Objective: To measure the effect of 4 different matching strategies on the accuracy of computer navigation on the face and within the nose and rhinopharynx.

Design: Survey.

Setting: Laboratory study.

Subjects: Six human cadavers studied within 24 hours of death.

Interventions: A commercially available navigation system with infrared optical tracking was used for computer navigation on the face and within the nose of the subjects after matching with external fiducials or with 3 different configurations of anatomical landmarks. Navigation errors were measured and correlated to matching strategies and compared through statistical analysis.

Results: Matching with external fiducials on the face results in smaller navigation error than matching with anatomical landmarks. The configuration of matching strategies with anatomical landmarks also significantly determines the accuracy of computer navigation, especially when different locations of accuracy measurement are considered.

Conclusion: Statistically significant findings have shown that the choice of a matching strategy is a major factor in the accuracy of computer navigation for ear, nose, throat surgery.


MEDICAL imaging is important in sinus and skull base surgery not only for diagnosis, but also for anatomical reference during the surgical procedure. This is especially true in endoscopic sinus surgery where disorientation can lead to serious complications. May et al1 reported a 0.89% incidence of major complications in endoscopic sinus surgery, with complications occurring even in experienced hands. Since there is considerable variation in individual facial skull anatomy, a surgeon performing endoscopic sinus procedures requires a computed tomographic (CT) study of the paranasal sinuses (preferably in coronal incidence) available in the operating room. This also applies to external approach sinus surgery or skull base procedures. A computer navigation system essentially offers higher accuracy in meeting the same goals. Modern navigation systems are sufficiently accurate, available, and user-friendly, making them applicable in daily practice. Some surgeons even claim these systems be used routinely in every endoscopic sinus procedure.2 Probably the major limiting factor in the accuracy of present navigation systems is the matching procedure that links the computer data to the anatomy of the patient on the operating table.

Matching can be done through externally applied fiducials or anatomical landmarks, or with surface matching. Each of the methods presents typical advantages and disadvantages that influence applicability and accuracy.

The spatial distribution of the matching points that are chosen—fiducials, anatomical landmarks, and surface points—and their distance from the focus of the operative act will probably also influence accuracy of navigation. The individual anatomy of the facial skull, and the laxity and consistency of the facial skin are other possible causes of navigation error.

The aim of this study was to establish the accuracy of navigation and to investigate the source of errors. Therefore, matching strategies were investigated on cadavers, using fiducials or anatomical landmarks in different configurations. In addition, the influence on accuracy of the patients’ individual characteristics and the location of the measurement points were evaluated.
METHODS AND MATERIALS

TEST SUBJECTS

Six human cadavers were evaluated within 24 hours of death. All manipulations were performed in accordance with accepted standards of postmortem study. Approval was obtained from the Medical Ethics Committee of the Antwerp University Hospital, Antwerp, Belgium.

CT IMAGING

Helical CT scans of the cadaver heads were obtained in the axial scanning plane from the vertex to the mastoid process. The following scanning parameters were used: 140 kV, 230 mA, and 23-cm field of view. The heads were scanned using a section thickness of 3 mm, with a pitch of 1 to 1.5, depending on the tube cooling condition of the system. Interpolation of the data with recalculation into 1-mm slices was obtained. Data were stored on an optical disk from which they were again transferred to the navigation computer.

NAVIGATION SYSTEM

All navigation was done using the Medivision Image Guided Surgery System (Medivision AG, Oberdorf, Switzerland), which is used jointly by the Ear, Nose, Throat (ENT) Department and the Orthopaedics Department at the Antwerp University Hospital.

The hardware of the system consists of a Unix-Sun Ultra 1 computer workstation and an Optotrak 3020 (Northern Digital, Waterloo, Ontario) infrared active optical tracking system.

The system uses "pair-point matching," which means that a set of landmarks is entered by the user and stored in the data file preoperatively. At the time of surgery, the same set of landmarks is pointed on the patient on the operating table, which allows the computer to compare the spatial distribution of the 2 sets of points entered. The system then calculates an "error score," which is the mean mutual distance in millimeters of all pairs of points. The system will only proceed to the actual navigation if the error score is less than 2.

