Accuracy of drilling guides for transfer from three-dimensional CT-based planning to placement of zygoma implants in human cadavers

Key words: 3D computerized tomography, drill guide, oral implant, preoperative planning, zygoma

Abstract: The accuracy of surgical drilling guides was assessed for placement of zygoma implants. Six zygoma fixtures of length 45 mm (Nobel Biocare, Göteborg, Sweden) were placed in three formalin-fixed human cadavers using surgical drilling guides. The fabrication of these custom-made drilling guides was based on three-dimensional computerized tomography (3D-CT) data for the maxillary-zygomatic complex. The installation of the implants was simulated preoperatively using an adopted 3D-CT planning system. In addition, anatomical measurements of the zygomatic bone were performed on the 3D images. The preoperative CT images were then matched with postoperative ones in order to assess the deviation between the planned and installed implants. The angle between the planned and actually placed implants was $\approx 102^\circ$ in four out of six cases. The largest deviation found at the exit point of one of the six implants was 2.7 mm. The present study showed that the use of surgical drilling guides should be encouraged for zygoma implant placement because of the lengths of the implants involved and the anatomical intricacies of the region.
under general anesthesia. Head movements, indeed, decrease the transfer accuracy to clinically significant levels.

Alternatively, personalized drilling templates may be fabricated by a computer-based transfer from the available 3D CT planning data [Fortin et al. 1995]. This allows incorporation of all predetermined biomechanical, aesthetic and anatomical factors during the surgical procedure. These drilling guides are commercially available for oral implant placement and allow the drill to be guided according to the preoperative planning data. Their clinical effectiveness has been described and the fabrication error of such guides is usually reported as being below 0.5 mm [Fortin et al. 1995, 2000; Demey & Vrielinck 1999]. Nevertheless, the transfer error to the surgical field has not yet been assessed.

For zygoma implants, intraoperative transfer is even more crucial, demanding a certain level of accuracy of the applied technique to reach a predictable treatment outcome. This is not documented in the literature and the present study therefore aims to address this issue by a validation study in human cadavers. To enable the obtained transfer accuracy from planning to surgery to match a clinical acceptance level, the maximum allowable error for zygoma implants will be established using dimensional measurements of the human zygoma.

Materials and methods

Three formalin-fixed adult cadavers of humans who had donated their bodies for scientific research and education to the Department of Anatomy, Faculty of Medicine, Catholic University Leuven, were selected for a zygoma implant placement procedure. Spiral CT scan images (Somatom Plus S®; Siemens, Erlangen, Germany) of the maxillary–zygomatic complex were taken to enable preoperative implant planning in the zygoma. Based on the preoperative CT images, a total of six zygoma fixtures with a 45-mm length (Nobel Biocare, Göteborg, Sweden) were planned in the three cadaver heads using the adopted 3D CT planning system developed at the Katholieke Universiteit Leuven (Verstreken et al. 1996). This image-based surgery simulation environment allows consideration of all critical aspects involved in zygoma implant placement. The planning system encompassed features such as dynamic 2D reslicing in 3D space, manipulation of the implant models in relation to the surrounding structures, covisualization of image reslices, 3D models of bony structures and implants and deliberate composition of views of the surgical field containing any number of such elements. Additional features were added specifically for zygoma implant planning, and included a true 3D curve defined for orthogonal reslicing along the jaw arch to better span the region from the zygoma to the maxillary ridge and a 2D reslicing along the implant axis, enabling improved inspection of the implant axis in relation to the anatomical structures and in particular to the sinus cortex (Fig. 1). In addition, the planning system allows assessment of the implant configuration as a whole.

