Navigated Surgery at the Lateral Skull Base and Registration and Preoperative Imagery

Experimental Results

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Objectives: To assess factors that affect the accuracy of navigated surgery at the human lateral skull base, including the choice of registration procedures and preoperative computed tomography (CT) section thickness, and to compare target registration error, a measure of clinical application accuracy, with root mean square, an accuracy variable provided by several surgical navigation systems.

Design: Experimental cadaver study.

Setting: Medical university.

Participants: Anatomic specimen.

Main Outcome Measures: Target registration error.

Results: A combination of high-resolution CT images, 0.5-mm section thickness, with pair-point matching of a combination of markers on the anatomical specimen, and the registration element was found to be superior (mean [SD], 0.72 [0.28] mm). No correlation was found between target registration error and root mean square. A statistical analysis that considers image registration and acquisition method did not show any correlation between target registration error and root mean square error ($r = -0.175, P = .15$).

Conclusions: High-resolution CT images, 0.5 mm, of the petrous bone and a pair-point registration using loci on the patient and registration superstructures worked best under experimental conditions. Only target registration error was found to provide reliable information on accuracy intraoperatively. In line with the literature, these data prove that root mean square bears little relevance for clinical application accuracy.


Navigation systems are widely accepted and used for different surgical procedures in otorhinolaryngology today.2 Whereas navigation is clinically routine for sinus surgery,3,5 it is not routine for surgery of the lateral skull base, especially regarding microscope-guided navigated interventions. This fact can be attributed partly to the inherent complexity and smallness of the anatomical area under consideration and partly to the technological challenges associated with it.3,6,8 As a rule of thumb, an application accuracy that resembles the typical dimensions of the surgical targets should be the goal intraoperatively. At the lateral skull base, this would imply submillimetric precision.

Two immediate factors have the most affect on clinical application accuracy: image section thickness8 and the intraoperative registration process. Herein, we do not consider hardware-related aspects, such as the spatial position–sensing power of the 3-dimensional (3-D) camera in use. Registration is the step that links preoperative patient imagery with the physical patient10 by determining the physical coordinates of select patient features using the tracked probe of the navigation system; these coordinates are then used to translate position data into coordinates of preoperative imagery used for navigation so that the tip of the probe can be visualized in the patient’s data. For navigated sinus surgery, registration is performed by correlating facial structures to the computed tomography (CT) data.11,12 At the lateral skull base, however, the small area of surgically exposed anatomy and the specific imaging protocols for the petrous bone impede this approach severely.13 Temporal bone high-resolution (HR) scans do not provide enough distinct shapes and structures suitable for registration at the
plane of the squamous part of the temporal bone; moreover, the external ear is inadequate for registration. Invasive techniques for registration, such as placing titanium screws in the patient’s skull as external landmarks for registration before imaging,14 are performed with the patient under general anesthesia using intraoperative imaging or under local anesthesia before surgery, which is acceptable only in a few patients. Thus, navigating the lateral skull base noninvasively in HR diagnostic images is still an open challenge.

A variety of approaches, including extrinsic registration structures17 and axial CT data sets, have been studied16-20 but none of these approaches could convincingly be used in a real clinical setting. In fact, microscopic surgery is hardly ever navigated. Consequently, no standard for noninvasive, accurate, and clinically practicable registration is available for this surgical problem.21,22 External superstructures fixed to the patient by means of dental imprints,23,24 implantation of titanium screws before imaging,25,26 and invasive head fixation are described.27,28 However, systematic comparisons of different registration techniques for the lateral skull base are rare.

When intraoperative navigation is accurate, the position of a pointing device (or an instrument) is ideally displayed at exactly the same location on the computer monitor as in the patient. In reality, this is never the case.29,30 The application accuracy of navigation is, however, crucial to surgical acceptance. Frequently, the root mean square (RMS) error of the registration31-33 is given and only quantifies the quality of a least-squares optimization process,34 with little, if any, relevance to the surgical process.35 Among the various figures of merit found in the literature is the target registration error (TRE),30,36,37 which describes the difference between the actual probe position on the patient and the calculated position in the data. The TRE is the most important quantity intraoperatively because it reflects clinical accuracy.30

Surgical navigation systems typically provide the RMS of the registration as a type of guideline for application accuracy, although the user is advised to check the accuracy on the patient. The RMS describes the residual error between world and data coordinate systems after registration.38 The TRE30 is the spatial difference between corresponding points after registration, measured using the navigation system. The aim of this work was to assess the performance of different patient registration strategies and image acquisition protocols and to test whether RMS and TRE are correlated in the lateral skull base.

