Electrical impedance sensing to preserve the facial nerve during image-guided robotic cochlear implantation

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Keywords Electrical impedance · Facial nerve · Robotic · Cochlear implantation

Purpose

In image-guided robotic cochlear implantation (CI) the surgeon relies on a highly accurate image-guidance system (accuracy < 0.2 mm) to drill a ~ 1.5 mm tunnel from the surface of the mastoid to the cochlea [1]. The drilling path may pass at distances as low as 0.2 mm to the facial nerve (FN), the most critical structure that needs to be preserved during cochlear implantation. In order to ensure the integrity of the FN, an image-guidance system for minimally invasive CI requires intraoperative safety measures independent from navigation. Currently a number of methods are proposed to enhance facial nerve safety during robotic CI including a redundant tool positioning algorithm based on correlations between drilling forces and bone density profiles [2], a neuromonitoring approach through the facial recess combining monopolar and bipolar measurements [3] and intra-operative imaging. The combination of these methods is expected to enable a more reliable measure of facial nerve safety, however additional or redundant safety methods may be useful to reduce uncertainty. Electrical impedance sensing has been proposed [4], [5] as a reliable approach to detect unsafe tool positioning during pedicle screw insertion. This technique is capable of detecting a transition between tissues with different electrical impedance (e.g. cancellous, cortical and soft tissue). Differences in electrical impedances among tissues is related to deviations in water contents amongst them. The facial nerve is surrounded by the fallopian canal, which has a much higher density than the nerve tissue itself. The ultimate goal of this study is to analyze feasibility of using electrical impedance to detect an unsafe trajectory during robotic CI. We hypothesize that changes in electrical impedance in the facial recess region correlate with variations in bone density profiles. If this hypothesis is positive, electrical impedance measurement could enhance the robustness and reliability of a safety network for robotic CI.

Methods

Electrical impedance is defined as the opposition of a volumetric medium to charge flow. It can be measured applying an alternate current (AC) through two electrodes covering the volume of interest and measuring the voltage drop between them. Resistance in a uniform conductor of length L and cross sectional area A is defined as

$$R = \text{rho } L/A \text{ (ohm)}$$

Resistance depends on the specific resistivity (rho) of the conductive material. The properties of bony tissue can be quantified from computer tomography (CT) measurements, whereby Hounsfield units (HU) are the standard units used for tissue density classifications in the human body. The mastoid presents variable densities in anisotropic distribution, mostly a combination of cancellous and cortical bone areas as well as the existence of air cells (1–2 mm spherical air filled cavities), and large variances among patients can be observed.

To determine if changes in electrical impedance in the facial recess region correlate with variations in bone density profiles, electrical measurements were made using a multi-electrode probe during a live animal study in sheep (Bernese cantonal animal commission, approval number 57/12). The measuring probe (1.8 mm Ø) had a working electrode (conical shape, r = 0.3 mm) at the tip, and three possible counter electrodes (rings) at distances d = 2, 4 and 7 mm from the tip. A needle electrode located in the ipsilateral mastoid surface enabled a fourth counter electrode configuration of the probe. A configurable system (MP150 and Stmisola, Biopac, USA) was used to measure electrical impedance by applying a current sinewave signal between each working and counter electrode configuration. In each of n = 5 animals, an image-guide CI robotic system and protocol [1] was applied to accurately drill up to 4 trajectories relative to the facial nerve. Per drilled tunnel, five measurement points were taken at controlled facial nerve distances, and at each point electrical impedance was measured at a frequency of 1 kHz and with an amplitude below 0.1 mA. Per trajectory and per electrode configuration, the cross-correlation between normalized impedance and normalized density values was evaluated. To determine the goodness of a potential fitting between impedance and density profiles, root mean square error (RMSE) was used.

Results

From 17 trajectories evaluated in five different subjects, a low correlation was found between impedance and density among all measured data points (Fig. 1). The average cross-correlation and RMSE scores through all 17 data sets was found to be 0.69 and 0.15 (Table 1). An example of impedance-density correlation pattern can be seen in Fig. 2.

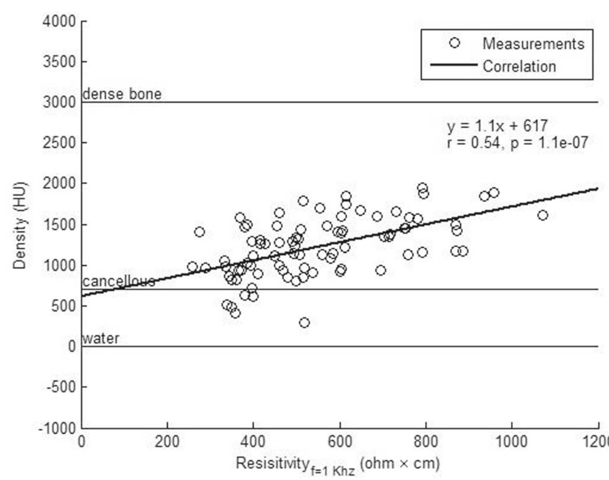

Fig. 1 Correlation between resistivity (f = 1 kHz) and density values from CT scan for the electrode configuration of working to counter electrode distance d = 7 mm

