Comparison of different registration methods for surgical navigation in cranio-maxillofacial surgery

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Abstract

BACKGROUND: Surgical navigation requires registration of the pre-operative image dataset with the patient in the operation theatre. Various marker and marker-free registration techniques are available, each bearing an individual level of precision and clinical practicability. In this study the precision of four different registration methods in a maxillofacial surgical setting is analyzed. MATERIALS AND METHODS: A synthetic full size human skull model was registered with its computer tomography-dataset using (a) a dentally mounted occlusal splint, (b) the laser surface scanning, (c) five facial bone implants and (d) a combination of dental splint and two orbital bone implants. The target registration error was computed for 170 landmarks spread over the entire visceral- and neurocranium in 10 repeats using the VectorVision2 (BrainLAB AG, Heimstetten, Germany) navigation system. Statistical and graphical analyses were performed by anatomical region. RESULTS: An average precision of 1mm was found for the periorbital region irrespective of registration method (range 0.6-1.1mm). Beyond the mid-face, precision linearly decreases with the distance from the reference markers. The combination of splint with two orbital bone markers significantly improved precision from 1.3 to 0.8mm (p<0.001) on the visceralcranium and 2.3-1.2mm (p<0.001) on the neurocranium. CONCLUSIONS: An occlusal splint alone yields poor precision for navigation beyond the mid-face. The precision can be increased by combining an occlusal splint with just two bone implants inserted percutaneously on the lateral orbital rim of each side.
Comparison of different registration methods for surgical navigation in cranio-maxillofacial surgery


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SUMMARY

Background: Surgical navigation requires registration of the pre-operative image dataset with the patient in the operation theatre. Various marker and marker-free registration techniques are available, each bearing an individual level of precision and clinical practicability. In this study the precision of four different registration methods in a maxillofacial surgical setting is analyzed.

Materials and methods: A synthetic full size human skull model was registered with its CT-dataset using (a) a dentally mounted occlusal splint, (b) the laser surface scanning, (c) five facial bone implants and (d) a combination of dental splint and two orbital bone implants. The target registration error was computed for 170 landmarks spread over the entire viscero- and neurocranium in ten repeats using the VectorVision® (BrainLAB AG, Heimstetten/Germany) navigation system. Statistical and graphical analyses were performed by anatomical region.

Results: An average precision of 1mm was found for the periorbital region irrespective of registration method (range 0.6 to 1.1mm). Beyond the mid-face, precision linearly decreases with the distance from the reference markers. The combination of splint with two orbital bone markers significantly improved precision from 1.3mm to 0.8mm (p<0.001) on the viscerocranium and 2.3mm to 1.2mm (p<0.001) on the neurocranium.
Conclusions: An occlusal splint alone yields poor precision for navigation beyond the mid-face. The precision can be increased by combining an occlusal splint with just two bone implants inserted percutaneously on the lateral orbital rim of each side.

Keywords:
Surgery, Computer-Assisted,
Surgery, Maxillofacial
Comparative Study
Phantoms, Imaging
Tomography, X-Ray
INTRODUCTION

The complex three-dimensional geometry and the requirement for precise facial symmetry pose challenges to reconstructive maxillofacial surgery. Performing pre-operative surgical planning on a rapid prototyping model created from the computer tomography (CT) scan is a sophisticated and costly approach (Hassfeld and Muhling, 1998). Despite diligent planning on the stereolithography models, the procedure remains subject to considerable imprecision due to the difficulty to assess the complex craniofacial anatomy during the operation. More recently, computer-based 3D pre-operation planning based on CT datasets opened the door to surgical navigation (Hassfeld et al., 2000; Luebbers, 2004; Yeshwant et al., 2005a; Yeshwant et al., 2005b; Ritter et al., 2006). Surgical navigation assists the surgeon in transporting the pre-operative plan into the OR (Marmulla and Niederdollmann, 1998; Marmulla, 1999) and is today an established method in cranio-maxillofacial surgery (Hassfeld and Muhling, 2000; Gellrich et al., 2002; Schmelzeisen et al., 2002; Marmulla et al., 2004c; Schmelzeisen et al., 2004; Hohlweg-Majert et al., 2005).