METHODS

SKULL BASE SPECIMEN

A formaldehyde-fixed anatomical human cadaver (aged 60 years, male) was provided by the Department of Anatomy, Innsbruck Medical University. Access to the internal structures of the left petrous bone was gained by cutting the specimen horizontally in the submaxillary and supraorbital planes after removing the brain. The left posterior fossa was removed (Figure 1 and Figure 2), and fiducials (X-Spots; Beekley Corporation, Bristol, Connecticut) (radiolucent sphere diameter, 1.5 mm) were fixed on the specimen. A locking acrylic dental splint17 external superstructure (VBH [Vogele-Bale-Hohner] head holder; Medical Intelligence Medizintechnik GmbH, Schwabmünchen, Germany) was adapted to the upper jaw of the anatomical specimen29 and was additionally secured with titanium screws on the maxilla. The mouthpiece served to stabilize the specimen on the operating table and carried radio-opaque fiducial markers that were used for registration purposes. Unlike in the intraoperative condition, this configuration allowed direct measurements at the targets of interest inside the temporal bone and then were used to determine the TRE.

NAVIGATION SYSTEM

An active optical navigation system (Surgical Tool Navigator [STN]; Carl Zeiss Inc, Oberkochen, Germany) was used with an active optical tracking system (Flashpoint 3000; Image Guided Technologies, Boulder, Colorado). The system as a whole is no longer available for purchase, but core components are in clinical use40 and compose parts of commercially available navigation systems.41 For medicolegal reasons, the STN is a closed system and, thus, no direct access to positional 3-D data and CT coordinates is possible.

REGISTRATION STRATEGIES

Three common bases for registration were used: anatomical landmarks, an external superstructure (the VBH system) for point matching, and surface registration. The VBH system carried 5 fiducials; 4 unilateral anatomical landmarks were defined (the tip of the mastoid, the supraorbital foramen, the root of the helix of the pinna, and the supra-aurale). X-Spots were sewn to the anatomical locations to improve identification during the registration process. Note that we were using unilateral registration, which is the only approach suitable for HR data sets. For consistency, the axial data sets were registered similarly. As is well known,37 this approach will yield surgically useful application accuracies in a limited anatomical area only. By design of the registration spots on the anatomy and the external registration element, this limited anatomical area will be the
The configuration of the registration points actually encloses the surgical area. For surface matching, 40 points of the surface of the specimen that were visible in the 3-D reconstruction of the CT data were collected using the tracked pointer. The hardware limitations of the Zeiss STN system did not allow us to cover more points for the surface registration. Specifically, we experimentally determined the TRE and studied the performance of registration based on the use of external superstructures only, external superstructures plus anatomical landmarks, and external superstructures plus anatomical landmarks plus surface for the axial data sets only.

**IMAGE ACQUISITION**

Three different CT data sets with identical scanning variables (140 kV, 220 mA) (Siemens Plus 4 Volume Zoom; Siemens AG, Erlangen, Germany) were obtained: 1 axial data set with 1-mm section thickness (2-mm table feed, 4-mm focus) displaying the whole cadaver head and 2 HR data sets with 1- and 0.5-mm section thickness (1-mm table feed, 2-mm focus) displaying the temporal region only. Three registration approaches and 3 different image data sets allow 9 combinations. However, we could not include surface matching with HR data sets because temporal bone HRCT images have a reduced field of view, providing an inadequate surface for surface matching.

**ASSESSMENT OF TRE**

Fifteen different target points were defined throughout the specimen, all different from the registration points. Five points were skin-fixed fiducial markers, and the remaining 10 were defined as anatomical landmarks in and around the petrous bone.

**Table 1. Targets Used for Measurement of Target Registration Error**

<table>
<thead>
<tr>
<th>Number</th>
<th>Target Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fiducial on the right gradient of the nose</td>
</tr>
<tr>
<td>2</td>
<td>Fiducial on the mastoid</td>
</tr>
<tr>
<td>3</td>
<td>Fiducial attached to the ear lobe</td>
</tr>
<tr>
<td>4</td>
<td>Fiducial attached to the tragus</td>
</tr>
<tr>
<td>5</td>
<td>Fiducial attached to the back side of the auricle</td>
</tr>
<tr>
<td>6</td>
<td>Corner of the dura caused by resection</td>
</tr>
<tr>
<td>7</td>
<td>Bony corner of the calvarium caused by resection</td>
</tr>
<tr>
<td>8</td>
<td>Bony depression in the eminencia arcuata</td>
</tr>
<tr>
<td>9</td>
<td>Mastoid cell</td>
</tr>
<tr>
<td>10</td>
<td>Mastoid cell</td>
</tr>
<tr>
<td>11</td>
<td>Mastoid cell</td>
</tr>
<tr>
<td>12</td>
<td>Most caudal ridge of the truncated internal carotid artery</td>
</tr>
<tr>
<td>13</td>
<td>Most lateral aspect of the truncated internal auditory canal</td>
</tr>
<tr>
<td>14</td>
<td>Lumen of a small vessel in the apex of the petrous bone</td>
</tr>
<tr>
<td>15</td>
<td>Bony corner of the truncated frontal sinus</td>
</tr>
</tbody>
</table>

