Placement of Endosteal Implants in the Zygoma after Maxillectomy: A Cadaver Study Using Surgical Navigation


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Endosteal implants facilitate obturator prosthesis fixation in tumor patients after maxillectomy. Previous clinical studies have shown, however, that the survival of implants placed into available bone after maxillectomy is generally poor. Nevertheless, implants positioned optimally in residual zygomatic bone provide superior stability from a biomechanical point of view. In a pilot study, the authors assessed the precision of VISIT, a computer-aided surgical navigation system dedicated to the placement of endosteal implants in the maxillofacial area. Five cadaver specimens underwent hemimaxillectomy. The cadaver head was matched to a preoperative high-resolution computed tomograph by using implanted surgical microscrews as fiducial markers. The position of a surgical drill relative to the cadaver head was determined with an optical tracking system. Implants were placed into the zygomatic arch, where maximum bone volume was available. The results were assessed using tests for localization accuracy and postoperative computed tomographic scans of the cadaver specimens. The localization accuracy of landmarks on the bony skull was 0.6 ± 0.3 mm (average ± SD), as determined with a 5-df pointer probe; the localization accuracy of the tip of the implant burr was 1.7 ± 0.4 mm. The accuracy of the implant position compared with the planned position was 1.3 ± 0.8 mm for the external perforation of the zygoma and 1.7 ± 1.3 mm for the internal perforation. Eight of 10 implants were inserted with maximal contact to surrounding bone, and two implants were located unfavorably. Reliable placement of implants in this region is difficult to achieve. The technique described in this article may be very helpful in the management of patients after maxillary resection with poor support for obturator prostheses. (Plast. Reconstr. Surg. 107: 659, 2001.)

The prosthetic supply for patients after maxillectomy exhibits a number of problems. Soft-tissue shrinkage resulting from a lack of support from underlying bone often prevents satisfactory long-term aesthetic and functional rehabilitation. Proper sealing of the nasopharynx toward the oral cavity is essential for phonetic function and swallowing. Myocutaneous or osteomyocutaneous microvascular flaps are widely used to achieve this goal.1–4 Immediate flap surgery may, however, prevent the early detection of residual or recurrent cancer.5 When flap reconstruction is not indicated, an obturator prosthesis enables functionally and aesthetically satisfying rehabilitation.4,6–9

Often a sufficient retention of the obturator prosthesis can be achieved without additional anchorage. If retention is not sufficient, osseointegrated implants can be used for prosthesis fixation.6,10–12 Two problems with endosteal implant placement arise in these cases. First, bone in close proximity to the resection cavity is usually sparse. In most cases, only the root of the zygomatic arch offers sufficient bone volume for implant placement. Second, implant osseointegration is often delayed by previous irradiation treatment.13 Roumanas et al.14 published the largest collective of patients treated with placement of endosteal implants after maxillectomy: 102 implants were inserted in 26 cases. The overall rate of implant survival was 69.2 percent. For patients with additional irradiation treatment, the implant survival rate was 63.6 percent.
whereas a survival rate of 82.6 percent was reported in nonirradiated patients. The survival rate of the implants placed close to the maxillectomy defect was poor (33 percent); however, this percentage is not significant because of only six implants being inserted.

Fixing the obturator prosthesis on implants placed in the contralateral maxilla is biomechanically problematic because the prosthesis forms a long lever. The intense mechanical stress on the implant shaft leads to the loss of peri-implant bone.\textsuperscript{15,16} The bilateral placement of implants avoids excessive biomechanical stress, resulting in longer implant survival.\textsuperscript{17}

The purpose of this study was to assess the possibility of optimizing the placement of endosteal implants in patients after maxillectomy by means of computer-aided navigation techniques.\textsuperscript{18–24} Computer-aided surgery is currently used in various surgical specialities, for instance, in stereotactic neurosurgical procedures and for pedicle screw insertion in spine surgery. In craniofacial and maxillofacial surgery, computer-aided surgery is introduced for various indications. A cadaver study for the evaluation of a specialized navigation system developed for the placement of endosteal implants is presented.