On the operating table, a "reference base" equipped with LEDs attached to the patient’s head serves to track position changes, but has no role in the matching procedure.

MEASUREMENT OF THE ACCURACY OF NAVIGATION

Metal pins were placed in the heads of the cadavers: at the vertex, both mastoid processes, the cartilaginous nasal septum, and the posterior wall of the pharynx. This made measurements possible at the periphery of the skull as well as anteriorly and posteriorly in the operative field of a typical endoscopic sinus procedure. The pinheads are easily recognized visually on CT image. The navigation computer easily allows distance measurements between a starting point (defined as the position of the navigation pointer held against the pinhead in the test subject) and an end point (defined as the position of the same pointer against the same pinhead seen on the computer screen). This distance is denoted as "navigation error" (NE) in the "Results" section.

MATCHING STRATEGIES

Four different matching strategies were used (Figure 1), one method (A) using only externally applied fiducials, and 3 methods (B-D) using only anatomical landmarks: A, Four external fiducials: 2 placed on the frontal skin and 2 placed on both malar regions. B, Four anatomical landmarks: the anterior end of left and right frontozygomatic sutures, the midline at the junction between the anterior nasal spine and the premaxilla, and the nasion on the midline. C, Four anatomical landmarks: the anterior end of left and right frontozygomatic sutures, and the skin point overlying the most lateral aspect of the junction of the tragus and antitragus on the left and right ears. D, Six anatomical landmarks: a combination of the landmarks used in strategies B and C.

STUDY SEQUENCE

The external fiducials and the pins were applied to the cadaver head. Computed tomographic scanning was performed and data were stored on an optical disk and transferred to the navigation computer. Matching procedure A was performed followed by accuracy measurements, then procedures B, C, and D in turn were performed, each followed by accuracy measurements. After each procedure, all matching data were erased from the computer before the next matching procedure was started. All procedures were done a second time in sequence ABCD in the same subject.

STATISTICS

The test-retest issue was first investigated by means of a paired t test. Analysis of variance was used (SPSS 9.0; SPSS Inc, Chicago, Ill) to investigate the effect of different "sources of error" on NE. These sources of error were the matching procedure, the location where accuracy was measured, and the test subject. Matching method and location were considered as fixed factors, whereas test subject was considered as a random factor. The chosen model was set up to investigate the effect of matching method, location, and test subject, as well as the interaction between matching method and test subject and between matching method and location. These are the relevant interactions that point out whether the average NE for the different test subjects is dependent on the matching method and whether the NE for the different locations is dependent on the matching method. Post hoc multiple comparisons were adjusted with the Waller-Duncan method.

RESULTS

The test-retest analysis (t11=0.9, P=.35) revealed that NE did not systematically change or improve upon a second matching trial on the same test subject.

The analysis of variance showed that the matching method (P=.007), the location (P=.005), the interaction between matching method and location (P=.008), and the interaction between matching method and patient (P<.001) had a significant effect.
on NE. Figures 2, 3, and 4 show the mean±SE NEs of the different test subjects, matching methods, and locations. The Table lists the averages for the matching methods as well as other relevant data.

Post hoc analysis indicated that method A, which has the smallest NE, and method D, the next best strategy, differ significantly from the other methods. Methods B and C do not differ from each other. Post hoc analysis of the NE for the different locations reveals that the vertex has the largest mean, differing significantly from the other locations, except for the right mastoid measurements. The NE at the rhinopharynx level is the smallest, although it forms a homogeneous subset with the anterior nasal septum and the left mastoid. The anterior nasal septum and both mastoids compose the third subset of statistically indistinguishable values.

Casiano performed a MEDLINE search of the English-language literature between 1993 and 1998 for scientifically based reports on accuracy of computer navigation for ENT surgery. He states that “None of the studies evaluated these parameters in a well-controlled scientific manner comparing the same parameters with and without the use of image-guidance technology.”

The aim of this study is not to report the accuracy of a specific system. It is, rather, to measure the influence of matching strategies on the accuracy of computer navigation for ENT surgery. The absolute value of NE, as defined herein, cannot be compared with measurements of accuracy mentioned in other studies or with other equipment or even in a clinical setting, since the mean NE used in the calculations is measured at different locations. In this study design, 3 of the 5 locations where NE was measured are “peripheral” (ie, both mastoids and the vertex), which makes NE not only a more sensitive parameter, but also higher in absolute value.