**RESULTS**

Of 3149 TRE raw measurements, 114 were discarded because they were greater than 3 SD from the mean. The
overall mean (SD) TRE in the lateral skull base was 2.88 (2.09) mm. The TRE data differed significantly depending on the registration technique and the image acquisition method used. As expected, TRE values at bony landmarks in the petrous bone were smaller than those at measurement points located at superficial soft tissue ($P < .01$; data not shown).

EFFECT OF REGISTRATION STRATEGY

Registration strategies significantly affected TRE values ($P < .001$). The lowest (most accurate) TRE values were obtained by combining external superstructures and anatomical landmarks (mean [SD], 1.11 [1.0] mm). For low-resolution axial CT data, the addition of a surface registration yielded worse results than did a mouthpiece plus anatomical landmarks without surface registration (Table 2).

EFFECT OF IMAGE ACQUISITION

The choice of image acquisition methods had no significant effect on TRE ($P = .31$). Noticeable differences were observed using the 0.5-mm HRCT scans, which yielded the highest (worst) TRE values using the external superstructure only and the lowest (best) values when anatomical landmarks were used additionally.

INTRACLASS CORRELATION OF REPEATED MEASUREMENTS

Ten repeated measurements were performed at the 15 target points for the available registration strategies and
imaging data. The intraclass correlation coefficient for the repeated measurements was 0.62 mm (95% confidence interval, 0.54-0.69 mm).

**CORRELATION OF TRE AND RMS**

Mean (SD) RMS values (1.88 [0.33] mm) were significantly smaller than were mean (SD) TRE values (2.88 [2.09] mm, \(P < .001\)), pretending an unrealistic accuracy. Controlling for the effects of registration and image acquisition methods, no correlation between TRE and RMS was found (\(r = -0.175, P = .15\)).

**COMMENT**

In computer-assisted surgical navigation, accuracy means that the virtual position displayed by the navigation system is consistent with the actual surgical position in the patient. A clinically relevant variable of accuracy is the TRE, that is, the deviation of the displayed position from the actual anatomical target. In this study, a segment of the petrous bone in a human cadaver head was removed to expose 15 targets of potential surgical interest for TRE measurements in the lateral skull base (Table 1). Accuracy is affected by many variables, and, ideally, the effect of each single link in the chain of the workflow of navigated procedures should be subject to investigation. Herein we studied the effect of 3 registration procedures and 3 types of radiologic data. Moreover, information on the consistency of the registration process was gained by evaluating 10 repetitions of the whole registration process. Finally, we correlated TRE with RMS, an accuracy variable provided by several navigation systems.

Across all registration and image acquisition methods used, a mean (SD) TRE of 2.88 (2.09) mm was measured under experimental conditions in the lateral skull base. Considering the dimensions of surgically relevant structures in the petrous bone, this accuracy is considered insufficient for navigated lateral skull base surgery. Registration method had a statistically significant effect on TRE (\(P < .001\)), whereas image modality did not (\(P = .3\)). The lowest TRE (mean [SD], 0.72 [0.28] mm) was achieved with 0.5-mm HRCT scans and the combination of an external superstructure and intrinsic landmarks for registration. Herein, the TRE is close to the resolution power of the Polaris digitizer.33 However, unlike during surgical procedures, we did not remove and reinsert the bite block in this experimental setup. The external superstructure alone yielded inaccurate results, probably because of the distance of the mouthpiece from the lateral skull base. Other external superstructures, such as reference arrays fixed at the skull or at a Mayfield clamp, may yield more accurate results. Because only a small surface area of the petrous bone is displayed, surface registration was not feasible in HRCT scans. It is still unknown whether surface matching would improve the TRE in this anatomical area. In low-resolution axial CT scans, additional surface registration did not improve but rather deteriorated the TRE.

The low intraclass correlation coefficient of 0.6 in 10 repeated registrations suggests that the registration process is a major cause of inaccuracy in lateral skull base navigation. One probable reason for this inaccuracy is the lack of prominent landmarks at the surface of the lateral skull. Various factors may affect the registration process, including small movements, soft-tissue deformability, reduced skin turgor in elderly patients, and changes in skin properties during general anesthesia.13,45,46 These factors sum to a major source of inaccuracy in lateral skull base navigation.

