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ORIGINAL RESEARCH–OTOLOGY AND NEUROTOLOGY

A minimally invasive registration method using Surface Template-Assisted Marker Positioning (STAMP) for image-guided otologic surgery

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OBJECTIVE: A new, minimally invasive registration method was developed for image-guided otologic surgery. We utilized laser-sintered template of the patient's bone surface to transfer the virtual markers to the patient's bone intraoperatively and eliminated the necessity for preoperative marker positioning or additional CT scan.

STUDY DESIGN: Simulation surgeries and clinical application.

SUBJECTS AND METHODS: We measured registration errors in 10 trials using replicas and six ear surgeries (two cochlear implant insertions, four translabyrinthine acoustic tumor removals).

RESULTS: The target registration errors varied among the surgical targets. Errors were less than 1 mm near the cochlear implant insertion target both in phantom study and in actual surgeries.

CONCLUSION: Our newly developed method reduced the preoperative procedures for patients but did not reduce the accuracy in cochlear implant surgery. Our method would be a useful image-guided surgery method in the field of otology, where both accuracy and noninvasiveness are required.

Navigated surgery is becoming popular in various fields, and certainly the ear, nose, and throat area is not the exception.[1] The temporal bone that is drilled in otologic surgery conceals many important organs inside and surgeons need to reach surgical target(s) without injuring or, ideally, without exposing these organs. Thus, there is a huge necessity of image guidance with high accuracy in otologic surgeries.[2,3] However, since ear surgeries are basically less invasive unless important organs are injured, the navigation system should also be minimally invasive in order to be applied in more common surgeries.

The registration between the "real" patient and the radiographic image of the patient ("virtual" patient) is one of the key processes that determine the overall accuracy of surgical navigation, or image-guided surgery (IGS). Registration for otologic surgery, which sometimes requires submillimetric accuracy, would be one of the most demanding processes in IGS.[2,4] There are several known factors to improve registration accuracy. Paired-point registration results in smaller errors than laser-scanned surface-matching registration,[5,6] which is widely used in commercially available image-guided paranasal sinus surgeries. The fiducial markers for paired-point registration should be anchored on bone rather than on skin.[7] Practically, titanium screws are often elected for paired-point registration in skull base surgeries.[8] The invasive preoperative screwing procedure would be justified in selected patients preparing for life-threatening surgery, but may not be applicable for more common cases in a daily otologic field.[4] Another practical problem in paired-point registration lies in the surgical team. Preoperative CT scan should be taken prior to the surgery after fiducial markers are attached to the patient. Since the markers should be left attached until the surgery, this CT scanning cannot be prepared long before surgery. The time for the surgical team to prepare images for IGS is usually much less than a day. Thus it is difficult for the surgeons to take enough time for discussion and simulation for the surgery. If these problems of preoperative invasive bone marking process, necessity of another CT scanning, and lack of preparation time are solved, the indication for otologic IGS would be dramatically widened from selected special cases to more daily cases.

To reduce the invasiveness of the bone marking process, fiducial markers on a rigid frame have been successfully attached on the patient's upper teeth,[4,9,10] the only exposed bone-anchored organs in the head and neck. It is, however, still necessary to take another CT scan for IGS. Another idea is to use anatomical landmarks, eg, suprameatal spine of Henle or ossicles that can be identified on CT without markers and can be visualized during the surgery. However, paired-point registration using visually identified bony landmarks seems to result in much less accuracy.[7] In addition, ironically, it is the surgery with unusual or totally lacking

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anatomical landmarks for which surgeons feel the true necessity for IGS.

We developed a novel "STAMP registration system" that noninvasively utilizes bone-anchored fiducial markers. We edited each patient's CT data to virtually place markers on the patient's bone. The template of the bone surface is then produced to transfer the virtual markers to the patient during the surgery. The "STAMPed" markers offered comparable registration errors with conventional registration methods in phantom study and in actual surgeries. The preoperative preparation can be done much before the surgery using the already-taken CT, providing enough preparation time as well as keeping patients from additional exposure to x-ray. These features indicate that this method is suitable for otologic surgeries, where both accuracy and noninvasiveness are required. Here we introduce our potential future IGS for daily otologic surgeries.

METHODS

The institutional review board of Kyushu University approved all the following procedures.

