Methods

A drilling protocol designed to optimize the safety of the procedure was proposed and integrated into a custom planning software and robotic system [2]. Software allows the segmentation of the structures within the mastoid and the definition of the trajectory, with optimization of the drilling path completed based on the distances from the trajectory to surrounding critical anatomy. Once optimization is complete, the trajectory is automatically divided into multiple segments. The first segment commences at the mastoid surface and terminates 3 mm distally to the level of the facial nerve; the segment is assigned a drilling protocol (2 mm intervals) designed to provide sufficient thermal control whilst optimizing drilling time. During drilling of the first segment the forces observed at the tip of the drill are recorded and comparison of these forces with sampled surrounding bone density profiles allows the estimation of the tool pose independently from registration error [3]. Intraoperative cone beam CT imaging is performed prior to commencing the second segment which passes the close lying nerves. Based on the acquired images, the projected distance at which the current drill trajectory will pass anatomical structures, in addition to the drilling error, is calculated automatically using custom software. For distance calculations, a titanium rod inserted into the drill tunnel is automatically segmented and registered to the preoperative plan using a mutual information registration. The second segment terminates 3 mm past the level of the facial nerve and defines a region in which a heat sensitive drilling protocol, previously determined experimentally [4], is to be employed (0.5 mm drill intervals) to ensure thermal damage of the surrounding nerves is avoided The final segment completes the drilling to the middle ear cavity at the original drilling parameters as the drilling returns to a less critical region.

The effectiveness of safety measures were assed in minimally invasive drillings performed on 16 temporal bone specimens. Registration of the specimen to the pre-operative images was required to meet heuristically determined error thresholds of FRE < 0.04 mm and a maximum Euclidean difference from a leave-one-out registration test at the planned target < 0.5 mm. Trajectories were drilled by the robotic system according to the planned protocols and safety measurements were performed on completion of the drilling of the first segment. Accuracy of the drilling, intraoperative image based safety calculations and force-density tool pose calculation as well as the preservation of anatomical structures were assessed on high resolution CT (xtremeCT, Scanco Medical, CH).

Results

Minimally invasive access to the middle ear, targeting the round window of the cochlea, was successfully performed in all 16 cases. Inability to assess one case on the postop CT lead to its exclusion from subsequent analysis. Registration accuracy thresholds resulted in the detection of a fiducial that had been mistakenly removed and returned to the same hole after preoperative imaging. The procedure was successfully performed after the acquisition of a second image. A drilling accuracy of 0.15 ± 0.07 mm was observed at the target on the round window and accuracies of 0.08 ± 0.04 mm and 0.12 ± 0.05 mm were observed on the surface of the mastoid and level of the facial nerve respectively. In all specimens the preservation of the facial nerve and chorda tympani was confirmed on postoperative high resolution CT images; in one case the chorda tympani was sacrificed due to a narrow facial recess. The drilling error predicted at the level of the facial nerve at the round window target point, based on the acquired intraoperative images were calculated with accuracies of 0.14 ± 0.1 mm and 0.19 ± 0.11 mm respectively. The distance from the drill to the facial nerve was estimated with an accuracy of 0.04 ± 0.04 mm, suggesting the major segmentation and prediction errors did not occur in the direction towards the nerve. The force-density algorithm predicted the actual tool path at 3 mm before the facial neve with an accuracy of 0.22 ± 0.14 mm (Fig. 1).

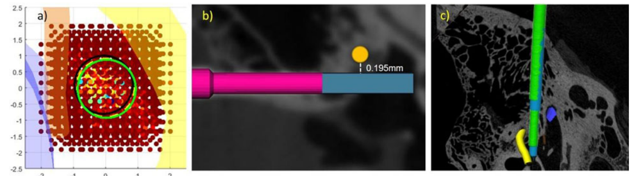

Fig. 1 Drilling safety mechanisms using (a) force and density data, and (b) image data (b), were assessed on post-operative microCT images (c)

Conclusion

Presented above is a drilling protocol and safety mechanisms designed to ensure the safe completion of minimally invasive cochlear implantation procedures. The described mechanisms are designed to prevent both mechanical and thermal damage to the structures of the facial recess and were evaluated on a total of 16 human temporal bone specimens; in all cases the structures of the facial recess remained intact according to the pre-operative plan.

