Eur Arch Otorhinolaryngol (2009) 266:955–960
DOI 10.1007/s00405-008-0825-3

OTOLOGY

New strategies for high precision surgery of the temporal bone using a robotic approach for cochlear implantation

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Received: 11 July 2007 / Accepted: 25 September 2008 / Published online: 21 October 2008

Abstract The aim of the study was to demonstrate a collision-free trajectory of an instrument through the facial recess to the site of planned cochleostomy guided by a surgery robot. The indication for cochlear implantation is still expanding toward more substantial residual hearing. A cochleostomy as atraumatic as possible will influence the preservation of inner ear function. The employment of a highly precise instrument guidance using a robot could represent a feasible solution for a constant reproducible surgical procedure. Screw markers for a point-based registration were fixed on a human temporal bone specimen prepared with a mastoidectomy and posterior tympanotomy. A DICOM dataset has been generated thereof in a 64-multislice computer tomography (CT). A virtual trajectory in a 3D model has been planned representing the path of instrumentation toward the desired spot of cochleostomy. A 1.9-mm endoscope has been mounted onto the robot system RobaCKa (Staeubli RX90CR) to visualize this trajectory. The target registration error added up to 0.25 mm, which met the desirable tolerance of <0.5 mm. A collision-free propagation of the endoscope into the tympanic cavity via the facial recess has been performed by the robot and the spot of cochleostomy could be visualized through the endoscope. Using a DICOM dataset of a high-resolution CT and a robot as a positioning platform for surgical instruments could be a feasible approach to perform a highly precise and constant reproducible cochleostomy. Furthermore, it could be a crucial step to preserve substantial residual hearing in terms of expanding the indications for cochlear implantation.

Keywords Minimal invasive surgery · CAS · Cochlear implantation · Cochleostomy · Point-based registration

Introduction

During the last two decades, cochlear implantation has been established to treat patients with severe to profound deafness. It became an indispensable component in the rehabilitation of these patients. New strategies for patients with residual hearing suppose an advantage in stimulating the same ear by electric and acoustic transmission.

However, by creating a cochleostomy and inserting the electrode array through the cochleostomy, residual hearing could be destroyed to a greater extent and existing functions of the inner ear could thereby irreversibly get lost.

This paper was presented at the 79th Annual Meeting of the German Society of Otorhinolaryngology, Head and Neck Surgery, Erfurt, May 2005, and at the 9th International Conference on Cochlear Implants and Related Sciences, Vienna, June 2006.

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The location and the orientation of the opening of the bony inner ear have crucial influences on the subsequent positioning of the electrode and the associated trauma [1–5]. Even if the implant is functioning postoperatively, trauma of the inner cochlea could yet lead to an invisible long-term damage, e.g. the loss of neural structures [6, 7]. Additionally, it could exclude the cochlea with its literally preservable sensory cells and neural structures from further medical developments [8, 9]. Furthermore, own preliminary results show an advantage in the outcome of hearing improvement if the electrode has been inserted into the scala tympani [10].

Within the last years, the implementation of robots in the operating theaters has been a big challenge for both engineers and all medical professions. Through the advancement of minimal-invasive surgery, this trend has been accelerated. The characteristics of a robot like accuracy, missing fatigue, and rapidity have led to a growing acceptance for an application in research in the diversified fields of medicine, so also in surgery of the lateral skull base [11]. The employment of instrument guidance using navigation [12] and a precise robot as a positioning platform during surgery could represent a feasible solution to perform a precise cochleostomy. If a mostly atraumatic, highly accurate surgery could be accomplished to preserve the function of the inner ear, the model to be constructed has to operate in a submillimeter range. This is necessary to predict a safe and reproducible opening of the scala tympani during cochlear implantation.

Materials and methods

On a human temporal bone specimen, a mastoidectomy with a posterior tympanotomy has been performed as routinely used for the approach to the basal turn of the cochlea in cochlear implantation. Thereafter, the specimen has been drenched in a 2 M sodium hydroxide solution for 24 h to remove residual soft tissue. Subsequently, it has been disinfected with hydrogen peroxide for 24 h to be used in the technical laboratory. Four titanium screw markers with a recessed head (Aesculap, Tuttlingen, Germany) have been attached on the lateral surface of the prepared temporal bone around the mastoidectomy (Fig. 1) for later registration of the navigation and robotic system.

