Patient Specific Simulation for Planning of Cochlear Implantation Surgery

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Abstract. Cochlear implantation is a surgical procedure that can restore the hearing capabilities to patients with severe or complete functional loss. However, the level of restoration varies highly between subjects and depends on patient-specific factors. This paper presents a software application for planning cochlear implantation procedures that includes patient-specific anatomy estimation using high resolution models, implant optimization for patient-specific implant selection, simulation of mechanical and electrical properties of the implant as well as clinical reporting.

Keywords: Cochlear implant · Patient specific · Simulation · Planning

1 Introduction

A Cochlear Implant (CI) is a sound-to-electrical transducer device that can restore hearing to patients suffering hearing impairment, a condition affecting over 24 % of the population worldwide [12]. Cochlear Implants consist of a speech processor which performs filtering of the audio signal to improve the hearing of specific frequencies, and a sub-cutaneous transductor and an Electrode Array (EA) that is inserted into the cochlea and can stimulate the auditory nerve fibers, bypassing the damaged hair cells (Fig. 1).

Cochlear implantation surgery requires to gain access to the inner ear, to make the cochlea accessible, by drilling the temporal bone behind the ear. The target structure is small and the access through the middle ear is close to delicate

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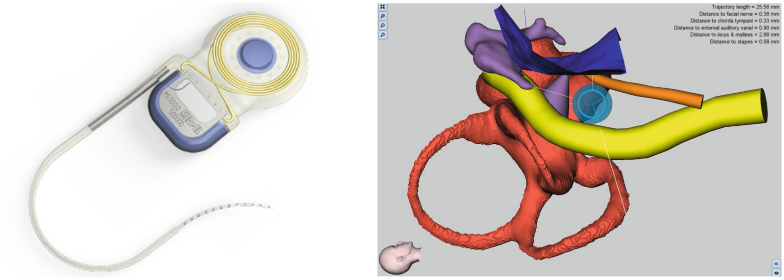

Fig. 1. (Left: Sub-cutaneal part of the cochlear implant with the transductor and electrode array. Right: Segmentation of structures of the middle and inner ear: Cochlea and semicircular canals (red) ossicles (purple), external auditory canal (blue), facial nerve (yellow) and chorda timpany (orange) (Color figure online).

structures such as the ossicles, chorda tympani and facial nerve. Careful planning of the access path considering the risk areas, is the element that decides if the electrode insertion will be performed through the membrane that covers the round window of the cochlea or through a hole drilled into the cochlea (cochleostomy). In this complex scenario, a planning software can help the surgeon to estimate the risks of the intervention and choose the best approach. Extreme care has to be taken during the insertion of the electrode array inside the cochlea. The depth and angle of insertion has to be the adequate to provide improved hearing without jeopardizing residual hearing capabilities. This is because the cochlear inner structures are delicate, and can be damaged easily by an incorrect insertion procedure. It follows that the specific anatomical variability of the cochlea of the patient plays an important role in the optimal insertion angle and depth. But the traditional Computerized Tomography (CT) or Cone Beam CT (CBCT) acquired prior to the surgery procedure cannot provide the surgeon with sufficient shape information given that the resolution of the current devices is not high enough to capture the small structures of the cochlea.

In this paper we present a software for planning electrode array insertion, that enriches conventional imaging based planning with data coming from high resolution models adapted to the patient specific anatomy. The rest of the paper is organized as follows: Sect. 2 describes the overall infrastructure of the software. Section 3 describes the modules and methods used by the application. Section 4 includes final remarks and future work.

2 Software Description

The outcome of the surgical procedure depends among other factors on the correct position of the CI's electrode array inside the cochlea and the depth of the insertion. However, conventional preoperative CT does not provide enough resolution to perform detailed analysis or simulations. High resolution models are needed to better evaluate the outcome of the procedure. The application presented herein is designed to provide surgeons with insight of what happens inside the cochlea when the electrode is inserted.

By combining high resolution models with patient-specific information, we can use several analysis tools that would be difficult to use with the low resolution pre-clinical data. Out application closes the gap between the clinical planning stage and advanced high resolution tools applied to the electrode insertion stage. This is achieved following a workflow (Fig. 2) of tasks that starts with the patient's pre-clinical images and ends with cochlea response simulations after the implantation procedure.