References

[1] Labadie RF, Balachandran R, Noble JH, Blachon GS, Mitchell JE, Reda FA, Fitzpatrick JM (2014). Minimally invasive image-guided cochlear implantation surgery: First report of clinical implementation. Laryngoscope, 124(8), 1915–1922.

[2] Bell B, Gerber N, Williamson T, Gavaghan K, Wimmer W, Caversaccio M, Weber S (2013). In Vitro Accuracy Evaluation of Image-Guided Robot System for Direct Cochlear Access. Otology & Neurotology, 34, 1284–1290.

[3] Williamson TM, Bell BJ, Gerber N, Salas L, Zysset P, Caversaccio M, Weber S (2013). Estimation of tool pose based on force-density correlation during robotic drilling. IEEE TBME, 60(4), 969–76.

[4] Feldmann A, Anso J, Bell B, Williamson T, Gavaghan K, Gerber N, Zysset P (2015). Temperature Prediction Model for Bone Drilling Based on Density Distribution and In Vivo Experiments for Minimally Invasive Robotic Cochlear Implantation. Annals of Biomedical Engineering. [Epub ahead of print]

Ex-vivo evaluation of a chorda tympani prediction model for minimally invasive cochlear implantation

C. Rathgeb[1], K. Gavaghan[1], C. Dür[2], O. Scheidegger[3], T. Williamson[1], L. Anschütz[2], M. Caversaccio[2], S. Weber[1], N. Gerber[1]

[1]University of Bern, ARTORG Center for Biomedical Engineering Research, Bern, Switzerland

[2]Inselspital Bern, Department of ENT, Head and Neck Surgery, Bern, Switzerland

[3]Inselspital Bern, Department of Neurology, ENMG-Station, Bern, Switzerland

Keywords Chorda tympani · Prediction model · Minimally invasive · Cochlear implantation

Purpose

Minimally invasive cochlear implantation (MICI) requires the definition of an access tunnel from the surface of the mastoid to the cochlea, passing through the facial recess. Bounded by the facial nerve, chorda tympani, the medial aspect of the external auditory canal and the incus, the definition of a safe drilling trajectory requires the accurate calculation of distances to these close lying structures to ensure sufficient safety margins are respected. Previously described planning systems calculate distances using automatically or semi automatically segmented anatomy from preoperative CT images.

However, to date, the inability to visualise the chorda tympani within the middle ear cavity on standard CT images has meant that the full structure cannot be assessed, possibly placing it at risk. To ensure a sufficient safety, a path prediction model of the chorda tympani based on the segmented section of the nerve passing through bone was developed and tested in a study on temporal bone specimens.

Methods

A petrous bone specimen was extracted from a human cadaver head preserved in Thiel and prepared for MRI scanning. The specimen was inserted into inert perfluoropolyether fluid (Solvay Solexis Fomblin® Inert PFPE Fluid) and placed under vacuum for more than 12 h to remove possible air bubbles. This step ensured a good contrast between the chorda tympani and the middle ear cavity filled with Fomblin® in MRI images. A high-resolution three-dimensional gradient echo 14T MRI scan of the petrous bone was acquired (GRE3D, isotropic resolution of 0.13 mm). The high resolution images allowed the visualisation of the chorda tympani not only in the bony structure but also in the middle ear cavity. The course of the chorda tympani inside the tympanic cavity and the transition to the tympanic orifice of canal for chorda tympani tympani were identified to form the basis of a prediction model based on cubic spline interpolation. The model was then used during planning of MICI.

An previously developed planning software for robotic cochlear implantation was adapted to include the prediction model and the software was used to plan access tunnels for robotically performed MICI procedures on N = 23 temporal bones (17 preserved in Formalin and 8 preserved in Thiel). Planning of the procedure included segmentation of the chorda tympani in a two-step process. The posterior part of the chorda tympani encased in bone was segmented using previously described methods. The part inside the middle ear cavity was created using the above mentioned prediction model built using the selection of landmarks on the CT slices at the iter chordae posterius and the malleus processus anterior. The prediction model was used to assess the distance at which an access tunnel could be planned from the chorda tympani (see Fig. 1). The planned procedures were drilled utilizing a robotic system MICI, followed by cochlear electrode array insertion and postoperative assessment.