**Materials and Methods**

**Hardware and Software**

VISIT, a modular software system for the development of exploratory software for surgical applications, was used in this study. VISIT is based on AVW 2.5, a software library dedicated to biomedical image processing (Biomedical Imaging Resource, Mayo Clinic, Rochester, Minn.).\textsuperscript{25} Surgical instruments and patient motion were tracked using an optical position measurement system (Flashpoint 5000, Image Guided Technologies Inc., Boulder, Colo.). Accuracy of the system was found to be in the vicinity of 1 mm.\textsuperscript{26,27} The workstation used was a Sun UltraSPARC 10 (Sun Microsystems, Palo Alto, Calif.). The software system was developed for implant dentistry and was used without modification for the experiments.\textsuperscript{28}

Because the position of the drill bit relative to the optical probe (V-probe) must be determined intraoperatively to visualize the position and direction of the drill bit, a special-calibration light-emitting diode assembly was developed. This calibration probe contains a precision-machined titanium inlay that matches a 2-mm pilot drill. By inserting the drill into this sterilized calibration probe, a geometric relation (referred to as offset vector) can be determined intraoperatively (Fig. 1).

**Preoperative Imaging and Planning**

The initial precision tests and preliminary planning procedures were performed on a macerated bony skull. Then, five cadaver heads underwent a left hemimaxillectomy that preserved the orbital floor and the zygomatic arch. To match the coordinate system of a sensor assembly mounted to the skull with the coordinate system of the computed tomograph, miniature titanium screws (Leibinger AG, Freiburg, Germany) were inserted in the periorbital region and the zygomatic arch. These screws are referred to as fiducial markers in this article.

High-resolution computed tomographic scans were done on a Philips Tomoscan 7000 SR (Philips AG, Best, The Netherlands). The resolution of the resulting volume image was $0.35 \times 0.35 \times 1.00$ mm$^3$. Preoperative planning was performed by determining a starting point and a second point that defined the direction of the implant on the axial computed tomographic slices (Fig. 2). The implant position was assessed and corrected if necessary by using multiplanar orthogonally reformatted axial, coronal, and sagittal slices. In a second step, the planned implant positions were also visualized using transparent volume renderings of the bone.

![Fig. 1. Tool set for intraoperative computer navigation:](image-url)
Registration

To compute a mathematical transformation that conveys the coordinate system of the computed tomographic scan to the patient (usually referred to as patient-to-scan registration), an LED emitter array was attached to the skull of the cadaver specimens by using a single titanium osteosynthesis screw. All position data of surgical tools are reported relative to the position of this emitter array, thus making the fixation of the patient by means of an external head-frame, such as in neurosurgical procedures, unnecessary (Fig. 3).

For patient-to-scan registration, at least three of the preoperatively inserted titanium microscrews must be identified on the patient, using the 5-df pointer probe, and on the computed tomographic volume image. The mathematical registration transformation that translates the position of a surgical instrument relative to the reference sensor from the cadaver head to the scan was computed by the algorithm given by Horn.

Visualization

The aim of our surgical navigation system is to position endosteal implants in exact agreement with the preoperative plan. For general orientation in the operating field, transparent volume renderings were generated that displayed both the bone surface and the planned implants. The position of the drill tip was projected into frontal and lateral renderings in real time (Fig. 4, above).

The position of the drill was also visualized on obliquely reformatted computed tomographic slices. Two slices are perpendicular to each other, intersecting the axis of the drill. The third slice is in normal position with the drill axis and touches the tip of the drill. When the drill matches the preoperative planning, the implants appear in full length and diame-
ter on the reformatted slices (Fig. 4, below). All images are updated twice per second with reference to the drill position.