The specimen has then been scanned with a new generation of 64-multislice computer tomography (CT) scanner (Siemens Sensation 64, Erlangen, Germany). The voxels have the dimensions of 0.18 mm × 0.18 mm × 0.60 mm.

By dint of the DICOM dataset, 3D surface models of the tympanic cavity have been generated by manual segmentation (Fig. 2) and by automatic reconstruction through marching cubes algorithm using an adapted version of the open source DICOM-viewer OsiriX (Version 2.0).

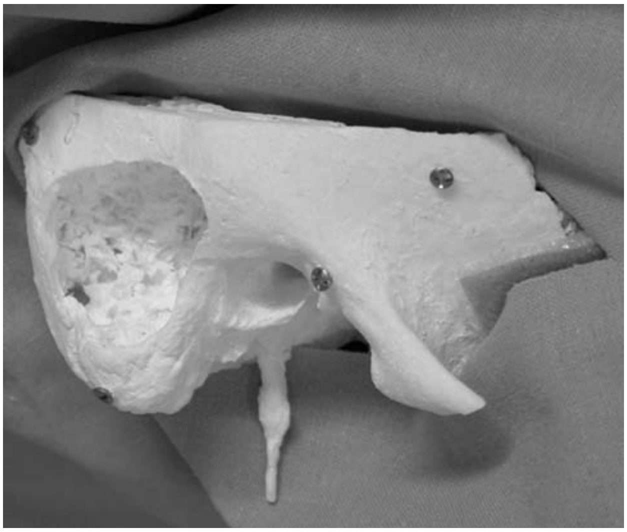

Fig. 1 Human temporal bone with a mastoidectomy and a posterior tympanotomy. Four titanium screw markers are attached for later registration of the navigation and robotic system

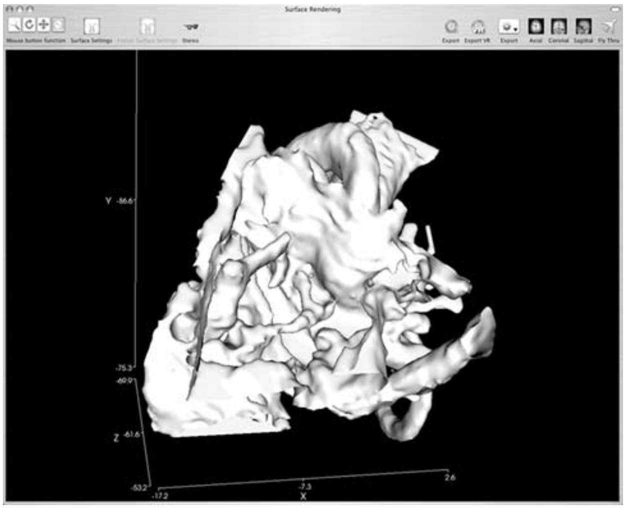

Fig. 2 Three-dimensional surface model of the middle ear cavity of a temporal bone by dint of a DICOM dataset of a 64-multislice Computer Tomography (CT), an adapted version of the open-source program OsiriX, and by manual segmentation

Thereafter, the desirable point of cochleostomy on the promontory has been defined in the virtual 3D model shown in Fig. 3. OsiriX has been enhanced in the way mapping the corresponding location of the chosen cochleostomy on the axial slices of the CT dataset. This offers the possibility to refine the position of cochleostomy in the 2D image. A virtual trajectory for the endoscope has been planned through the facial recess in direction to the basal turn of the cochlea.

In the experimental setup, the temporal bone has been fixed stable to the operating table. A point-based registration has been performed by piloting the force-controlled robot system RobaCKa (IPR, Karlsruhe, Germany) [13, 14] with a Staeubli RX90CR robot (Staeubli AG, Pfäffikon,

