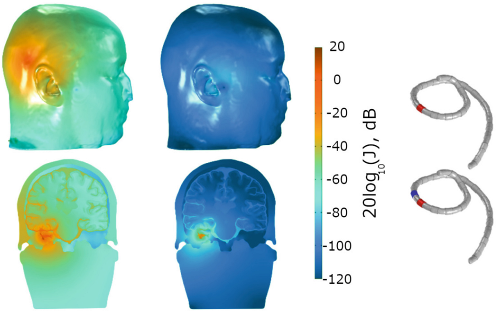


Fig. 5. Current spread through head tissues based on multiphysics simulation for two different CI stimulation modes: monopolar and bipolar.

4 Discussion and Future Work

Conventional CT images of the temporal bone and the proposed OTOVIRT workflow allowed ENT surgeons to easily and intuitively visualize the anatomy of the patient prior to surgery. Virtual modeling surgical tools prove relevant and useful in the training of both novel and specialized surgeons as well as in the planning, optimization, and customization of ENT surgical approaches. The accuracy of the models generated with OTOVIRT was validated subjectively with the help of ENT specialized surgeons and anatomists using a customized questionnaire. The proposed workflow proves to be an useful and intuitive tool to improve the understanding of the anatomy of the patient as well as to optimize surgical planning. The simulation of the intervention showed to be useful for surgeons who improved their knowledge of the subject-specific anatomical region before the procedure. Providing them with the simulated model on a portable device during the actual surgery also proved to be beneficial. However, a more comprehensive and quantitative validation of the accuracy of the OTOVIRT workflow is still needed.

The pipeline was tested in a limited group of seven patients. As future work, we will validate the modelling processes with more patients and surgeon experts in order to systematize and generalize the workflow into the daily clinical practice. This will allow for a systematic preoperative planning that will hopefully improve patient safety and surgical outcomes. More experienced ENT surgeons will be able to process the data faster with the proposed workflow and will have a greater chance to analyze the optimal path for the surgery.

The 3D Slicer plugin developed in this work can also be used to gather individual metrics during preoperative phases and further quantify inter-individual differences in CI patients. Further analysis based on anatomical surgical parameters can be made to predict CI outcomes, e.g., based on characteristics such as electrode depth insertion, type of intervention, etc.

Furthermore, the OTOVIRT pipeline has been shown to be independent of image-type acquisition and has been tested and validated with standard clinical

CT, cone-beam CT, and micro-CT images (Fig. 5). Therefore, its application may provide a multi-purpose tool with high impact in generating large datasets that will help developing automatic methodologies to simplify CI surgeries.

The use of open-source and widely available software and technologies proves possible, efficient in cost and development time. This facilitates the diffusion and provides a solid substrate on which to continue the integration of new tools that complement the workflow in an efficient and targeted manner.

In the future, with the development of artificial intelligence (AI) neural networks and deep learning algorithms, the entire workflow may be a fully automatized process, with validations tools more widely available.

A further step forward will be using the OTOVIRT pipeline to sistematically perform multiphysics simulations, including other modeled tissue data, which will allow us to quantify current spread over the head and optimize CI stimulation strategies in an individual manner.

5 Conclusion

OTOVIRT worflow has been designed and implemented in this work. Its validation with patient-specific image data has proven to be succesful, and provide surgeons with an affordable and easy-to-use pipeline to train surgical capabilities and improve surgical outcomes while preserving patient safety. The proposed OTOVIRT pipeline paves the way for further multimodal analysis and personalized multiphysics simulation to better understand current spread under different cochlear implant stimulation strategies.

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