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Navigation for Cochlear Implantation

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***Abstract*— A cochlear implant is an artificial sensory organ for patients with severe to profound hearing loss who have little benefit from hearing aids. The fact that more patients with previous temporal bone surgery or cranial malformations are receiving cochlear implants implies that the number of atypical cochlear implantation will continue to grow. Surgical navigation, or image-guided surgery may be helpful for surgeons who perform atypical surgeries. We report our research on an image-guided system specifically designed for otologic surgery with an improved surgeon-computer interface.**

I. INTRODUCTION

A. Cochlear implant

A cochlear implant is a device for direct electrical stimulation of the cochlear nerve, and it is used for patients with severe to profound hearing loss who receive little advantage from conventional hearing aids [1]. The cochlear implant is regarded as one of the most successful artificial organs of the 20th century, and is the only successful artificial sensory organ available today. The cochlear implant is composed of two components: the external device, the speech processor, which converts sound into an electrical signal, and the surgically-implanted internal device, the receiver stimulator, which receives a transmitted electrical signal and relays it to the cochlear nerve (Fig. 1). By stimulating different locations in the cochlea (stimulating different nerve bundles of the cochlear nerve) cochlear implant users can distinguish different sound frequencies. The majority of the postlingually deaf cochlear implant recipients are able to restore auditory communication. In addition, prelingually deaf children can also acquire speech language communication if implanted early enough (< 6 years; < 2, ideally) and if sufficient auditory and speech therapy is available to the recipient [2]. Currently, there are over 120 000 recipients worldwide.

B. Surgery for cochlear implant

The receiver-stimulator of the cochlear implant must be surgically implanted. After skin incision, the mastoid portion of the temporal bone is drilled (mastoidectomy) for surgical access to the cochlea. The surgery requires precise drilling of the temporal bone to approach a small anatomical target with the least damage or injury to other important structures. Although the procedure is established and life-threatening complications are rarely reported, surgeons occasionally experience difficulty in certain cases, especially in children with cranial malformations [3].

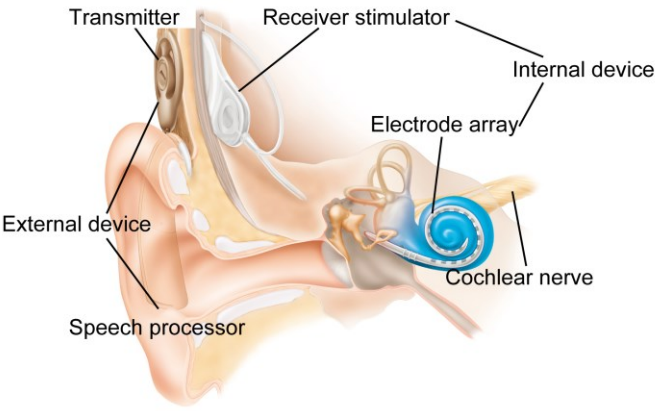

Figure 1. Overview of the cochlear implant. Modified scheme from the original drawing provided by Cochlear Japan Ltd.

C. Image-guided cochlear implantation

Image-guided surgery (IGS) can detect the location of the surgical device and display its location on the radiographical image of the patient [4, 5]. It can help surgeons to reduce the risk of iatrogenic injuries by giving feedback to the surgeon to identify unseen anatomy. The image-guided surgery (IGS) system for cochlear implantation requires highly accurate and minimally invasive registration between the patient and radiographical images because critical structures inside temporal bone are very small and because cochlear implantation is usually not a life-threatening surgery.

In addition, surgeons had to watch the system's monitor to obtain necessary information from conventional IGS systems. Therefore, there has been an irony that the closer the surgeons approached a critical anatomy that requires uninterrupted visual attention, the less the IGS information became accessible because surgeons stayed focused on the surgical microscope. Thus, suitable feedback for the location of the surgical device is necessary for real-time drilling without moving the surgeon's visual attention from the surgical field.