The key element to all surgical navigation is the correct registration of the image dataset to the patient (Eggers et al., 2006). Precise registration is crucial as it has direct repercussion onto the precision of all subsequent navigation tasks. Registration involves identifying structures in the preoperative scan and matching them to the patient’s current position in the operation setting (Maurer and Fitzpatrick, 1993; Wirtz et al., 1998; Schramm et al., 2000a).

Registration techniques can be categorized into two main groups: (I) marker-based registration (Altobelli et al., 1993; Hassfeld et al., 1995; Howard et al., 1995;
Schramm et al., 1999; Luebbers, 2004) and (II) marker-free registration (Troitzsch et al., 2003; Marmulla et al., 2004b; Hoffmann et al., 2005; Marmulla et al., 2005b). Marker-based registration requires markers that are apparent in the preoperative images and are easily detectable on the patient during the procedure. These can be (a) percutaneously inserted bone-implanted screws (Simkovic et al., 2007), for example on the orbital rim, (b) a referencing dental splint fitted to the maxillary teeth (Schramm et al., 2001) or (c) self-adhesive reference markers glued to the skin (Alp et al., 1998; Hardy et al., 2006).

As opposed to these marker-based methods, marker-free registration relies on the patient's craniofacial anatomy itself. One approach is to register defined bone protuberances, e.g. as the Anterior Nasal Spine (Swennen et al., 2006), to the corresponding structures apparent in CT bone scan. A very distinct marker-free registration technique is the laser surface scanning. This method matches random points on facial skin surface to the soft tissues in the CT scan (Grevers et al., 2002; Hoffmann et al., 2005; Marmulla et al., 2005a).

Each of these registration methods is subject to error. In this in vitro study we compare the precision (van den Elsen et al., 1982; Maciunas et al., 1994) of four registration techniques specifically in respect to cranio-maxillofacial deployment. Prior precision studies evaluated values of general precision (Schlaier et al., 2002; Hoffmann et al., 2005) or concentrated on navigation precision in the maxillary and periorbital region (Marmulla et al., 2004a; a. b; Hardy et al., 2006). In contrast, this investigation examines the precision beyond the mere mid-face, i.e. the zygomatic arch, the frontoorbital band and the cranium.
The Journal of Cranio-Maxillofacial Surgery as repeatedly reported procedures that rely on computer-assisted surgical navigation (Lauer et al., 2006; Mischkowski et al., 2006). Some of these procedures exceed the scope of mid-face (Fei et al., 2007). Although the precision of navigation based registration techniques has been described previously (Hoffmann et al., 2005), so far reliable strategies for selecting the appropriate referencing technique depending on the anatomical region are missing. Prior studies imply that the measured navigation precision is identical over the entire skull. This study analyses the target registration error depending on both registration method and operation site and concludes with a recommendation of which registration technique to employ under which circumstances.
MATERIALS AND METHODS

Ten in vitro registrations were performed on a synthetic human skull model (A20, 3B Scientific, Hamburg/Germany) and navigated using the VectorVision® optical navigation system (BrainLAB Inc, Feldkirchen/Germany).

Model preparation

The skull model was prepared with both fiducial bone implants and a maxillary occlusal splint. The maxillary splint comprised four radio opaque markers positioned in different X, Y and Z directions (Cranial marker set, Stryker, Duisburg/Germany). Further, five 1.5 x 6mm titanium screws (Medartis Inc., Basel/Switzerland) were inserted. Screws were placed bilaterally on the fronto-zygomatic process and the zygomatic buttress of the maxilla. The fifth screw was inserted in the midline at the inferior part of the Anterior Nasal Spina. For precision measurement, 170 landmarks were created by drilling 1.2 mm holes at random on the model. A drilling diameter >1 mm was selected in order for the holes to be clearly visible on computer tomography slices. These landmarks were evenly spread over viscerocranium (Figure 1).

The skull model was scanned using a high resolution computer tomography scanner (Siemens Somatom Sensation 16, Siemens Medical Solutions, Erlangen/Germany). The 512x512 pixels dataset was acquired at a resolution of 0.39mm/pixel and 0.75mm slice thickness. The DICOM data was subsequently imported into the BrainLAB iPlan CMF 2.5 software and depicted as a 3D surface model. All
landmarks, including the center of the splint markers, the screw heads and the drillings were manually identified on the coronary, sagittal and axial slices as well as on the 3D surface (Figure 2). A 10-fold on-screen magnification was employed to ensure maximal precision. The 3D dataset along with the identified reference points were transferred to the navigation system by ZIP-Disk.

