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Surgical planning for minimally invasive cochlear implantation: landmark based approach

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Introduction

Minimally invasive cochlear implantation aims to insert the electrode array in a specific lumen of the cochlea, the scala tympani. Correct planning in image-guided interventions relies on an accurate representation of the anatomy. However, clinically applicable imaging modalities do not provide sufficient resolution for direct detection of the scala tympani (Fig 1).

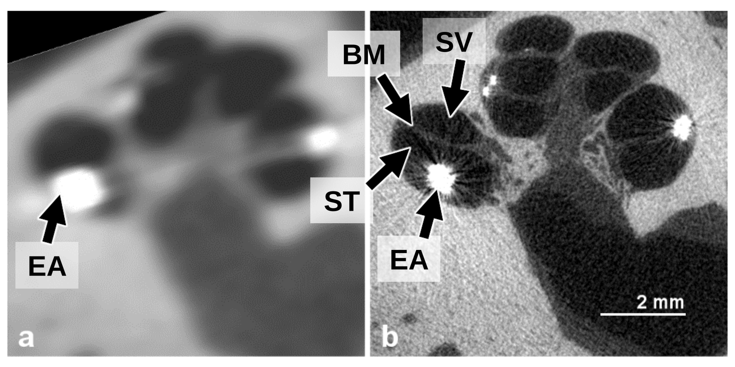

Figure 1: Axial slice of a human cochlea with implanted electrode array (EA) in 2 different imaging modalities [1]. ***(a)*** *Cone-beam CT (130 μm resolution) is clinically applicable, but intracochlear structures cannot be identified.* ***(b)*** *Micro-CT (18 μm resolution) provides sufficient resolution for the visualization of the basilar membrane (BM), which separates the scala tympani (ST) from scala vestibuli (SV), but is limited to ex vivo examinations.*

For this reason, a landmark based planning procedure was introduced. The method approximates the position of the scala tympani and can be used with conventional clinical CT data. The objective of this work is to assess the approximation error and to validate the implantation outcome using in vitro experiments.

Materials and Methods

Landmark based planning procedure

The planning procedure starts with the identification of common landmarks of the human cochlea. A local cochlear coordinate system is generated, and the position of the basilar membrane is approximated by a plane intersecting the basal turn of the cochlea (blue line in Fig 2).

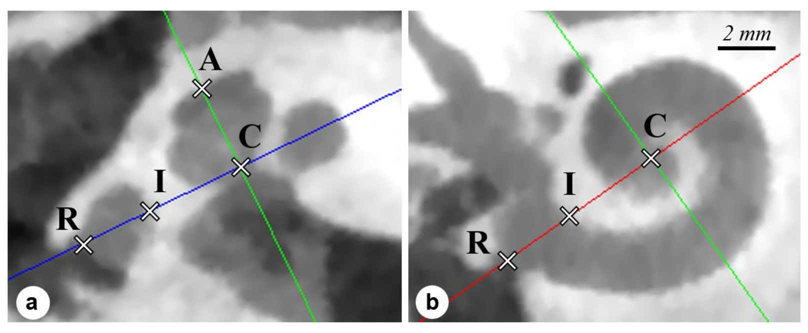

Figure 2: Landmark identification of a right human cochlea using cone-beam CT.
Axial ***(a)*** *and coronal* ***(b)*** *slices showing the round window center (R), the inner wall border (I), the center of the modiolus in the basal turn (C), and the apical center of the modiolus (A).*

The cochlea is segmented and a surface model is generated. Using the coordinate system, the surfaced model is truncated to the first half of the scala tympani. An automatic algorithm is used to find the optimal insertion trajectories by following the center line of the scala tympani (Fig 3).