In this study, we describe the methodology of our noninvasive IGS with high accuracy and feedback of the IGS information for cochlear implantation. To obtain high accuracy, template-based registration was performed using temporal bone model and patient-specific tooth template. Upon providing the feedback information, the proposed IGS system generated auditable information according to the direction and distance between the critical anatomy and the drill tip

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II. METHODS

A. Minimally invasive registration

A minimally invasive and highly accurate registration method is one of the most important requirements. In addition, simple and fast processes are required to reduce operation time. To achieve these requirements, we used the pre-registered surface template-assisted marker positioning (p-STAMP) method with the template attached to infrared reflective markers [6, 7] (Fig. 2). To improve increasing target registration error (TRE) inside temporal bone, anatomical landmarks were added using the temporal bone model [8]. In the preoperative stage, anatomical landmarks of the temporal bone model virtual marker points of the template are touched with a tracker pointer. And they are stored in the T^S_V matrix, where T^S_V represents the position and the orientation of the virtual markers (V) as fiducial markers in relation to the p-STAMP (S). T^S_V is calculated by:

$$T^S_V = T^S_C T^C_V \tag{1}$$

where C is the position and the orientation of the camera. Intraoperatively, the relative position of V′ against the position and the orientation of the patient (P) is stored in the $T^P_{V'}$ matrix, where $T^P_{V'}$ is calculated by:

$$T^P_{V'} = T^P_C T^C_{V'} \tag{2}$$

When the template is placed on the temporal bone of the patient, V′ is the same as V.

Therefore, (2) can be written as:

$$T^P_{V'} = T^P_C T^C_S T^S_V \tag{3}$$

This process matches the inner surface of the template and the outer surface of the patient's temporal bone, as well as the patient's anatomical landmarks. Finishing most of the registration processes before surgery can reduce the number of intraoperative procedures and the surgeon's workload for surgical navigation.

Next, the paired-points registration that resulted in the least fiducial registration error (FRE) is obtained as follows [9, 10]:

$$y = Rx + t \tag{4}$$

$$FRE = \sqrt{\frac{1}{N}\sum_{i=1}^{N} w_i^2 \left| Rxi + t - yi \right|^2} \tag{5}$$

where t and R denote the translation vector and the rotation matrix, respectively; w is a weighting factor set to 1.0 in this study; and N is the number of markers. The transformation matrix is determined for the patient coordinate x and image coordinate y for the smallest FRE.

Using the computed transformation matrix, TRE was measured from the distance between the drill tip point to the target in physical space and the target point in image space.

The registration between the patient and the surgical drill must be maintained upon movement of the patient's head or repositioning of the surgical bed. To compensate and track for head movement, we fabricated patient-specific tooth templates to fix to the skull (Fig. 3). A reference marker for tracking was fixed on the template and acrylic fitted over the patient's teeth was custom-made for each patient [11].

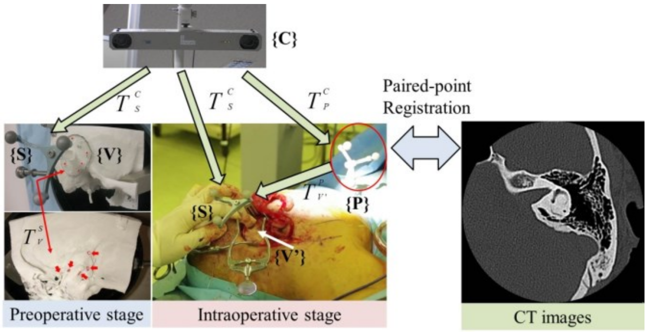

Figure 2. Registration procedures using pre-registered STAMP for submillimeter accuracy.

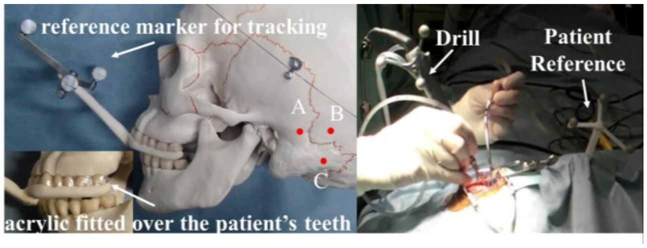

Figure 3. Patient-specific tooth template with reference marker for tracking and compensating for the patient's head movement.

B. Feedback system for monitoring organs in the temporal bone

To approach surgical targets without injury, surgeons need to monitor the locational relationship between the position of the drill tip and anatomical organs. While drilling temporal bone, real-time monitoring without moving the surgeon's visual focus from the surgical field can help surgeons to reduce the iatrogenic risk, using auditory feedback with information about the closest distance from the targets as well as the direction of the target from the drill tip [12]. To implement the feedback system for monitoring, the free open source software (3D Slicer, Version 3.6, Brigham Women's Hospital, Boston, MA, USA) was installed on a Linux workstation and used as a software platform. The user interface of the monitoring system was developed as a plug-in module and incorporated into the 3D Slicer.