After the planning procedure, the patient-specific data were used to design a custom-made drilling guide (SurgiGuide®, Materialise, Leuven, Belgium). The drilling guide was fabricated by stereolithography from the data set provided by the 3D planning software program in a United States Pharmacopoeia (USP) Class 6 approved
resin that can temporarily be used in contact with body fluids and may be sterilized by different methods. This drilling guide was designed to allow intimate fitting between the interior aspect of the guide and the superficial jaw bone underneath. The unique and stable fit onto the jaw bone was possible because of the complex shape of the jaw bone. To incorporate the previously made preoperative plan of implant placement, drilling cylinders were inserted into the drilling guide. These cylinders were positioned at exactly the same place and in the same direction as the implant simulation on the computer. In the cylinders, adaptable stainless steel (316L) tubes were inserted to guide the drill during surgery. The internal diameter of the tubes was adapted according to the different drill diameters used during implant installation. The risk of abrasion could not be completely excluded, although it was never experienced during surgery. The ample cooling of the drill would take care of eventual particles through the various lateral openings in the drilling template. The use of similar guides for the installation of more than 1000 implants never revealed any side-effects.

The surgeon (CM), who also conducted the 3D planning, performed surgery on the cadavers according to the instruction manual for zygoma implant placement (Nobel-Biocare, Göteborg, Sweden). After palatal incision and reflexion of the soft tissue up to the zygoma level and after drilling through a template prefabricated following the indications of the radiological preoperative planning, the zygoma fixtures were inserted with a low-speed motor and finally with a special screw-driver. During the installation procedure different drills were applied: starting with a round burr, then switching to a 2-mm diameter drill, proceeding with a 2.9-mm and terminating with a 3.5-mm diameter drill of 45 mm length to enable insertion of zygoma implants with a 45 mm length. It should be noted that the zygoma fixtures have two diameters on the same fixture: 3.9 mm on the top and 4.5 mm at the maxilla level. Another important factor to note is that actual drilling was performed without opening the usual small sinus slot in the outer cortex of the sinus. The latter procedure is usually carried out to install zygoma fixtures, because it allows adjustment of the drilling direction intraoperatively (Stella & Warner 2000; Tamura et al. 2000). In the present study, however, it was our intention to assess the complete dependence on the template and, thus, only the personalized template served to guide drilling.

In addition to these measurements, a pilot study was set up to enable the obtained transfer accuracy from planning to surgery to match the maximum allowable error for zygoma implant placement. For this purpose, dimensions of human zygoma bone were retrieved from 3D CT images by accumulating evidence from the six zygoma bones used in the present study from ex vivo subjects and from another eight human zygoma bones, taken from four patients (four females, mean age 42 years, range 23–53 years) who had actually undergone zygoma implant insertion starting from the 3D CT planning data. Measurements were made directly on the 3D images and rounded to the nearest 0.1 mm. For each zygomatic bone, dimensional measurements included the height of the zygoma measured along the planned implant axis and the width of the zygoma measured midway and perpendicularly on this implant axis in sagittal and frontal directions. The latter was obtained using a careful reslicing procedure perpendicular to the axis.

Data analysis

After implant insertion, postoperative CT scanning was performed according to the aforementioned procedure. The resulting images [including the zygoma implants placed] could thus be matched to the preoperative CT images [including the zygoma implants planned] using the fusion approach of Maes et al. (1997), which remains unaffected by local image deformations. After resampling postoperative over preoperative data, the zygoma implants were easily segmented, which allowed them to be visualized and inspected in the preoperative space. For each implant, the fit between planned and actual state was expressed by the triplet $\mu, \alpha, \zeta$ being the angle between planned and actual axis, $\alpha$ being the distance between planned and actual entry point at the maxilla, and $\zeta$ being the distance between planned and actual exit point at the zygoma.

Results

The installation of zygoma implants based on custom-made drilling guides in three adult human cadavers allowed the surgeon to place the implants without making a sinus slot. The surgical procedure was performed without major difficulties or complications. Figure 3 indicates the differences in implant axis between the planned and the actual implant positions. In four of the six cases, the angle between the planned and actually placed implants was <3°. In the right implant of cadaver 3 [C3] it was 3.1° while the left implant in cadaver 1 [C1] showed the largest deviation (6.9°). These angular differences resulted in a measurable deviation of the implant position in the horizontal and/or vertical direc-

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**Fig. 2.** For each implant, matching between planned and actual implant position is expressed by the triplet $\mu, \alpha, \zeta$. $\mu$ represents the angle between planned and actual axis, $\alpha$ is the distance between planned and actual entry point at the maxilla, and $\zeta$ is the distance between planned and actual exit point at the zygoma.