Preparing Preoperative CT

We used digital data of temporal bone CT in Digital Imaging and Communications in Medicine (DICOM) format for the preparation. No specific requests were made for IGS use. Our institutional protocol for temporal bone CT scan gives the resolution of 0.155 mm/pixel for X and Y axes and 0.5 mm slice pitch. Since we routinely use CT scan of temporal bone as one of the necessary pieces of information for deciding surgical indication, we usually have these data ready at the time the patient is scheduled for operation.

Designing and Production of the Temporal Bone Template

First, we designed virtual markers on CT data (Fig 1). The marking locations are selected within the place where we plan to expose the bone surface during surgery. Five to eight fiducial markers were usually attached. The coordinates of the virtual markers are listed and sent to two groups, the bone model manufacturing company (Ono and Co, Tokyo, Japan) and the IGS team in our institute. This first process can be done using OsiriX software, an open-source DICOM viewer,[11] on a Macintosh computer.

Then we edited the CT data to attach 2-mm-diameter, 10-mm-long cylinders as bone-attached virtual markers on the surface of the selected locations (Fig 1B). Thus, the edited CT now looks as if it were taken after the cylinders were screwed onto the patient's skull (Fig 1C). The second process was done using Mimics software (Materialise Japan, Tokyo, Japan), a DICOM editor on a Windows computer.

Next, we designed a 3- to 4-mm-thick template of the surface of temporal bone using the above edited CT data so that the inner surface (contour) of the template matches the outer surface (contour) of the patient's temporal bone. The location of the cylinders as virtual markers will be expressed as holes in the template. The template is trimmed so that it fits in the area of bone exposure during the patient's surgery (Fig 2). A 3D structure was created using the laser sintering process from the edited 3D data of the template.[12,13] The third process was done at the bone model manufacturing company (Ono and Co, Tokyo, Japan). The produced template was sterilized, covered with a sterile film (Tegaderm, 3M, St. Paul, MN, USA), and used during the surgery.

STAMP Registration

The IGS team prepared the navigation image in an open-source surgical navigation software (3D slicer, Brigham Women's Hospital, BA, USA) installed on a Linux workstation. The important organs were segmented and colored as needed. In our surgical cases we usually segmented cochlea, facial nerve, semicircular canals, and internal acoustic canal (see Fig 3).

The surgery was started in a standard way and the bone surface was exposed. After the periosteum was removed and the bone surface was wiped dry, the template was placed on the surface of the exposed temporal bone. The inner surface of the template matched almost perfectly with the outer surface of the patient's temporal bone. The holes on the template showed the exact locations of the virtual markers designed on CT data. A marking pen or 1-mm diamond burr was inserted through the holes on the template; thus, the virtual markers were now successfully transferred onto the patient's bone. We named this entire process of transferring virtual markers to the real patient the "surface template-assisted marker positioning (STAMP)."

Validity Assessment in Simulation Surgeries

We simulated STAMP-registered temporal bone surgery using replicas of the normal temporal bone, which is commercially available for surgical training (OMeR, Ono and Co, Tokyo, Japan), but customized to have four "targets" embedded on surgical landmarks, ie, incudostapedial joint (ISJ), round window (RW), foramen lacerum (FL), and porus acusticus (PA). ISJ can be visualized in most of the ear surgeries. RW is near the final target of cochlear implant insertion. FL was chosen to represent important landmarks on middle cranial fossa whereas PA was chosen to represent posterior cranial fossa. The target was designed as a sphere with cone-shaped concave for the ease and repeatability of pointing with navigation probe. The customized temporal bone replica with target spheres was produced with the same laser sintering process.[12,13] The original CT data were edited to attach virtual markers and the template was produced as described above.