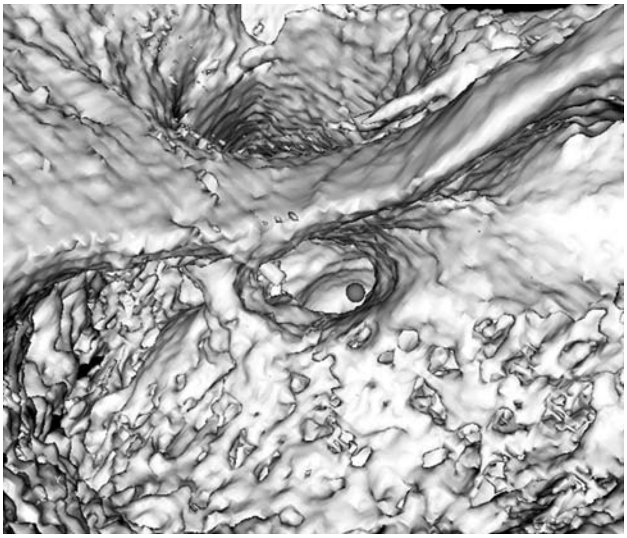

Fig. 3 View through the facial recess toward the selected point of cochleostomy on the surface of the promontory in a 3D model

Switzerland) onto the registration markers. The registration has been repeated four times and the fiducial and target registration errors have been calculated. The robot system is based on a conventional industrial robot using articulated arm kinematic structures. An endoscope (Panoview 8860.431, diameter 1.9 mm, Richard Wolf GmbH, Knittlingen, Germany) (Fig. 4) has been firmly mounted on the robot as an end-effector, which imitated the intervention with a drilling tool by moving to the predefined borehole. The robot has been programmed with a planned stop on the promontory as mentioned earlier [15]. During the robotic procedure, the endoscopic view has been video-recorded.

Results

The experiment has been conducted and validated regarding the target registration error with a designated tolerance of <0.5 mm. This tolerance has been determined on histological examinations of the human cochlea. The fiducial registration error (FRE) and target registration error (TRE) generated in the first part of this experiment were 0.3 and 0.25 mm, respectively (Table 1). Referring to this data given, the desired accuracy for a robotic approach has been planned guiding the endoscope through the facial recess.

After starting the system of the robot, the endoscope advanced continuously and passed through the facial recess right up to the promontory without collision and interference. This has been repeated for four times. The facial recess had the maximum dimensions of 6.34 mm × 3.92 mm. The tip of the endoscope stopped at the promontory at the point of the desired cochleostomy.

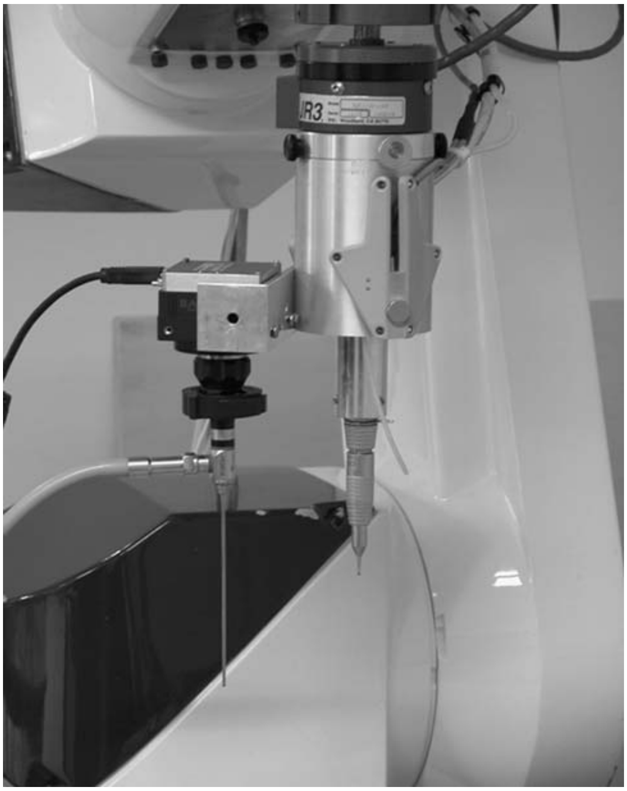

Fig. 4 Fixation of an endoscope (Panoview 8860.431, diameter 1.9 mm, Richard Wolf GmbH, Knittlingen, Germany) on the force-controlled robot system RobaCKa (IPR, Karlsruhe, Germany) with a Staeubli RX90CR robot (Staeubli AG, Pfäffikon, Switzerland)

Table 1 Fiducial and target registration errors

	Fiducial registration error (FRE, in mm)	Target registration error (TRE, in mm)
1	0.42	0.30
2	0.19	0.13
3	0.51	0.37
4	0.24	0.17
Mean	**0.3**	**0.25**

The endoscopic view has been compared with the model of virtual endoscopy of the 3D dataset. No major aberration has been detected (Fig. 5a, b).