**Fig. 3.** The angular deviation between planned and actual implant axis did not exceed 3° for four of the six implants placed. For the left zygoma implant in C1, an important angular difference was noted (6.9°).
the present chart demonstrates that, in four of the six implants installed, the linear deviations were smaller than 2.5 mm. For the left zygoma implant in C1, the largest deviation was noted with a difference between actual and planned implant position of 7.9 mm at the exit of the zygoma bone.

Fig. 4. In agreement with the angular deviations reported in Fig. 3, the present chart demonstrates that, in four of the six implants installed, the linear deviations were smaller than 2.5 mm. For the left zygoma implant in C1, the largest deviation was noted with a difference between actual and planned implant position of 7.9 mm at the exit of the zygoma bone.

In Fig. 4. Again, it was clear that four of the six implants were placed within a reasonable distance from the planned implant (<2.5 mm difference at the measuring point). The right implant in C3 showed a deviation at the exit point of 2.7 mm, while at entry the deviation was only 1.1 mm.

A more detailed presentation of the deviation between planned and placed implants in horizontal and vertical directions is found in Table 1. In general, deviations in the caudocranial direction were larger than those in the frontal and sagittal directions. The maximum deviation in the caudocranial direction was 6.74 mm, found for C1 at the exit point of the zygoma, with the placed implant in a more cranial position than the planned implant (Fig. 5).

To determine whether the measured differences were clinically significant, dimensional measurements of the zygoma were performed (Table 2). When compared to the required width and height of the zygoma implants, it was noted that the height along the implant axis varied quite extensively (from 7.9 to 24.9 mm). The same applied to the sagittal width (variation from 11.2 to 28.2 mm). Frontal dimensions were less variable (6.6–11.1 mm).

Discussion

Zygoma implant placement is a complex surgical procedure with a very specific goal, namely the insertion of implants through the posterior maxilla in the zygoma to obtain a steady anchorage when the anterior maxilla does not offer sufficient bone volume (Weischer et al., 1997; Stella & Warner, 2000; Tamura et al., 2000). The strength of the anchorage in the zygoma compensates the bad quality of the bone, mostly type IV in the posterior maxilla. From a biomechanical point of view, it has been demonstrated that, if the zygoma fixtures are connected to anterior implants, the masticatory forces applied to the fixed prosthesis are transferred to the zygoma. Because of the anatomical conditions, the curve of the lateral wall of the sinus and of the posterior wall of the zygoma can have a sinusoid shape, making the insertion of the fixture difficult. For these reasons, a 3D reconstruction of the maxilla and the zygoma and a preplanned positioning of the implants are required to achieve a reliable treatment outcome. From a radiological point of view, 3D CT is the primary preoperative examination for indications that benefit from treatment by zygomatic fixtures (Schramm et al., 2000). Indeed, given an appropriate visualization, 3D CT images provide an unparalleled depiction of the complex anatomical topography that has to be respected when deciding on the trajectory of a zygoma implant. Our 3D imaging software allows the bone structures to be followed along the implant trajectory. The irradiation involved and the

Table 2. Dimensional measurements of the human zygoma, assessed on 3D CT images (n = 14)

<table>
<thead>
<tr>
<th>Height of zygoma measured along implant axis (mm)</th>
<th>Width of zygoma measured midway and perpendicularly on implant axis (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frontal width</td>
<td>Sagittal width</td>
</tr>
<tr>
<td>Mean 14.1</td>
<td>8.3</td>
</tr>
<tr>
<td>SD 4.7</td>
<td>1.4</td>
</tr>
<tr>
<td>Min 7.9</td>
<td>6.6</td>
</tr>
<tr>
<td>Max 24.9</td>
<td>11.1</td>
</tr>
</tbody>
</table>