Surgical Procedure

Because of the limited space, the implant sockets were drilled using an extraoral approach. This approach can be easily transferred to the patient because only a small incision is necessary and the zygoma need not be exposed. Implant sockets were drilled in both zygomatic bones in each cadaver specimen. The implant sockets were marked with radiopaque gutta-percha points. For postoperative evaluation, a computed tomographic scan with parameters identical to those of the preoperative scan was performed.

Evaluation of System Performance

Preliminary evaluation of the system’s precision was performed after registration by comparing the position readings of the osteosynthesis screws used as fiducial markers with the position readings in the computed tomographic volume using the 5-df probe. The accuracy level of the drill calibration was determined similarly.

To evaluate the final results, both the preoperative computed tomographic scans containing the surgical plan and the postoperative scans with the gutta-percha points in situ were loaded into a medical image processing software package (Analyze, Biomedical Imaging Resource). A tangent to the bone of the orbital floor (of-tangent) was drawn on coronally reformatted computed tomographic scans, and a tangent to the infratemporal fossa (if-tangent) was constructed on the original axial scans. Virtual points marked the region where the implants perforated the zygomatic bone on the outer surface (external perforation) and on the inner surface (internal perforation). The shortest distance from these two points to the tangents were measured on both the preoperative and postoperative computed tomographic scans (Figs. 5 and 6). These data were analyzed using Excel 5.0 (Microsoft, Redmont, Wash.). Accuracy was assessed by calculating the average value of the deviations from the positions on the preoperative computed tomographic scans compared with those on the postoperative scans. The experimental error was given as the empirical SD of these measurements, calculated as follows:

$$\sigma = \sqrt{\frac{\sum_{i=1}^{N}(\hat{x} - x_i)^2}{N - 1}},$$

where $\sigma$ is the square root of the empirical variance (= SD), $N$ is the number of single measurements, $x_i$ is a single measurement, and $x$ with an overbar is the arithmetic mean of the single measurements.

RESULTS

The average localization accuracy of the pointer probe on 28 microscrews was $0.6 \pm 0.3$ mm, ranging from 0.2 to 1.0 mm. This deviation was the same for the screws that were used as fiducial markers for registration as for those that were not. The same procedure repeated with the pilot drill on 28 microscrews resulted in an average deviation of $1.7 \pm 0.4$ mm, ranging from 0.9 to 3.0 mm. Table I shows all measurements concerning the relative deviation of planned and postoperative implant distances from the fossa infratemporalis tangent (axial slice orientation) and the orbital floor tangent (coronally reformatted slices). The measurements were performed on 10 implants in five specimens, and the data were analyzed using Microsoft Excel 5.0.

The average deviation from the preoperatively planned external perforation of the implant channel was $1.3 \pm 0.8$ mm, ranging from 0.1 to 2.8 mm. The average deviation of the
FIG. 4. Intraoperative visualization of the drilling procedure. (Above) The actual position of the drill on frontal and lateral volume renderings. Both the position of the drill tip (arrow) and the future direction of the implant channel according to the actual orientation of the drill are visualized (blue line). The planned implant channels are visible on both views as red or green graphics visible through the transparent surface. (Below) The same position on three multiplanar reformatted computed tomographic views (drill tip indicated by the endpoint of the yellow line or circle, implant position in red).
The internal perforation was 1.7 ± 1.3 mm, ranging from 0.1 to 4.9 mm. Therefore, the gross accuracy for implants positioned in the cadaver specimens was 1.5 ± 1.1 mm, ranging from 0.1 to 4.9 mm. It is noteworthy that unwanted perforations of the cortices did not occur. Visual inspection showed that 80 percent of the implants were inserted successfully.