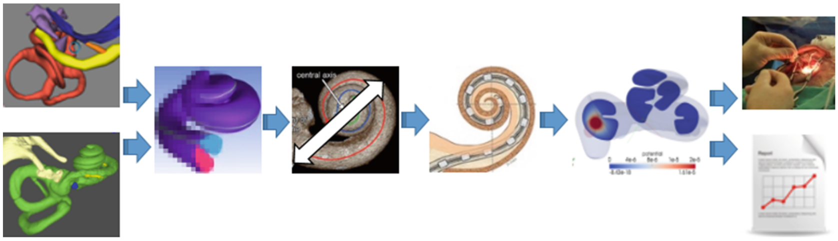

Fig. 2. Workflow of the software. From left to right: segmented structures and high resolution Statistical Shape Model as input. Patient-specific high resolution fitting. Cochlea Characterization, virtual insertion, electrical simulation, and finally, surgery and reporting.

The software runs on top of solid proven open source technologies as shown in Fig. 3. It is designed to be agnostic of operating system so it is compatible with the most popular operating systems. The Visualization Toolkit (VTK) is used as main graphical library. Qt and the Common Toolkit (CTK) are the basis of the User Interface. The communication with the clinical planning software [5] is performed using XML files defining the CT/CBCT and the segmented structures, as well as the planned path, safety volumes and any other patient relevant data.

3 Modular Structure

The software is comprised of different modules (Fig. 3) that provide individual information: patient specific high resolution anatomy model, cochlear characterization, virtual electrode insertion, electrical simulation and reporting.

3.1 Patient Specific Anatomy Model

To improve visualization and allow a more detailed modeling, a Statistical Shape Model (SSM) has been built using 17 microCT (μCT) samples of cadaveric temporal bone [7] obtained with Scanco Medical AG microCT-100 at 24 micron resolution. The inner ear structures were segmented semi-automatically using

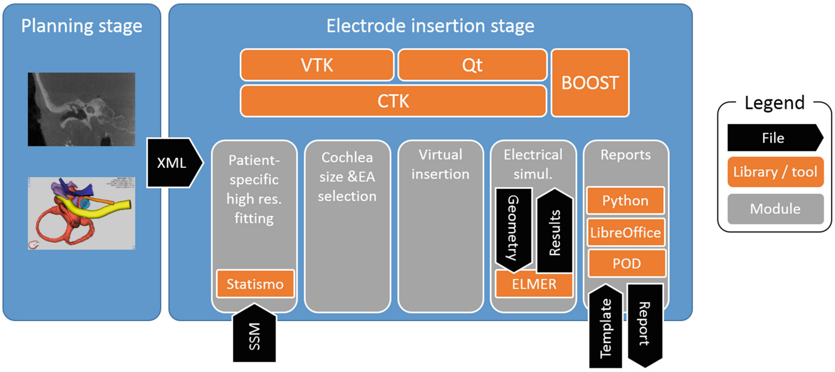

Fig. 3. Overview of the application structure, showing its modular structure as well as its software elements.

ITK-SNAP [13] and Seg3D2 [2]. The mesh resulting of the segmentations were post-processed using Markov Random Field Surface Reconstruction [10]. The datasets were registered (using Elastix [8]) to a image chosen as a reference. The transformation was applied to the reference segmentation so obtain the individual datasets with point correspondence. The SSM was built using the Statismo [9] software package. An Active Shape Model (ASM) is used to fit the high resolution model to the pre-clinical CT. The software allows inspection and generation of the SSM space through generation of specific samples (Fig. 4).

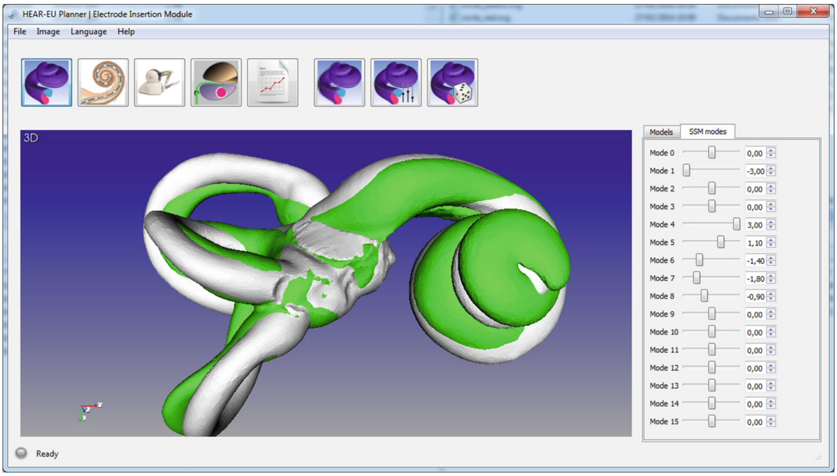

Fig. 4. Cochlear SSM loaded in the software. The mean shape of the SSM is displayed in white. Patient specific models can be generated according to the low resolution anatomy.