Table 1. Deviation in caudocranial, frontal and sagittal directions between actual and planned implant positions determined at the entry point of the implant to the maxilla and the exit point from the zygoma

<table>
<thead>
<tr>
<th>Deviation (mm)</th>
<th>Cadaver 1</th>
<th>Cadaver 2</th>
<th>Cadaver 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>At entry to maxilla</td>
<td>At exit from zygoma</td>
<td>At entry to maxilla</td>
</tr>
<tr>
<td>Caudocranial</td>
<td>Left</td>
<td>Right</td>
<td>Left</td>
</tr>
<tr>
<td></td>
<td>3.86</td>
<td>0.28</td>
<td>6.74</td>
</tr>
<tr>
<td></td>
<td>4.52</td>
<td>1.33</td>
<td>1.65</td>
</tr>
<tr>
<td></td>
<td>0.22</td>
<td>0.10</td>
<td>3.76</td>
</tr>
</tbody>
</table>

Positive values indicate a deviation of the planned implant position in the indicated directions (caudocranial, frontal or sagittal). Negative values indicate a movement in the reverse direction.
expense incurred, especially in the manufac-
turing of the stereolithographic models and
drilling guides, seem justified consider-
ing the high risks associated with the
placement of such long implants into the
zygoma. Although no reports on zygoma
implants are available in this context,
some deviations from the planned route
have been observed by other teams.

The transfer error from preoperative
planning to the surgical field remains a
critical factor. Besimo et al. (2000) reported
transfer errors within acceptable ranges of
0.3–0.6 mm, but noted that transfer errors
from reformatted CT to the surgical site
may result in more significant errors. For
3D computer-based transfer to drilling
guides, a higher transfer precision (1.1°
rotation and 0.2 mm translation) was ob-
tained (Fortin et al. 2000). For transfer from
planning to surgery by means of conven-
tional surgical guides, Naitoh et al. (2000)
found angular deviations between planning
and placement ranging from 0.5° to 14.5°
with an average of 5.0°. The templates used
in such studies were teeth-supported. The
CT data were used to transfer only the po-
tions and/or inclination of the implants to
a laboratory-made template placed on
working plaster models.

The present study is the first to report on
transfer accuracy through 3D CT-based
templates to surgery. These stereolitho-
graphic templates are bone-supported. The
present study focused on the zygoma im-
plant procedure, and the transfer error was
noted to be within acceptable ranges for
five of six implants placed with angular de-
viations below 3.5° and linear deviations
below 3.3 mm. For the zygoma bone dimen-
sions recorded in the pilot study, these
deviations were clinically not relevant. For
the sagittal dimensions, the results were mostly
satisfactory because the zygoma bone is
known to have a quite variable sagittal width,
depending on the presence or ab-
sence of a pronounced concavity at its pos-
terior aspect. A posterior fenestration could
indeed result in damage to the muscular
and neurovascular structures in this tim-
eral region. It should, however, be noted
that one implant placed at the left zygoma
of cadaver 1 showed angular and linear de-
viations which were much larger. Based on
the dimensional variability of the zygoma
bone, such errors might, even with accu-
rate 3D CT-based planning and transfer,
create some potential dangers. This devi-
ation could be explained by several factors,
such as limited mouth opening and the
backward position of the bony structures
to be implanted. The lack of a metal cylin-
der at the stage of implant insertion follow-
ing the serial drilling probably explains the
deviation for that one implant.

Conclusions

For zygoma implant placement, the com-
plex surgical procedure and the variable zy-
goma anatomy encourage the use of a vali-
dated 3D CT planning system. To achieve
optimal transfer of this planning to the
surgical field, drilling guides should be 3D CT-
derived models with bone-fitting. Zygoma
drilling guides seem to offer an accurate
tool to achieve a successful and reliable
treatment outcome in the majority of
cases. The extra effort seems appropriate
considering the eventual risk if the planned
route is not respected.

Acknowledgements

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toral researcher of the FWO Fonds Weten-
uschappelijk Onderzoek Flanders.