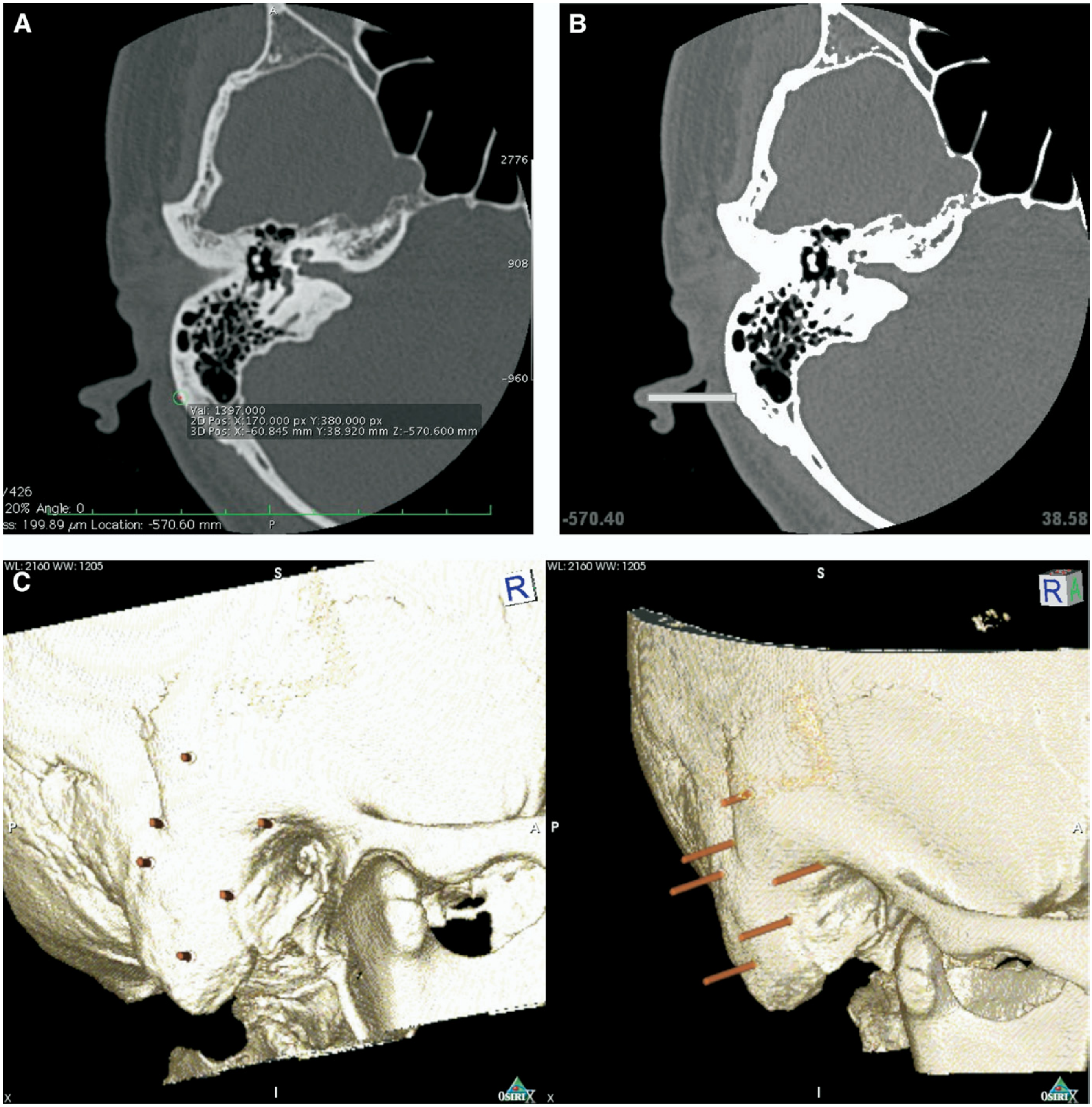

Figure 1 Virtual markers. **(A)** A CT slice showing one of the virtual markers. **(B)** The edited CT slice with a cylinder attached on the selected location shown in panel A. **(C)** 3D volume rendered; edited CT with virtual markers.

The customized target-embedded replica was paired-point registered to IGS system using STAMPed markers. The fiducial registration errors (FRE) and target registration errors (TRE) that reflect the actual errors during surgery[14] were measured and collected. These values were compared with errors measured in conventionally registered IGS using four different sets of fiducial markers: skin-attached markers, dental template,[4,9] visually identifiable anatomical landmarks, and the hybrid registration using combination of skin-attached markers and anatomical landmarks.[15]

Validity Assessment in Actual Surgeries

We performed STAMP-registered IGS in two cochlear implant insertions and four translabyrinthine acoustic tumor removals. All patients provided written informed consent that surgical navigation will be used as assistance and that the navigation system is still under development. We used a custom-made attachment on the drill[15] so that the drill tip was continuously monitored through an optical position sensor (Polaris, NDI, Waterloo, Ontario, Canada). A reference tracker was fixed on the upper