3.2 Cochlear Characterization

Measuring the cochlear size and shape is the first step to a correct electrode implant. The length of the cochlear duct, and the patient specific hearing impairment are key information to select the best fitting EA. The length of the unrolled cochlea has been extensively studied, and literature reports a 40 % variability with cochlear length ranging from 25 to 36 mm [6]. The final maximum insertion depth of the cochlear implant EA correlates with the diameter of the cochlea in the basal turn plane measured from the round window to the distal lateral wall [3]. This, in turn, enables the selection of the ideal electrode array from the portfolio of electrode array types that are integrated in the application (Fig. 5).

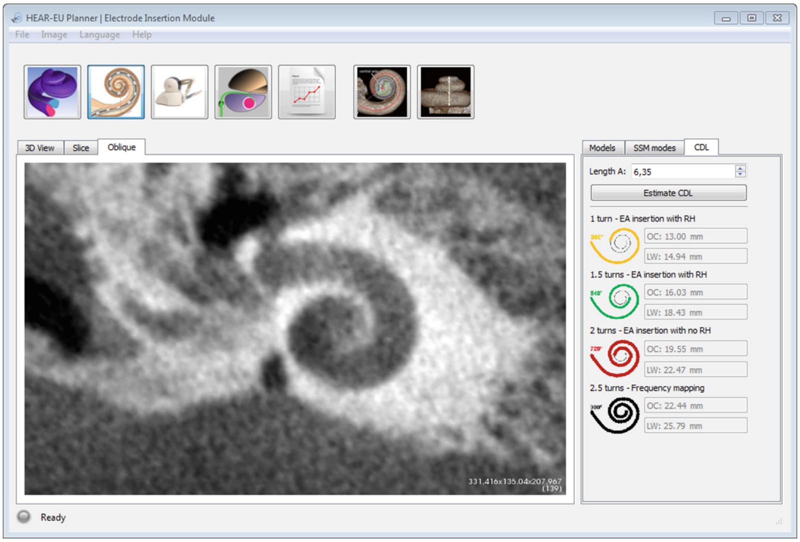

Fig. 5. Using the measurement from the diameter of the cochlea at the basal turn, the application estimates the unrolled length of the cochlea, and the different insertion depths of the electrode array.

3.3 Virtual Insertion

Once we have the patient's specific shape and a suitable electrode array has been selected, we can simulate the expected activation patterns of the implant. The last element needed for the simulation is to set the (virtual) position of the electrode array inside of the scala tympani, the chamber of the cochlea where the electrode is placed. An iterative method is used to compute the trajectory of a free-fitting electrode array, given the insertion point and direction. At each iteration the position and direction of the electrode tip with respect to the scala tympani is evaluated, ensuring that the tip proceeds tangentially and its distance from the wall is at least equal to the array radius. At each step the angle of impact to the wall and the margin between the cochlear implant array and the cochlear walls are evaluated too, providing an indirect measure of pressure against the wall. The iteration can stop prematurely if the electrode does not fit in the scala tympani dimensions or if it is subjected to excessive bending (Fig. 6).

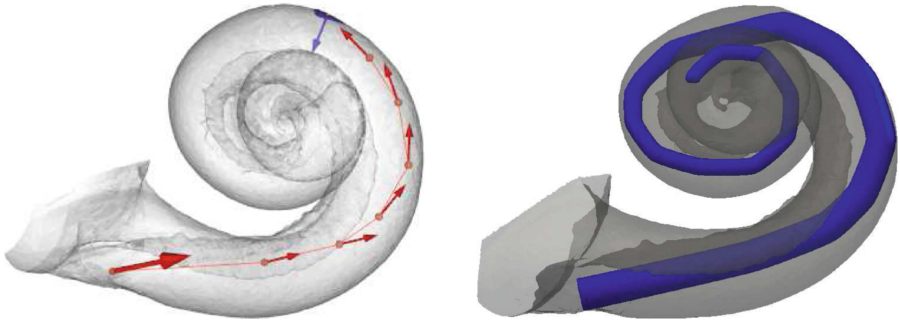

Fig. 6. Virtual insertion. Left: At each step of the insertion simulation, the tip position respect to the wall is evaluated and the direction is adjusted in order to lie tangentially to the wall. Right: Simulated electrode insertion. The final trajectory of the electrode is tangential to the scala tympani wall.