Résumé

La précision des guides pour le forage chirurgical a été éva-
uée pour le placement d’implants dans la région zygo-
matique. Six implants zygomatiques de 45 mm de lon-
gueur (Nobel Biocare, Göteborg, Suède) ont été placés
chez trois cadavres humains conservés dans du formol.
La fabrication de ces guides de forage a été effectuée sur
base de données de CT en trois dimensions du complexe
zygomatico-maxillaire. L’installation des implants a été simu-
lée prérachettée en utilisant un système de planifi-
cation CT tri-dimensionnel. De plus, des mesures
anatomiques de l’os zygomatique ont été effectuées sur
les images tri-dimensionnelles. Les images CT préopéra-
tives ont ensuite été mises avec les postopératoires afin
d’évaluer la déviation entre les implants planifiés et pla-
cés. L’angle entre les implants planifiés et placés demeu-
rat chez quatre des six cas en-dessous de trois degrés. La
déviation la plus importante trouvée au point de sortie
d’un des six implants était de 3.7 mm. L’étude présente
a montré que l’utilisation des guides de forage chirurgical
devrait être encouragée pour le placement des implants
dans la région zygomatica vu les longueurs des implants
utilisés et les problèmes anatomiques rencontrés dans
ce style.

Zusammenfassung

Es wurde die Genauigkeit von chirurgischen Bohrführungsschien-
en für die Plazierung von Zygoma-Implantaten untersucht. Sechs Zygoma-Implantate mit einer Länge von

45 mm (Nobel Biocare, Göteborg, Schweden) wurden bei 3
formalfixierten menschlichen Kadavern mittels chirur-
gischen Bohrführungsschienen eingesetzt. Die Herstel-
lung dieser individuell angefertigten Schienen basierte auf
Daten von 3-D CT der Oberkieferregion. Die Pla-
zierung der Implantate wurde präoperativ mittels eines 3-
D CT Planungssystems simuliert. Zudem wurden anato-
mische Messungen des zygomatischen Knochens auf den
3-D Bildern durchgeführt. Die präoperativen CT-Bilder
wurden dann mit den postoperativen verglichen, um die
Abweichung in der Richtung zwischen den geplanten und
den gesetzten Implantaten zu bestimmen. Der Winkel
zwischen den geplanten und den effektiv gesetzten Im-
plantaten blieb bei 4 der 6 Fälle unterhalb von 5°. Die gröss-
te Abweichung am Austrittspunkt eines der 6 Implantate
betrug 3.7 mm. Die vorliegende Studie zeigte, dass die Ver-
wendung von chirurgischen Bohrführungsschienen für die
Plazierung von Zygoma-Implantaten aufgrund der Länge
der betroffenen Implantate und der anatomischen Komple-
xität der Region gefordert werden sollte.

Resumen

Se valoró la exactitud de unas guias de perforación quirúr-
nicas para colocación de implantes en el zigoma. Se colo-
caron seis fijaciones de zigoma de 45 mm de longitud
(Nobel Biocare, Göteborg, Suecia) en 3 cadáveres huma-
os fijados con formol usando guías de perforación qui-
rúnicas. La fabricación de estas guias de perforación he-
chas a medida se basó en los datos de 3 de la complejo
zygomatico-maxilar. La instalación de los implantes se si-
muló preoperatoriamente usando un sistema de planifi-
cación 3-DCT adoptado. Además, se llevaron a cabo me-
diciones anatómicas del hueso zigomático en las imáge-
nes 3D. Las imágenes de CT preoperatorias se componían con las postoperatorias en orden a valorar las
desviaciones entre los implantes planeados e instalados.
El ángulo entre los implantes planeados y los actualmen-
te instalados permanecieron en 4 de los 6 casos por debajo
de los 5°. La mayor desviación encontrada en el punto de
salida de una de los 6 implantes fue 3.7 mm. El presente
estudio mostró que el uso de guias quirúnicas de perfora-
tión debería ser potenciada para implantes zigomáticos de-
bido a las longitudes de los implantes involucrados y la
intrincada anatomía de la zona.
References