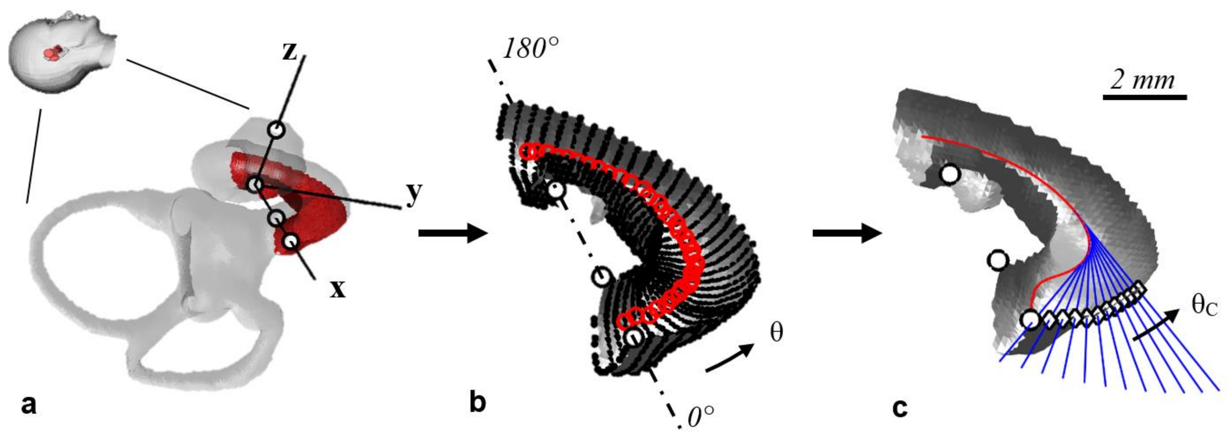

Figure 3: Insertion trajectory computation.
(a) *The surface model of the cochlea is truncated to approximate the location of the first half turn of the scala tympani.* ***(b)*** *Radial cross-sections and the center of gravity (red circles) are estimated starting at the round window.* ***(c)*** *The centroid line (red) is fitted with the data points, representing the mid-scala course. For a specified range, the tangents of the centroid line are computed, defining the optimal insertion trajectories. Implemented in Matlab (The MathWorks, Natick, USA).*

Evaluation of the approximation error

Five human cochleae were segmented using cone-beam CT and corresponding micro-CT scans. Image registration was performed with a surface alignment algorithm. A spline was generated following the course of the basilar membrane. Finally, the displacement error between the actual and the approximated position was measured (Fig 4).

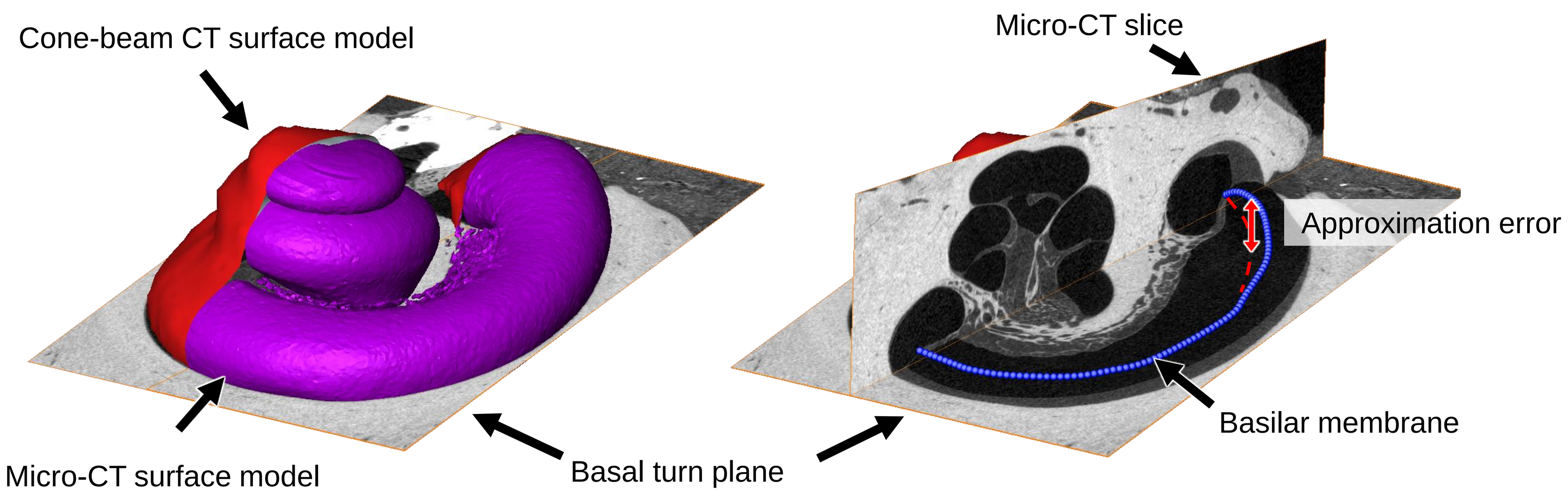

Figure 4: Approximation error evaluation.
The cone-beam CT and micro-CT surface models of the cochlea were aligned. The approximation error was measured as the distance between the actual position of the basilar membrane (as found in micro-CT slices), and the basal turn plane.