3.4 Electrical Simulations

The placed electrode is the last required step to perform the electrode simulations [1]. The simulation is performed using the multiphysics Finite Element Method (FEM) open source solver software ELMER [11]. In its current stage, the software can simulate bipolar simulation protocols (Fig. 7, left), where one electrode emits electrical current and the other is set to ground. Simulations also include modelizations of the electrical properties of nerve the fibers that start at the organ of Corti in the basilar membrane and form the auditory nerve, using the Generalized Schwarz-Eikhof-Frijns (GSEF) model [4] (Fig. 7, right).

3.5 Reporting

During the planning process, the operator has the option to save screenshots, possibly annotated with relevant information. After the process, the commented screenshots, along with the patient's clinical data, a Portable Document Format (PDF) report is generated for clinicians to review. The generation of the report employs the open source LibreOffice engine and POD (Python Open Document)[1] library to generate the report. For the generation of the reports with these technologies, a series of document templates are created that include embedded

[1] http://appyframework.org/pod.html.

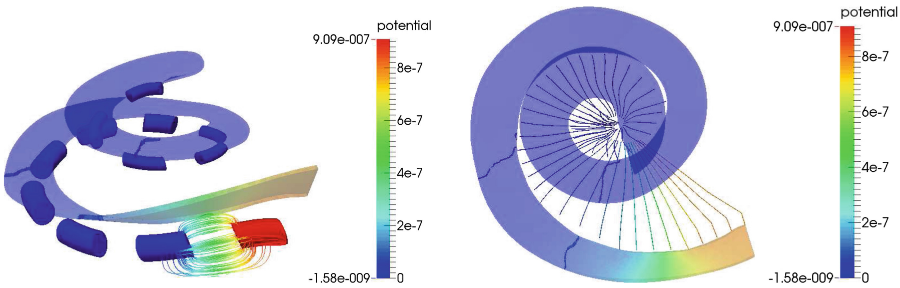

Fig. 7. Visualization of the simulation results. The basilar membrane has been rendered semitransparent for ease of visualization. Left: bipolar stimulation protocol of first two electrodes. Right: Nerve fiber stimulation after electrode activation pattern

Python code inserted into the document structure. The templates are post-processed using a Python script that can execute the embedded Python code and perform the adequate substitution of the variables. These variables include patient information and user generated screenshots and captions (Fig. 8).

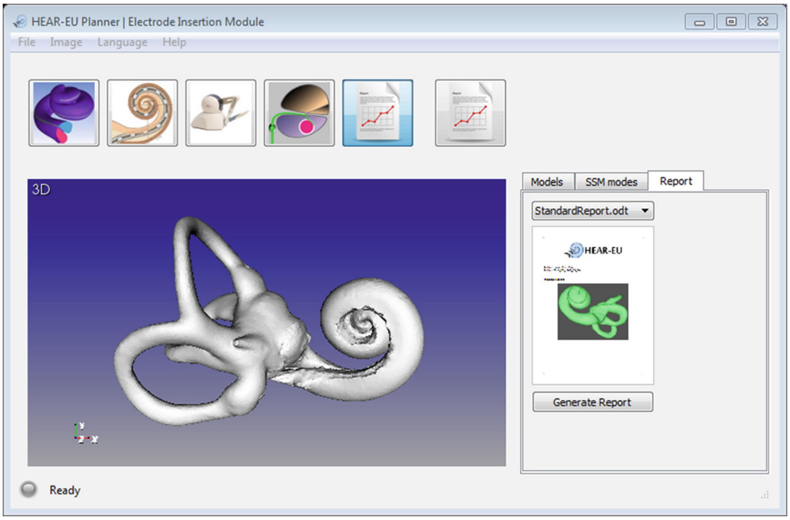

Fig. 8. Report generation interface.

4 Conclusions and Future Work

We have presented a software for the estimation of the patient specific inner ear and intra-cochlear anatomy, the planning and simulation of both the electrode insertion procedure, and the outcome of the surgery to the hearing capabilities for the patient. The software represents also a tool for the selection of the best electrode array for the patient and the reporting of the surgical procedure, making it a helping tool in the clinical practice. While the software is still evolving, it represents a collaborative effort in integrating many medical imaging tools, bringing the pre-surgery planning to a new level of information analysis.

Future work includes additional integration with more electrode models and tools from the electrode manufacturer, improvements on the virtual insertion phase using real-time simulation, and validation of the electrical simulations using audiometric tests are some of the future tasks planned for the software.

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