Referencing and navigation

The navigation system was setup in a partially obscured room to avoid infrared interference from ambient light. The same reference star routinely deployed during clinical navigation was securely screwed to the skull. Each experiment consisted of registration the skull using a defined method and subsequently identifying the drilled landmarks. Four registration methods were examined: (a) registering the markers on the oculusal splint, (b) registering the heads of the implanted screws, (c) registration using a combination of splint markers and orbital screws, (d) surface registration using the BrainLAB z-touch® laser scanner. The laser-scan was performed directly on the bone surface in the periorbital region, thus acquiring a cloud of approximately 200 distinct points. For each registration technique all 170 drilled landmarks were targeted with a tracked pointer. Although the pointer was placed exactly on the landmark, the navigation system recorded a fictive deviation, thus depicting the pointer head next to the landmark (Figure 3). The navigation software computes the target registration error (Fitzpatrick and West, 2001; Marmulla et al., 2005b) as the square root of the sum of squared deviation in all three spatial directions $\sqrt{\Delta X^2 + \Delta Y^2 + \Delta Z^2}$. This deviation was recorded for each landmark and registration method. The complete experiment was repeated 10 times with each of the four registration methods.

Data evaluation

For each examined landmark the referencing error was averaged over the ten experiment repeats. The landmarks were categorized into three anatomical regions:
periorbital region, viscerocranium beyond the periorbital region and neurocranium. Each anatomical region’s registration error was benchmarked against the precision achieved with the occlusal splint. The null-hypothesis was that all registration techniques yield comparable precision. Statistical analysis was performed using the two-tailed t-test. A probability p<0.05 was considered significant.

Graphical post-processing was performed in Matlab (Version 7.1/R14, TheMathworks Inc, Natick/USA). The distance between each landmark and the centre of gravity (COG) of the fiducials employed for referencing was calculated, e.g. COG of the four splint markers, or COG of the cloud of scanned laser points. The target registration error was plotted in relation to the distance from the COG. Further, a color map was wrapped around the virtual 3D surface model of the skull to better visualize the error for each anatomical region.
RESULTS

The target drillings could all be clearly identified on the reconstructed 3-D skull model in the iPlan (R) software. All registration and measurement repeats were carried out without difficulties. The average target registration errors for each registration method and anatomical region are shown in Table 1 and further visualized in Figure 4. Irrespective of registration technique, the periorbital precision is below 1.5mm. Beyond the mid-face, a linear correlation between target registration error and distance to the center of gravity of the reference marker polygon is found (Figure 5). Thereby, the largest targeting errors occur at the occipital and temporal landmarks. Imprecision ranges from 1.2 – 2.3mm, depending on the employed registration technique. Precision deterioration over distance is most prominent when registering only via dental splint and least pronounced when registering with the z-touch® surface scan. The regional precision after splint registration is best demonstrated by mapping the target errors onto a virtual 3D model of skull (Figure 6).

While all registration methods yield comparable results for the periorbital region, the combination of the occlusal splint with two orbital bone markers significantly improves precision from 1.3mm to 0.8mm (p<0.001) on the viscerocranium and 2.3mm to 1.2mm (p<0.001) on the neurocranium.
DISCUSSION

Our findings concur with pertinent literature (Schlaier et al., 2002; Marmulla et al., 2004b; Hoffmann et al., 2005; Hardy et al., 2006) and highlight the strong dependency of the targeting precision from the registration procedure (Eggers et al., 2006). In addition, our results demonstrate the correlation of targeting error and distance from reference markers in a maxillofacial application.

Dental reference splint

The utilized synthetic skull is a full size model of the human skull, thus yielding measurements comparable to those on a patient. In this in vitro study the dental reference splint was fitted just as on a real patient. The splint was mounted before image acquisition, then removed and replaced before each registration repeat. The measured target registration errors demonstrate an acceptable accuracy of approximately 1mm for clinical deployment in the periorbital mid-face region. However, targeting errors up to 3.5mm are found on the frontal, temporal or occipital skull. Thus, for these regions registration via dental splint alone is insufficient.