Finally, no correlation between TRE and RMS was found. To our knowledge, this is the first experimental verification of the prediction by Fitzpatrick35 that RMS and TRE are uncorrelated. Moreover, RMS values were significantly lower than were TRE values, falsely implying a nonexistent accuracy to the surgeon. This finding reinforces that RMS should not be used as a figure of merit for assessing patient-to-image registration intraoperatively.

The present experimental results are in line with those of previous studies45,46 and are comparable with the work of Caversaccio et al,20 Vrionis et al,47 and Labadie et al.17 However, the detailed analysis of the present data allows us to assess the theoretical framework of Fitzpatrick et al35 on a human cadaver.

In previous experimental investigations, we found that submillimetric application accuracy in the petrous bone is possible.45,46 In combination with the known submillimetric repositioning accuracy of maxillary splints for navigation (experimentally determined to be \(<0.73\) mm on 50 human volunteers23 and theoretically determined to be 0.66 mm44 on an anatomical specimen) and the fact that both TREs are uncorrelated, one can assume a significantly better TRE for navigation only.

The most interesting feature of these data regarding the combination of anatomical landmarks with the mouth-

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**Table 2. Target Registration Errors Obtained at 15 Targets at the Lateral Skull Base Using 3 Registration Techniques and 3 Image Acquisition Methods**

<table>
<thead>
<tr>
<th>Registration Strategy</th>
<th>Axial CT, 1 mm</th>
<th>HRCT, 1 mm</th>
<th>HRCT, 0.5 mm</th>
<th>Total ((P &lt; .001))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mouthpiece</td>
<td>4.01 (1.12)</td>
<td>4.04 (1.48)</td>
<td>5.31 (1.83)</td>
<td>4.47 (1.61)</td>
</tr>
<tr>
<td>Mouthpiece + anatomical landmarks</td>
<td>1.64 (1.49)</td>
<td>0.93 (0.49)</td>
<td>0.72 (0.28)</td>
<td>1.11 (1.00)</td>
</tr>
<tr>
<td>Mouthpiece + anatomical landmarks + surface registration</td>
<td>3.43 (1.66)</td>
<td>NA</td>
<td>NA</td>
<td>3.43 (1.66)</td>
</tr>
<tr>
<td>Total</td>
<td>2.97 (1.75)</td>
<td>2.54 (1.92)</td>
<td>3.09 (2.67)</td>
<td>2.88 (2.09)</td>
</tr>
</tbody>
</table>

Abbreviations: CT, computed tomography; HR, high resolution; NA, not applicable.

\(aP = .31\).
piece is that we demonstrate the decrease in TRE with increasing CT resolution\(^9\)\(^-\)\(^{45}\), thus, better application accuracy can be expected. However, this is limited by the 3-D position-sensing unit’s spatial resolution, beyond which any increase in voxel resolution is lost.

In lateral skull base navigation, any measurement taken is affected with unavoidable error that should be considered. Thus, to achieve a 95% probability that a measurement will be “correct,” an interval of ±2 SD has to be considered. Even for the best combination used in this study (0.5-mm HRCT, mouthpiece, and anatomical landmarks) and under favorable experimental conditions, this would imply that the measurements will fall in the interval of 0.16 to 1.28 mm, which is not in the submillimetric precision range. To support microscopic navigated surgery at the lateral skull base or robotic interventions there, registration, tracking, and imaging techniques for lateral skull base surgery should be improved. To locate minute structures in the skull base, the resolution of any measuring tool should be at least 1 order of magnitude better than the characteristic dimension of the problem. Ideally, the tracked instrument can be located with subvoxel precision in isotropic submillimetric radiologic imagery (novel flat-panel technologies provide this with a low radiation dose) so that the still open challenge is to develop submillimetric 3-D tracking and subvoxel application accuracy with noninvasive registration techniques.

In conclusion, navigation at the lateral skull base is proceeding at the borders of practicability as the ultimate surgical goal, submillimetric application accuracy, stretches the dimensions of currently available radiologic imagery and 3-D measurement technology. However, navigation in this delicate anatomical area will definitely be a supplementary tool intraoperatively.

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Author Contributions: All authors had full access to all the data in the study and take responsibility for the integrity of the data and the accuracy of the data analysis.

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Analysis and interpretation of data: Kral, Riechelmann, and Freysinger.

Drafting of the manuscript: Kral and Riechelmann.

Critical revision of the manuscript for important intellectual content: Kral, Riechelmann, and Freysinger.

Statistical analysis: Kral and Riechelmann.

Administrative, technical, and material support: Riechelmann and Freysinger.

Study supervision: Riechelmann and Freysinger.

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REFERENCES