In vitro implantation study

The planning method was validated in a human whole head cadaver model (a total of 10 implantations). Based on the computed targets and insertion trajectories, a minimally invasive access was drilled with an image-guided robotic system [2,3]. Cochlear implant electrode arrays were inserted and postoperative scans were performed to assess the position of the implanted electrode array.

Results

Approximation error

An overall mean error of 0.23 mm was found between the approximated and the actual position of the basilar membrane. In the region used for trajectory computation (i.e. from 45 to 60 degrees) an average error of 0.22 mm was measured. A positive displacement error was observed over the whole first half of the basal turn, which indicates that the algorithm underestimates the extent of the scala tympani (Fig 5).

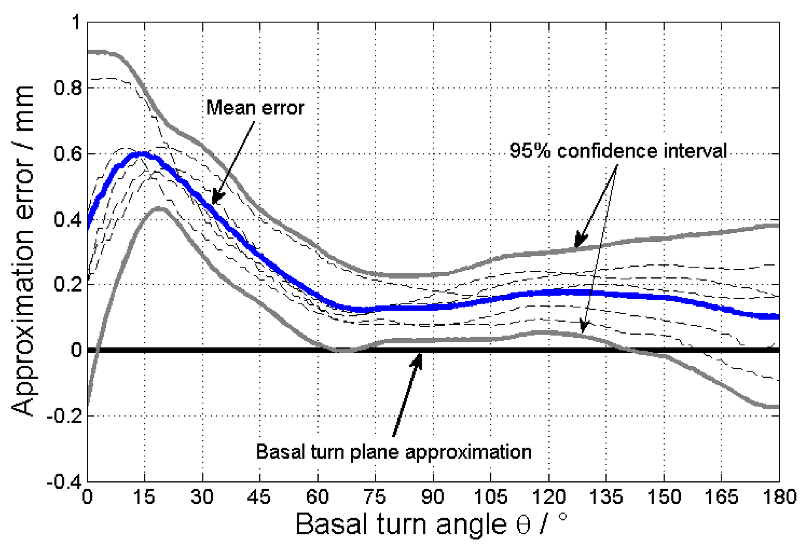

Figure 5: Approximation error results.
The distance between the approximated position of the basilar membrane (as computed with the landmark based approach) and its actual position in the corresponding micro-CT data of 5 human cochleae is shown. An average error of 0.22 mm was observed in the region used for insertion trajectory computation (i.e. 45 to 60 degrees).

Implantation outcome

Electrode insertion was feasible after robotic access drilling in all cases. Postoperative radiological examination showed 9 of 10 cases of complete placement into scala tympani and 1 case of scala vestibuli insertion caused by a target drilling error of 0.79 mm (Fig 6). This drilling error occurred because of the usage of broken fiducial screws required for patient-to-image registration of the robotic system.

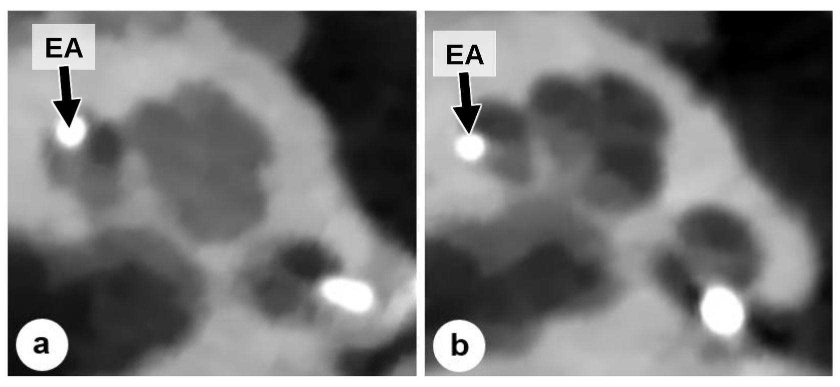

Figure 6: Postoperative radiological evaluation.
Two cases of the insertion outcome in axial cone-beam CT slices are shown. ***(a)*** *Left cochlea with scala vestibuli insertion caused by a target drilling error of 0.79 mm orientated anteriorly.* ***(b)*** *Complete scala tympani insertion in a left cochlea.*

Conclusion

In this work, a landmark based approach for scala tympani target and trajectory planning was presented. The method is applicable to clinical imaging modalities. In vitro experiments show that the landmark based approach enables for scala tympani target and trajectory planning with sufficient accuracy (approximation error < 0.5 mm). Although the method uses manual landmark selection and segmentation of the cochlea, targets can be planned in reasonable time (15 min).

References

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