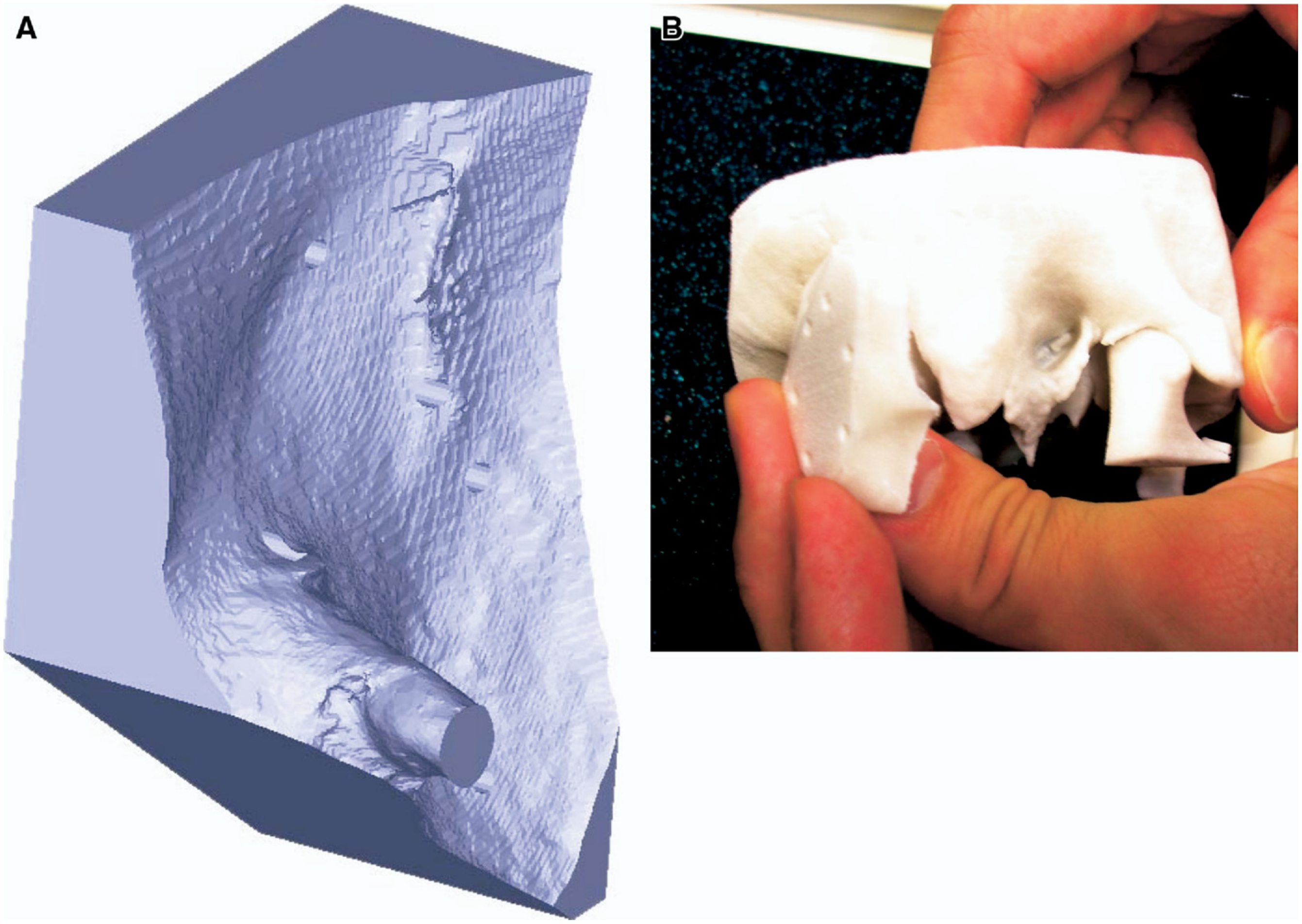

Figure 2 The template for the STAMP. **(A)** The template of the surface of edited temporal bone shown in Figure 1. The inner contour matches the outer contour of the temporal bone. The locations of the cylinders (virtual markers) can be seen as holes. **(B)** Produced template and the temporal bone replica.

teeth, or hard palate if the patient had no denture, using a tailor-made template to continuously monitor and compensate the head movement during drilling.[15,16] STAMP registration was performed after temporal bone surface was exposed and FRE was calculated in all cases.