The methodology of CT image acquisition inevitably influences the accuracy of navigation. This issue is rarely addressed in the literature. Spiral CT scanning offers several advantages over conventional slice-by-slice scanning. Data acquisition is much faster, which avoids inaccuracies due to patient movement. Recalculation of images to 1 mm or even submillimeter slices is possible without excessive accumulation of patient radiation dose. The continuous sampling in spiral CT scanning yields better contrast and spatial resolution along the z-axis than that which can be achieved with classical scanning with the same slice thickness.

Vorbeck et al measured accuracy of computer navigation in ENT sinus surgery using the navigation system and by pointing at anatomical landmarks within the surgical field. They used an optical tracking system and report a precision of 1 to 3 mm.

Several systems use a headset for matching, which is worn by the patient at the time of CT acquisition and again at the time of surgery. Accuracy of matching measured in reference to the headset cannot be compared with accuracy measured in reference to the patient’s anatomy (anatomical landmarks or skin fiducials). The headset has to be positioned twice, which is an additional cause of error, not detected by the computer and overlooked in several reports. In the operating room, this possible error is only verified visually by the surgeon at the start of the surgery. Headset shift can cause a change in accuracy during the procedure. Gunkel et al use a mouthpiece for matching, which also has to be positioned a first time for CT acquisition and a second time in the operating room. They call this repositioning the central limiting factor in the accuracy of the setup.
Accuracy of computer navigation has also been the subject of studies in the neurosurgical literature. Intraoperative precision reported with frameless navigation systems was 4.8±2.1 mm according to Barnett et al.8 and 4±1.4 mm according to Gumprecht et al.9 with both groups using externally applied fiducials for matching. We believe that this degree of accuracy might be insufficient for sinus and skull base surgery. From the absolute values of NE measurable at the location of rhinopharynx and the anterior nasal septum (which constitutes the operative field in the case of endoscopic sinus surgery), the system and matching strategies used in this study and in clinical practice appear to be more accurate. Part of this can be explained by the fact that the inherent shifting of brain tissue as occurs in neurosurgical applications is not an issue in the setup of our study, nor is it a source of error in the “bone surgery” applications of ENT sinus and skull base surgery.

Our results indicate that pair point matching using 4 fiducials (method A) externally applied on the skin is superior in accuracy over pair point matching using 4 anatomical landmarks in 2 different configurations (methods B and C). Others have come to a similar conclusion in neurosurgery using a stereotactic arm10,11 or in a study comparing the use of 5 externally applied fiducials to 6 anatomical landmarks with or without additional surface matching on a head phantom.12 External fiducials on a face or skull covered with skin are more mobile than they are on a head phantom. This is the basic reason we chose to perform this study on human bodies.

We find 6-point anatomical landmark matching (method D) more accurate than 4-point anatomical landmark matching (B and C). The number of landmarks used and their spatial spread on the skull seem to be of significance. It is generally accepted that matching points should be nonlinear or, even better, should not lie in the same virtual plane. Because we apply computer navigation for sinus or skull base surgery, we choose our matching points on the face rather than on the skull. Moreover, the spherical configuration of the skull makes its surface less suitable for matching since there may be more than one solution for the matching algorithm. A head-set frame, even when it is removable as in some navigation systems for endoscopic sinus surgery,6,13 is cumbersome in other applications and its removal and subsequent repositioning may be an additional source of error. The choice of available locations where fiducials can be placed on a flat segment of bone with preferably only thin overlying skin is limited. Anatomical landmarks on the facial skin or skull that are easily and accurately identifiable on CT as well as on the patient are also limited. A higher number of widespread landmarks can be expected to result in greater accuracy.14

The significant interaction between matching method and location of measurement illustrates the importance of the right choice of a matching configuration for different types of surgery. Measurements at the periphery or outside the space bounded by the landmarks used for matching (such as the vertex and mastoid locations in this study) will have larger errors than measurements in

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**Table 1. Descriptive Statistics of Navigation Error for 4 Different Matching Methods**