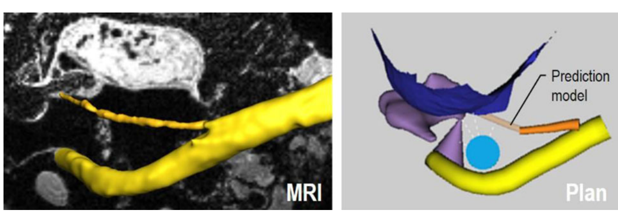

Fig. 1 Manually segmented facial nerve and chorda tympani on 14T MRI image (left). Plan of a drilling trajectory to the cochlea including the chorda tympani prediction model (right)

Results

The chorda tympani was successfully segmented in all specimens. In six cases, the chorda tympani was chosen to be sacrificed due to the small diameter of the facial recess in that sample identified during the planning of the drill tunnel.

In all cases, postoperative endoscopic inspection was performed by a surgeon. In three of the six chorda tympani chosen to be sacrificed during planning, no damage was observed by the surgeon. The other three structures were reported to be damaged as expected by the plan.

In two Formalin fixed samples, the chorda tympani was found to be damaged although the planned margin to the structures were suitable for drilling. Nevertheless, the surgeon reported very thin and fragile nerve structures due to the Formalin preservation liquid and indicated that the chorda tympani might have been damaged during elevation of the tympanic membrane prior to endoscopic inspection. In postoperative visual inspection on micro CT images, the two structures were confirmed to have safe margins to the drilled tunnel which supports the hypothesis that the damage occurred after the drilling process.

Conclusion

Results of this pilot study suggest that the proposed prediction model is an effective method of determining the path of the chorda tympani through the middle ear cavity when it is not visible on preoperative images. The method seems sufficient to aid in the preservation of the structure during minimally invasive cochlear implantation and may be used for the planning of alternative otologic procedures in the future on further validation of its accuracy.

Thermal monitoring of the facial recess during drilling for minimally invasive cochlear implantation

L. Fichera[1], N. Dillon[1], K. Kesler[2], M. Zuniga Manrique[3], J. Mitchell[1], R. Labadie[3]
[1]Department of Mechanical Engineering,
[2]School of Medicine and
[3]Department of Otolaryngology, Vanderbilt University, Nashville, United States

Keywords Temporal bone drilling · Thermal monitoring · Cochlear implantation · Facial nerve

Purpose

Cochlear implantation traditionally involves a mastoidectomy to gain access to the cochlea for electrode insertion. Recently, a less invasive approach has been proposed, in which a narrow linear hole is drilled from the external skull surface to the cochlea. Pre-operative and intra-operative computed tomography (CT) scans are used to plan a safe path to the cochlea that avoids vital, bone-embedded structures such as the facial nerve. Based on this plan, the drill is aligned using a microstereotactic frame [1] or a robot [2].

Accurate image guidance and specialized hardware minimize the risk of contacting the vital anatomy with the drill; however, nerve injury can occur via thermal damage secondary to heat generated by the bit cutting through nearby bone and/or from friction between the drill bit and the surrounding bone or bushing sleeve. Prior work by others provided evidence that the temperature at the facial nerve can reach potentially harmful levels if additional safeguards (e.g. irrigation, planned trajectories through more porous bone) are not employed [3]. The purpose of the present work was to evaluate the heat generated by both manual and automated linear drilling near the facial nerve in human cadaveric temporal bones. Several sets of drilling parameters were employed with the intent that results would guide the selection of drilling parameters to be used clinically.

Methods

An experimental setup and procedure was developed to evaluate the temperature rise near the facial nerve while drilling a path to the cochlea. Cadaveric temporal bones were obtained from Science Care Inc. (Phoenix, AZ, United States), and 3–4 drilling experiments per bone were undertaken. For each experiment, the hardware and planning procedures similar to those described in [1] were used. A microstereotactic frame ("Microtable") was manufactured and mounted to the specimen to align the drill along the desired path. Each specimen was cut along a plane perpendicular to the drill path in a region called the facial recess (Fig. 1a). The facial recess was selected because the drill passes very close to the facial nerve at this location. An infrared thermal camera (Flir A655sc, 50 µm close-up lens, Flir Inc. USA) was positioned to record the bone temperature at the cut plane (Fig. 1b) while drilling the medial stage of the path with