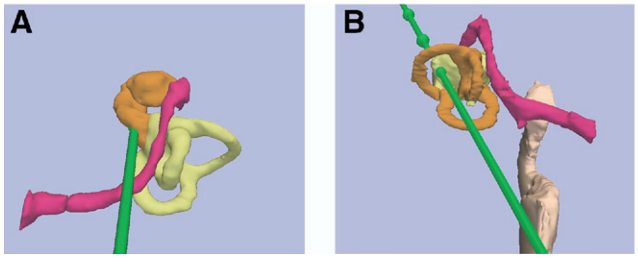

Figure 3 The IGS screen during surgery. **(A)** The navigation view of the surgery during cochleostomy. *Red*, facial nerve; *light green*, semicircular canals; *orange*, cochlea; *green*, drill. **(B)** The navigation view of the surgery during translabyrinthine approach to the internal auditory canal. The surgeon is now pointing to target "SA" of Table 2. *Red*, facial nerve; *orange*, semicircular canals; *light green*, internal auditory canal; *pink*, sigmoid sinus and jugular bulb; *green*, drill with 10-mm extension marks.

We estimated TRE intraoperatively by first specifying surgical landmarks in the CT and then pointing the corresponding landmarks during the surgery. We selected ISJ, RW, bifurcation of superior and posterior semicircular canals from common crus (CC), and the subarcuate artery at the plane of the superior semicircular canal (SA) as targets to be pointed during surgery. The surgeon pointed ISJ and RW in cochlear implant surgeries, and pointed ISJ, CC, and SA in translabyrinthine acoustic tumor removals. Thus, the surgeon's declaration was considered as the gold standard in error measurement. In actual surgery, measurement of TRE in strict definition is almost impossible because pointing a spot in CT and then pointing the corresponding spot on the actual patient in one-pixel accuracy is hardly achievable. Although we express the distance between detected drill tip and the declared spot on the CT as TRE, it should be noted that the TRE in actual surgery is an estimation. All patients had successful cochlear implant insertion or tumor removal. All six image-guided drillings were done by the same surgeon (NM, supervised by SK in translab cases).

Table 1
Registration errors measured in phantom study*

		TRE			
	FRE	ISJ	RW	FL	PA
STAMP	0.40 ± 0.07	0.92 ± 0.35	0.94 ± 0.29	2.71 ± 0.39	3.07 ± 0.24
Anatomy	0.66 ± 0.14	2.18 ± 1.03	2.77 ± 0.91	6.17 ± 0.85	6.04 ± 1.49
Skin	1.34 ± 0.05	2.02 ± 0.50	1.38 ± 0.42	2.50 ± 0.55	2.65 ± 0.66
Dental template	0.54 ± 0.20	2.97 ± 2.09	3.08 ± 2.48	3.64 ± 1.54	3.47 ± 1.72
Hybrid	1.12 ± 0.09	1.40 ± 0.28	0.96 ± 0.36	3.14 ± 1.55	1.73 ± 0.46

FRE, fiducial registration error; *TRE*, target registration error; *ISJ*, incudostapedial joint; *RW*, round window; *FL*, foramen lacerum; *PA*, porus acusticus.
*All error values are mean ± SD in mm from 10 (STAMP) or six (others) trials.

RESULTS

FRE and TRE at each target in phantom study were measured and are listed in Table 1. The FRE and estimated TRE in actual surgeries are listed in Table 2. STAMP-registered IGS showed <1 mm TRE within the depth of RW, although in the deeper level of FL and PA the errors were dramatically increased up to 3 mm, although the tendency of losing accuracy according to the depth of the target from the surface was more or less seen in any other registration methods. The same trend was also observed in the actual surgeries (Table 2). In our set of experiments, the hybrid registration was most robust against the depth of the surgical target (Table 1).

DISCUSSION

In general, accuracy and noninvasiveness are competing goals in the registration process of IGS. Paired-point registration based on fiducial markers results in better accuracy than less-invasive surface-matching registration. Markers screwed on bone require more invasive procedures than attaching markers on skin, but offer much better accuracy.[7] We transferred virtual bone-anchored markers to the patient's bone during the surgery. This is considered less invasive in two ways: first, patients do not need to have screws before surgery; and second, patients do not need to take another CT scan before surgery. These features also result in a shorter hospital stay before surgery because, in Japan, marking and additional CT scan is usually done after the patient is hospitalized. While we utilize STAMPed markers to register, our registration is based upon matching of the surface of the bone to the template and is thus surface registration. However, it is noteworthy that, unlike conventional surface matching, the registration can be repeated even after the original surface is drilled if a sufficient portion of bone surface is retained and the template can be correctly relocated.