Fig. 4 shows the configuration of the system for information on the target location with auditory feedback. Surface rendering was performed using segmentation of the target on computed tomography (CT) images, and the voxel data of the surface-rendered target were used to calculate the closest Euclidean distance (d) between the drill tip and the nearest surface of the targets or organs. Next, the closest point was transformed to the surgical drill coordinates. Then, the direction for the surgical drill was designated as a plus or minus sign of the transformed point with respect to the origin of the coordinate of the drill tip. If the signs of the transformed points (x_t, y_t and z_t) with respect to the drill tip were a minus, a plus and a plus, the direction designated "right up". Intraoperatively, when the drill tip approached the surface of the surgical target and entered the safe margin, the proposed system provided auditory feedback with visual text appearing on the monitor.

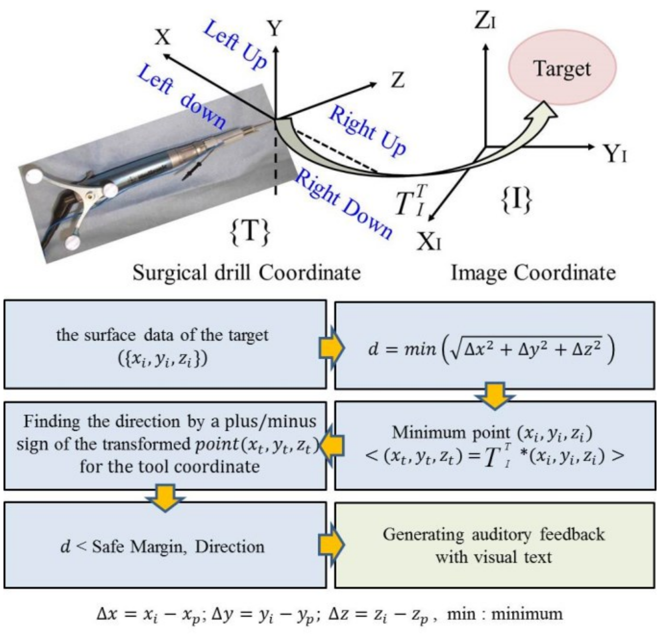

Figure 4. Configurations of the system for feedback of real-time monitoring of the target.

III. RESULTS

The proposed system was evaluated in a phantom study using a synthetic temporal bone model.

A. Evaluation of registration

The accuracy of registration was measured using the p-STAMP method. It was not necessary for the surgeon to have the patient's coordinates for registration during the operation because of preparation in the preoperative stage, with registration procedures completed quickly and easily. The required time to complete the intraoperative registration processes was 23.1 ± 1.93 s.

Fig. 5 shows TRE values for landmarks at a depth of 30 mm and 60 mm from the surface of the bone. The surface of the bone, posterior cranial fossa (PCF) and the foramen lacerum (FL) were 0.8 ± 0.04; 0.7 ± 0.03; and 0.7 ± 0.04 mm, respectively. Thus, the p-STAMP with additional anatomical landmarks inside temporal bone model prevented the increase of TRE even for deep anatomy and kept high accuracy. Moreover, it provided minimal invasiveness for the patient.

To evaluate the stability of the tooth template as the patient reference during surgery, as shown in Fig. 3, the distances between the patient's reference and points on the temporal bone were measured using the tracker pointer. Fig. 6 shows the distances from the patient's reference as elapsed time. In phantom study, for Point A, B and C, the values were 176.7 ± 0.09; 185.6 ± 0.07; and 200.0 ± 0.04 mm, respectively (Fig. 6a). In real surgery, the values for one predefined point on the surface of the temporal bone were 38.08 ± 0.37; 31.98 ± 0.12; and 27.46 ± 0.40 mm for each case (Fig. 6b). Therefore, the device can be kept stable without any deformation for the duration of the operating time.

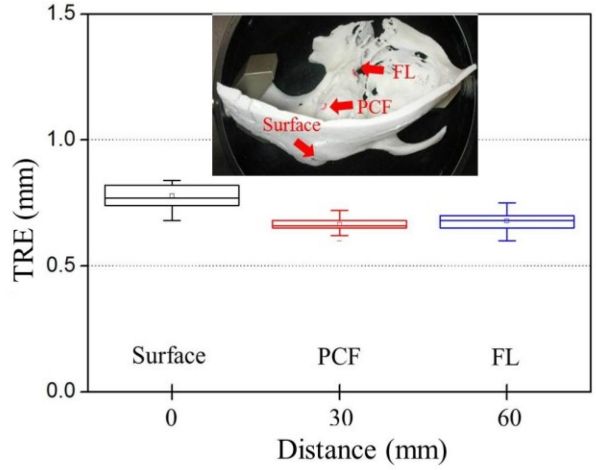

Figure 5. TREs for anatomical landmarks that are a distance of approximately 30 mm and 60 mm from the surface.