**DISCUSSION**

The positioning of dental implants in the zygoma after ablative tumor surgery in the maxilla is a new application of computer-aided surgery, which is difficult to perform without computer guidance. As stated by Roumanas et al., the biomechanically favorable position of implants in the zygoma after maxillectomy is associated with low implant survival rates. Using all available bone for the placement of endosteal implants will improve the outcome of this procedure. Preoperative computed tomographic scans and other visualization aids, such as stereo-lithographic models, provide information on the individual anatomic situation. Transferring preoperative planning data to the operating theater is, however, difficult. Drilling templates used in implant dentistry are difficult to apply because of the complex
intraoperative situation. Computer-aided surgery was applied in implant dentistry in a number of clinical trials. The first efforts\(^{32}\) suffered from problems in the electromagnetic tracking hardware used.\(^{33}\) The further development of this technique involved improved sensor technology.\(^{24}\)

A crucial point is the intraoperative usability and the reliability of such a navigation system. Concerning the latter, the results presented above seem to be appropriate. The direction of the surgical drill cannot be assessed visually by the surgeon because of the minimal invasive approach to the zygomatic arch. The localization accuracy of the microscrews measured with the 5-df probe was excellent (0.6 ± 0.3 mm, 1.1 maximum) compared with the resolution of approximately 1 mm of the high-resolution computed tomographic scans. The localization error of the tip of the implant burr is higher (deviation 1.7 mm ± 0.4 mm, maximum 3.0 mm), correlating well with the average postoperative accuracy of 1.5 ± 1.1 mm. This indicates that the V-probe and the intraoperative drill calibration procedure may require further improvement. Nevertheless, 8 of 10 implants in this study were placed in a satisfactory position. Two implants were in an unfavorable position: one was inserted considerably too steep compared with the surgical plan; the other was situated too far posteriorly. These problems occurred mainly because of the difficulty in maintaining good correlation of the implant burr and the planned axis of the implant. Deviations were induced by such mechanical problems as the mobility of the implant burr in the drill’s bearing and the deflection of the drill on its way through the bone because of anatomic factors. Because these two implants were planned in a very steep manner, we assume that this problem can be avoided by penetrating the cortex as perpendicularly as possible. Improved visualization techniques and the use of head-mounted displays might improve the accuracy of the procedure.

In conclusion, the success rate of 80 percent is impressive in a procedure that cannot be performed by using this minimal invasive approach without computer navigation. Therefore, in consideration of the results of the cadaver study, we think that clinical application is justified. Further refinement of the optical tracking probes also may improve the resolution accuracy of the computed tomographic scan used. This resolution, which is typically 1 mm in the case of conventional high-resolution computed tomography, is also the theoretical limit of the system.

### TABLE I

Measurements of the Relative Deviation of Planned and Postoperative Implant Distances from the Fossa Infratemporalis Tangent and the Orbital Floor Tangent

<table>
<thead>
<tr>
<th>Cadaver Specimen No.</th>
<th>Position on Skull/CT*</th>
<th>Slice Orientation</th>
<th>External Perforation (difference in mm)</th>
<th>Internal Perforation (difference in mm)</th>
</tr>
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<tbody>
<tr>
<td>I</td>
<td>Right/axial</td>
<td>1</td>
<td>1.4</td>
<td></td>
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<tr>
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<td>Left/axial</td>
<td>1.4</td>
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<td></td>
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<td>2.8</td>
<td>2.4</td>
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<td>Left/coronal</td>
<td>1.2</td>
<td>1.3</td>
<td></td>
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<tr>
<td>II</td>
<td>Right/axial</td>
<td>1.3</td>
<td>1.9</td>
<td></td>
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<tr>
<td></td>
<td>Left/axial</td>
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<td>1.4</td>
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<td>III</td>
<td>Right/axial</td>
<td>1.4</td>
<td>1.4</td>
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<td>2.5</td>
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<td>2.7</td>
<td>4.9</td>
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<tr>
<td>V</td>
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<tr>
<td></td>
<td>Left/axial</td>
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<td>0.2</td>
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<tr>
<td>Average</td>
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<td>1.7</td>
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<tr>
<td>Standard Deviation</td>
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<td>0.8</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>Range</td>
<td></td>
<td>0.1–2.8</td>
<td>0.1–4.9</td>
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</table>

* CT, computed tomographic.
ACKNOWLEDGMENTS

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