Table 2
Registration errors measured in surgeries*

		TRE			
	FRE	ISJ	RW	CC	SA
CI 1	0.59		0.57		
CI 2	0.55	1.20	0.79		
TL 1	0.48	0.64		2.07	1.05
TL 2	0.73	4.20		2.82	5.39
TL 3	0.46	1.46		1.91	1.02
TL 4	0.79	3.46		3.25	4.47

FRE, fiducial registration error; *TRE*, target registration error; *ISJ*, incudostapedial joint; *RW*, round window; *CC*, common crus; *SA*, subarcuate artery; *CI*, cochlear implant patients; *TL*, translabyrinthine acoustic tumor removal patients.
*All error values are in mm.

In addition, the workload for the surgeon's team is remarkably reduced. We take preoperative CT for conventional IGS usually a day before the surgery because the markers on the skin should be left attached until the surgery. Our time for image processing, segmentation of important organs, and fusion of CT and MRI was typically less than three hours. Our new method provides the necessary image for the IGS at the time the patient is scheduled for operation; thus we now usually have more than eight weeks to prepare the IGS. This time can be used for thorough and repeated discussion between the surgical team and the IGS team, or simulation and education for fellow doctors and medical students. On the other hand, it currently takes two weeks to design and produce the template for the STAMP registration. We are working on shortening this production time to apply this method to more urgent cases.

Since the relative locations of the fiducial markers on the templates are fixed and not independent among one another, the FRE of template-based registration is inherently small regardless of the overall accuracy. This may be a common pitfall when using template-based registration such as dental template[4,9] or STAMP. Indeed, registration using dental template and STAMP offered very small FRE value, but TRE at the deepest target (PA) was smallest when using hybrid registration (Table 1). Adding some independent markers would prevent the IGS team from being misled by falsely small FRE value. STAMPed markers and a few anatomical landmarks would become a useful combination without spoiling the benefits of noninvasiveness. Since the STAMPed markers are often tightly clustered within the small area restricted by the surgical exposure, independent fiducial points outside the STAMPed area would also help improve the accuracy.

The TRE that reflects the actual errors during surgery[14] being less than 1 mm within the depth of RW suggests that STAMP registration is already applicable in cochlear implant surgery, where we typically open 1.0- to 1.5-mm cochleostomy on the bone near RW. As predicted in phantom study, accuracy in STAMP-registered image-guided cochlear implant insertion was excellent. The surgeon could even confirm the drill tip entering the basal turn of the cochlea during cochleostomy (Fig 3A). On the other hand, the STAMP method may not be as accurate when the surgical target lies as deep as PA (eg, acoustic tumor removal). In actual translabyrinthine cases, we suffered from unstable TRE values: accurate enough in the first (Fig 3B) and third cases while relatively inaccurate in the second and fourth cases. It is highly probable that small errors at the bone surface were levered larger, to variable extents, in deep targets. Combining STAMPed markers with some additional anatomical landmarks would help decrease, or at least stabilize, the TRE in the deeper targets. Considering the relatively large size of the important organs deep in the temporal bone, such as the internal carotid artery or the jugular vein, submillimetric accuracy may not be as important in petrous apex as in shallower regions where we deal with smaller and more complex organs, such as semicircular canals, cochlea, or facial nerves. Thus, this method would be a candidate for future standard IGS registration in the field of otology, where both accuracy and noninvasiveness is required.

CONCLUSIONS

Surface template-assisted marker positioning (STAMP) utilizes bone-attached markers but does not require invasive preoperative bone marking process, while yielding very small registration errors. The less invasive registration method reported in this study would be a useful strategy to help patients and surgeons by improving safety without increasing the invasiveness. This idea may also be applicable to any field that operates on bony structures.

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AUTHOR CONTRIBUTIONS

Nozomu Matsumoto, project chief, designed and conducted phantom study, performed surgery, writer; **Jaesung Hong**, designed phantom study, prepared navigation surgery, analyzed data; **Makoto Hashizume**, prepared navigation surgery, analyzed data; **Shizuo Komune**, department chief, performed surgery, conducted the study.

FINANCIAL DISCLOSURE

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