<table>
<thead>
<tr>
<th>Method</th>
<th>n</th>
<th>Mean</th>
<th>SD</th>
<th>SE</th>
<th>95% CI for Mean</th>
<th>Minimum</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>A: Fiducials</td>
<td>46</td>
<td>2.1304</td>
<td>1.4237</td>
<td>0.2099</td>
<td>1.7076-2.5532</td>
<td>6.00</td>
<td>0.00</td>
</tr>
<tr>
<td>B: 4 Internal points</td>
<td>53</td>
<td>4.9811</td>
<td>2.8181</td>
<td>0.3871</td>
<td>4.2044-5.7579</td>
<td>11.00</td>
<td>0.00</td>
</tr>
<tr>
<td>C: 4 Internal points</td>
<td>56</td>
<td>4.5179</td>
<td>2.9848</td>
<td>0.3989</td>
<td>3.7185-5.3172</td>
<td>13.00</td>
<td>0.00</td>
</tr>
<tr>
<td>D: 6 Internal points</td>
<td>56</td>
<td>3.0536</td>
<td>1.5424</td>
<td>0.2061</td>
<td>2.6405-3.4666</td>
<td>7.00</td>
<td>0.00</td>
</tr>
<tr>
<td>Total</td>
<td>211</td>
<td>3.7251</td>
<td>2.5691</td>
<td>0.1769</td>
<td>3.3765-4.0738</td>
<td>13.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

*CI indicates confidence interval.

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**Figure 3.** Mean±SE navigation error for different matching methods. The horizontal bars group location measurements that are not statistically different after post hoc Waller-Duncan tests.

**Figure 4.** Mean±SE navigation error by different locations. The horizontal bars group location measurements that are not statistically different after post hoc Waller-Duncan tests.
a more central location (such as rhinopharynx and the anterior nasal septum). The matching methods used in this study are probably more suitable for endoscopic sinus surgery than for lateral skull base surgery.

The significant interaction between matching method and test subjects reflects our experience in clinical use of the navigation system. Frontozygomatic sutures are not always as easily found on the patient as they are on the CT image. Skin fiducials move more if skin laxity is high, which limits the use of external fiducials on the face of an obese patient.

In circumstances of comparable accuracy, anatomical landmark matching should be preferred over fiducial matching for reasons of patient comfort and higher cost-effectiveness. When anatomical landmarks are used, the diagnostic CT scan can serve for navigation also, provided it is saved on an optical disk. This obviates repetition of the CT examination. There is also no need to schedule the operation in conjunction with the “navigation CT examination” in a patient wearing fiducials on the face, with the additional risk of a fiducial coming loose or displaced in the time between the CT and the operation.

The Medivision Image Guided Surgery System uses active optical tracking, which has its advantages and disadvantages in comparison with electromagnetic tracking. A disadvantage of an optical system in clinical practice is that surgeons and assistants must stay clear of the “visual field” of the tracking cameras. This is not the case in electromagnetic tracking, which then again is influenced by magnetic fields in the operating room. In our department over the past year, we have used the Medivision system with pair point matching using 6 anatomical landmarks in varying procedures and found the system sufficiently accurate in each.

The method of surface matching has been introduced more recently into the software of our system. In addition to anatomical landmark matching, it appears promising in attaining higher accuracy. The additional use of surface matching will be the subject of a forthcoming study.

Modern computer navigation systems have an intrinsic accuracy that is amply sufficient for use in ENT surgery. In routine practice, the surgeon seeks economical, easy-to-use yet accurate equipment that permits procedures to be well tolerated by the patient.

The use of anatomical landmarks avoids additional CT examinations and further patient discomfort. Provided that use is made of a sufficient number of well-distributed anatomical landmarks on the facial skull, matching accuracy can become acceptable, superseding the present standard of fiducial matching.

While other factors such as individual patient anatomy and the experience with navigation undoubtedly affect the accuracy of computer navigation for ENT surgery, the major influence as concluded statistically is the choice of a matching strategy. Eventual loss of accuracy of computer navigation systems probably depends mainly on the way they are used in daily practice and specifically on the matching procedure that is chosen.

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REFERENCES