Table 1 Correlation and fitting results per each of the four electrode configurations

Counter electrode	Pearson's corr. (r, p)	Cross-correlation	RMSE
Concentric d = 2 mm	(0.47, 8.4e-6)	0.68 ± 0.11	0.15 ± 0.11
Concentric d = 4 mm	(0.52, 4.5e-7)	0.69 ± 0.11	0.15 ± 0.10
Concentric d = 7 mm	(0.54, 1.1e-7)	0.70 ± 0.09	0.14 ± 0.10
Far needle	(0.51, 8.5e-7)	0.69 ± 0.09	0.14 ± 0.10
Mean results	r = 0.51 ± 0.03, p < 1e-5	0.69 ± 0.01	0.15 ± 0.01

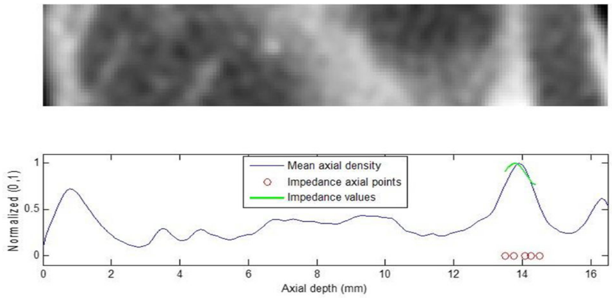

Fig. 2 Example of a trajectory showing the similarity between the density and impedance profiles in the region of the fallopian canal (bony canal surrounding the facial nerve). In the top, an arbitrary CT slice along the trajectory is depicted

Conclusion
Electrical impedance could be a potential marker to enhance overall system's safety during image-guided robotic cochlear implantation. An example of using this technique could be by combining it with drilling forces to further increase reliability of an existing pose estimation algorithm [2]. To further develop and verify this technique we propose to investigate integrated impedance sensing during continuous drilling into the mastoid.

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Electrode array insertion for minimally invasive robotic cochlear implantation with a guide tube

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Keywords Direct cochlear access · CI insertion models · Thiel vs. Formalin · Cochlear duct length

Purpose
Minimally invasive robotic cochlear implantation demands an adapted surgical procedure when compared with conventional cochlear implant (CI) surgery. During insertion, the visibility and maneuverability of the electrode array is limited because of the small size of the direct cochlear access (DCA) tunnel (1.8 mm in diameter). It has previously been shown that a manual insertion of CI electrode arrays is feasible by introducing a tympanomeatal flap as an auxiliary access to the middle ear cavity [1]. To further reduce the invasiveness of the implantation procedure, i.e. to avoid the tympanomeatal flap, an insertion guide tube was developed to bypass the middle ear cavity and to enable a direct insertion of the array from the mastoid surface through the DCA tunnel. The aim of this ex vivo study was to evaluate the new implantation procedure for clinical applicability.

Methods
An insertion guide tube prototype that resembles the shape of the DCA drill was manufactured. It consists of 2 parts to enable removal after array insertion. Sixteen temporal bone specimens (8 Thiel fixed and 8 Formalin fixed) were prepared by placement of 4 fiducial landmark screws. Preoperative CT imaging was performed and drill trajectories were planned to align with the center of the round window. A high-accuracy robotic system was used to drill DCA tunnels (1.8 mm in diameter) in the temporal bones [2]. Free-fitting electrode arrays (28 mm length) were marked to achieve an angular insertion depth of 540° as calculated from the cochlear size of each specimen [3]. Manual insertion from the mastoid surface through the round window was performed through the insertion guide tube (Fig. 1). After insertion was complete, the guide tube was removed and the electrode lead was fixed. Postoperative cone beam CT and microCT imaging was performed to evaluate the insertion outcome.

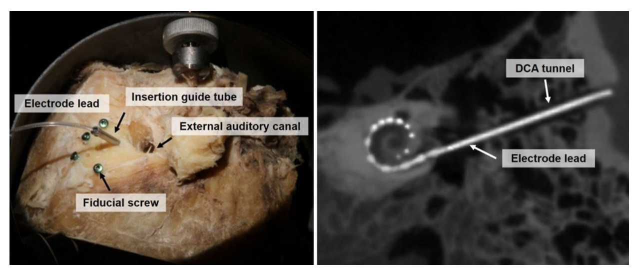

Fig. 1 (Left) Formalin fixed temporal bone with insertion guide tube and inserted CI electrode array. (Right) Postoperative pseudocoronal cone beam CT slice showing the implantation outcome in a Formalin fixed temporal bone

Results
In all specimens the direct CI array insertions from the mastoid surface into the cochlea were feasible without complications using the guide tube. The removal of the insertion guide tube was possible without retracting the inserted arrays. One minor problem was the visualization of the insertion depth marks on the arrays at the level of the round window. All electrode arrays (n = 16) were inserted into the scala tympani, with an average angular insertion depth of 538° (Thiel fixed) and 409° (Formalin fixed). The arrays inserted into Thiel specimens showed a smooth array course, whereas in 4 Formalin specimens bending of the electrode array at the hook region occurred.