Discussion

Cochlear implantation is the method of choice in rehabilitation of deaf and profound hearing-impaired patients. In the last years, indication expanded toward patients with residual hearing [1, 16–18]. New strategies favor an electric and acoustic stimulation on the same ear at the same time, the so-called electro-acoustic stimulation [1, 19, 20]. Therefore, it is mandatory to preserve inner ear function and

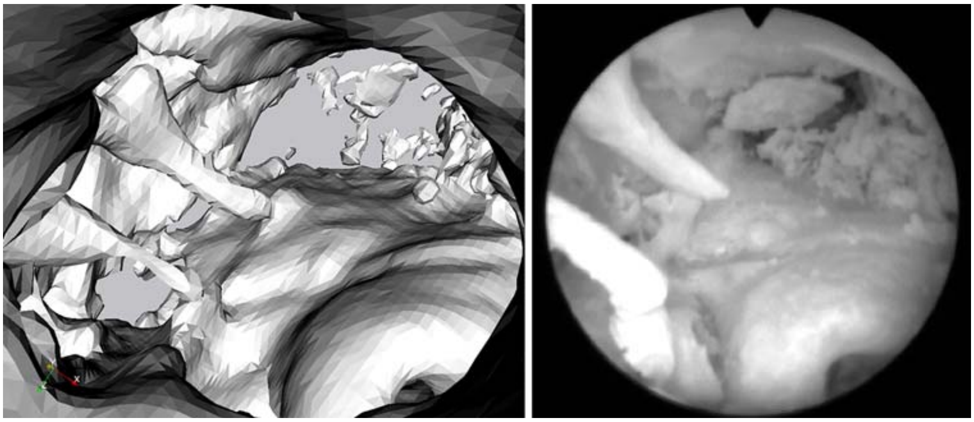

Fig. 5 **a** Virtual endoscopic picture through the facial recess in a 3D-reconstruction of a CT DICOM dataset. **b** Comparable endoscopic view into the middle ear and onto the promontory during the experiment

structures during and after implantation. Some studies showed that preservation of residual hearing is possible up to 50–70% in the low frequencies so far [21–24]. At higher frequencies above 2,000 Hz, the results are mostly poor. In our opinion, the precise and reproducible location of the cochleostomy has a crucial impact on preserving inner ear structures. In a different study using rotational tomography for analyzing the inner cochlear position of the electrode [4], we found in 13 out of 21 (62%) patients, a primary insertion into the scala vestibuli with the Nucleus Contour electrode array.

To preserve inner ear function, we follow the philosophy of soft surgery technique first described by Lehnhardt [25]. The bony wall of the basal turn of the cochlea has to be removed until one can identify an endostal layer of the labyrinth. The access to the scala tympani will be achieved by a small incision with a triangle knife or hypodermic needle but without a large opening of the scala itself. Through this, the basilar membrane will not be visualized during surgery. Therefore, it is mandatory for a correct position of cochleostomy to identify the right spot on the promontory to reach the scala tympani.

The experimental results showed that middle and inner ear structures could be clearly identified using a 64-multislice CT. Other studies have shown the clinical feasibility of virtual endoscopy and 3D imaging to evaluate pathologies of the middle ear for diagnosis and surgical planning [26]. Using an adapted software program for segmentation (OsiriX), a virtual endoscopy of the middle ear could be realized with respect to the normally hidden structures of the inner ear like the cochlear scales. This gives the surgeon an excellent planning tool for the ideal point of cochleostomy in addition to the 2D images.

Navigation

We showed in the past that conventional navigation tools are not precise enough to predict the spot of cochleostomy in a range of less than 0.5 mm [12]. Nevertheless, this could be a helpful instrument in severe temporal bone malformation to identify landmarks despite the changed anatomy [27].

Through the direct registration by the robot, the target registration error could be minimized. In this experimental setup, the temporal bone has been fixed to the operating table. In a patient-like setting, this could be accomplished by, for example, a Mayfield-clamp.

Regarding the voxel size of 0.18 mm × 0.18 mm × 0.60 mm, the thickness of the axial CT slices is still a handicap for the accuracy of navigation systems. Future developments of CT are promising to further improve their resolution and reduce the target registration error [28]. Nevertheless, the pictorial representation is a source of error, which cannot be avoided so far.