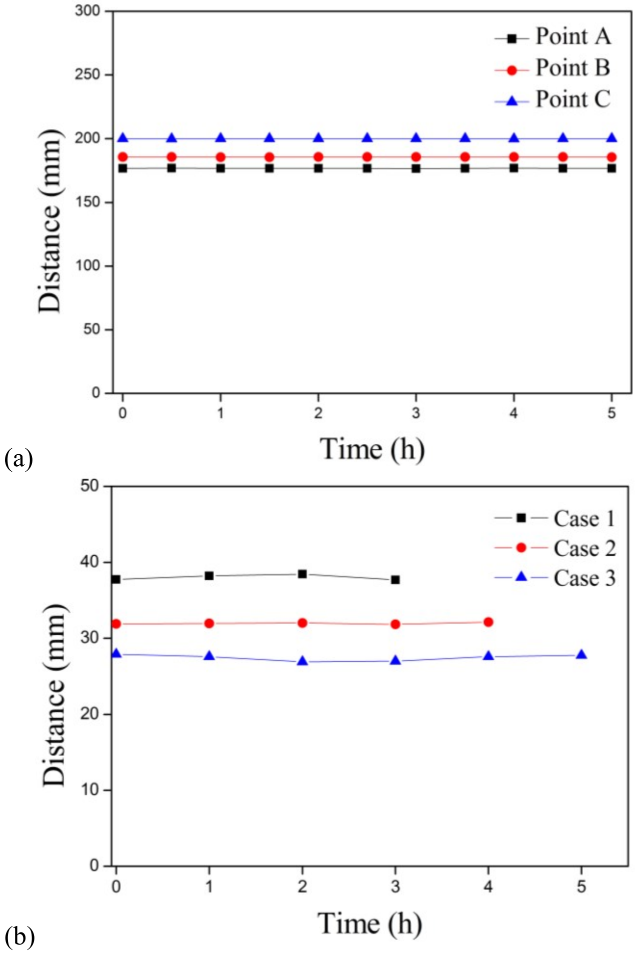

Figure 6. Distances from the patient's reference for points on the surface of the temporal bone (a) phantom study (b) real surgery.

B. *Auditory feedback navigation for monitoring targets*

Fig. 7 shows the outputs of the feedback navigation system for the facial nerve and cochlea. When the surgical drill approached the surgical targets, the proposed system provided auditory feedback according to the distance as well as providing visual text with the direction of the target. Auditory feedback generated different warning sounds for various degrees of risk and the surgical target could be selected and monitored in real time. In real surgery, even though the information about direction of the target displayed on system's monitor as visual text, the visual text of the direction of the target can be programmed and selected to change into auditory feedback when surgeons want to. The direction of the target helped surgeons to identify the location of the surgical target together with auditory feedback for the closest distance.

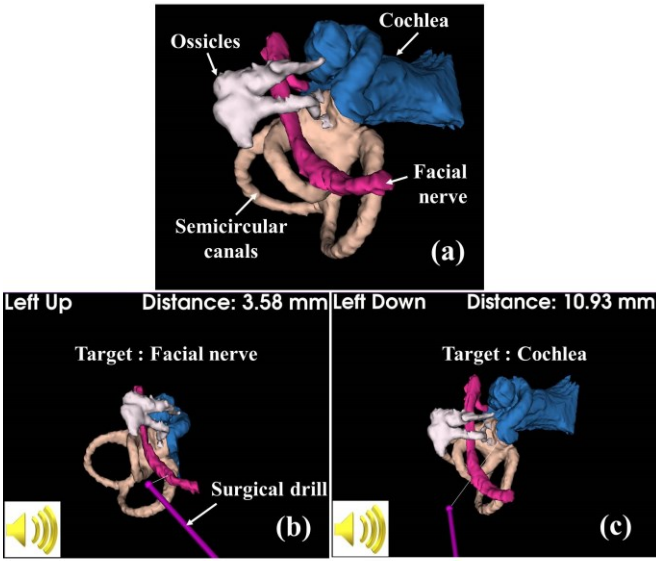

Figure 7. Outputs of the feedback navigation system: (a) surgical anatomy in temporal bone; (b) monitoring the facial nerve; (c) monitoring the cochlea.

IV. CONCLUSION

Cochlear implantation is an established surgical technique without much difficulty when performed on adult patients. However, various surgical difficulties are reported in patients with previous surgery and cranial malformations. Since more children with anomalies are receiving cochlear implants, we expect the number of difficult cochlear implantations will grow. Continuous improvement of image-guided systems may help future patients avoid surgical difficulties.

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