A highly accurate robot as a positioning platform for surgical instruments may be a feasible approach to perform a precise cochleostomy. The preservation of vulnerable anatomic structures and of remaining ear functions should be the desirable goal in the near future. The endoscope could be replaced by a bone-removing instrument. A drill is commonly used in most experimental setups [29]. To avoid occurring forces onto the bone, we are currently working on the implementation of a special CO_2-laser [30]. Upcoming challenges are minimizing the size of the robot, enhancing the accuracy of the robot system and using a noninvasive registration method.

As an outlook, the Staeubli RX90CR robot could be replaced by precise parallel kinematics in the form of a hexapod-based robot (Fig. 6), to enhance the positioning accuracy and reduce the size of the robot besides several other advantages over a serial robot to possibly avoid trauma to potentially preservable structures like the chorda tympani, e.g. [29, 31]. For instance, it does not exhibit summation of errors and has a small workspace acting as mechanical constraint of the motion available to the end-effector. Since a medical robot, by definition, only allows a very limited interference of the surgeon, this restriction could represent a safety aspect for the patient.

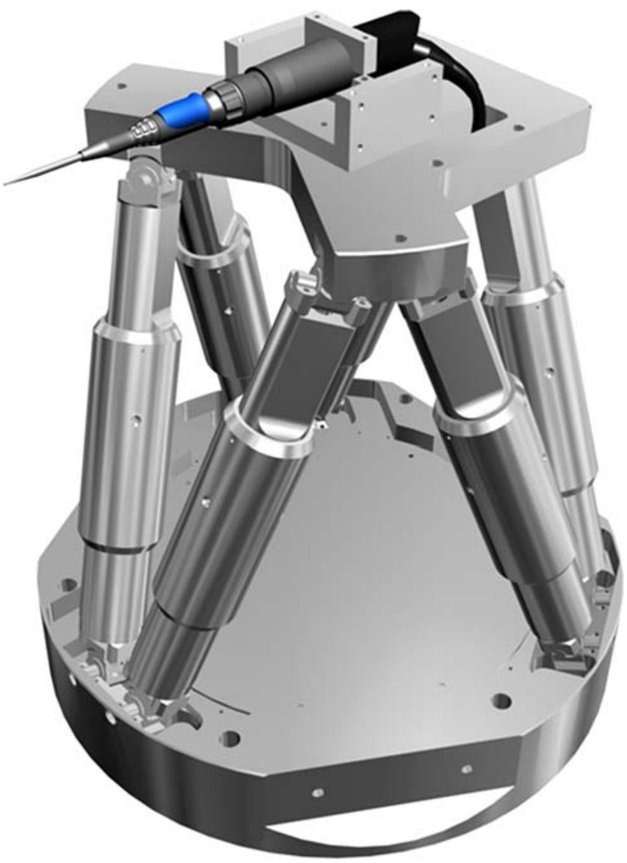

Fig. 6 Technical visualization of a hexapod-based robot with an attached drill

In addition, titanium screw markers are unfavorable, as they are invasive for the patient and necessitate a prior additional surgery. Otherwise, it is considered as the gold standard for registration in navigation surgery, especially on the lateral skull base. With further development of the accuracy of navigation systems in the future and the introduction of even more precise CT data, point-based registration could be replaced by a noninvasive registration method. One possible method is based on accurate topographical measurements across the surface of the tympanic cavity and ossicles by an optical probe. This is part of a different study in this project supported by the Federal Ministry of Education and Research of Germany (No. 01 EZ 0405). Then, the characteristic surface could be matched directly to the CT data. This way the location, orientation, and depth of a borehole may be defined leading accurately to the scala tympani underneath the bony surface of the cochlea. The drilling procedure could be performed via a hexapod with high repeatability.

Future advancements in navigation technologies let us hope for a clinical application. We are still far away from the implementation of a robot for a cochleostomy on the patient. Nevertheless, we should not exclude approaches to a more precise surgery especially on the lateral skull base. We showed the possibility of a collision-free trajectory of guiding an instrument into the middle ear by a Staeubli RX90CR robot. Further research has to be undertaken to improve the accuracy of the CT data, the navigation and the robot before applying it on the patient.

Acknowledgments This study has been supported by the Federal Ministry of Education and Research of Germany (No. 01 EZ 0405) and by the companies Cochlear GmbH and Richard Wolf GmbH, Germany.

Conflict of interest statement The authors declare no conflict of interest.

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