Occlusal splints provide an easy and non-invasive registration method (Schramm et al., 2001; Gellrich et al., 2002). But in a clinical setting the following practicability issues must be considered: Firstly, patient and care givers have been observed to forget mounting the removable dental splint before CT scan, thus rendering the dataset useless. Secondly, loosening or incorrect placement of the splint either during imaging or during subsequent registration can result in unforeseen errors (Marmulla et al., 2003). Poor stability of the maxillary teeth can cause imprecision even with a
well fitted splint. An edentulous situation can even completely inhibit the use of a splint (Schramm et al., 2001). Nevertheless, besides these caveats, we consider dental splinting a clinically viable and sufficiently precise registration method when navigation is confined to the periorbital region.

**Surface registration**

Laser surface scanning (z-touch®) has been shown to be sufficiently precise for clinical deployment in previous investigations (Grevers et al., 2002; Troitzsch et al., 2003; Hoffmann et al., 2005). It is comparatively practical to use due to its non-invasive nature. Also, it does not require application of any reference markers before image acquisition. It can thus avoid the necessity to repeat the primary diagnostic CT scan, should this have been taken without splint or other referencing kit. It is however important to realize that the soft tissues strongly influence the clinical precision of laser surface scanning. Particularly a decrease in post-traumatic edema can result in a significant registration error when registering to an initial CT scan where tissues were still swollen. In addition, performing a re-registration during surgery could be impossible due to alteration of the soft tissue situation throughout the procedure. This must be taken into consideration especially in cases where a coronal approach is chosen (Marmulla et al., 2004a).

In our in vitro study the rigid bone surface of the skull model was scanned for lack of soft tissues. The presented results thus describe the best possible technical precision of the surface scanning method. Thus laser scanning appears to be the most precise registration technique. Theoretically this can be explained by the larger set of
registration points acquired – up to 200 – as opposed to only four or five markers in conventional marker referencing. Taken as is, these excellent in-vitro laser surface scanning results must be interpreted with great caution as the soft tissues are not factored in. These in-vitro z-touch® measurements can serve as base-line for subsequent clinical studies.

**Bone-implanted fiducials**

Percutaneous insertion of bone implants, typically self-drilling screws, has been shown to be a viable referencing method (Schramm et al., 2000b; Schramm et al., 2001; Luebbers, 2004; Hohlweg-Majert et al., 2005; Wittwer et al., 2006). Screws can be inserted under local anesthesia e.g. on the fronto-zygomatic processes, on the zygomatic and the nasomaxillary buttresses of the maxilla and at the inferior part of the Anterior Nasal Spina. The main advantages of using screws as reference markers is that, unlike the occlusal splint, they are not subject to displacement between the time of image acquisition and the operation and that they are applicable in toothless cases. The downside is that screw insertion is an invasive procedure, with the risk of infection, scarring and prolonged skin irritation. The high precision demonstrated in this study using five screws is interpreted as result of the marker distribution. The polygon they span covers a large area of the viscerocranium and thus small errors are annihilated.
Combination splint and implants

The combination of a maxillary dental splint with only two fiducial screws inserted percutaneously on the lateral orbital rim can significantly improve the registration precision. The average target registration error significantly decreases from 1.1mm to 0.6mm \((p<0.001)\) in the periorbital region, from 1.3 to 0.8 \((p<0.001)\) in the viscerocranium and even from 2.3 to 1.2mm on the neurocranium \((p<0.001)\). The registration precision improvement is hereby not achieved by merely adding more markers in the region of the splint. Instead the fiducial screws are placed at a certain distance from the splint, on the easily accessible orbital rims. The combined reference markers (splint markers and two orbital screws) thus span a larger polygon over which patient registration is performed.

We noted that in clinical practice the splint position is verified primarily on the front fit, whereas bad fit on the molars can easily be overseen. The resulting axial targeting error can be compensated by the inert orbital screws. The combination of splint and fiducial implants permits a reduction from five percutaneously inserted screws to only two, thus lessening the patient’s discomfort. The eye brows mask any scarring that could result from screw placement. Scars from screw insertion are however themselves irrelevant if a classical brow approach is planned or has been performed previously, as in secondary trauma cases.
Combination splint and surface scan

Another approach to improve the registration precision would be to combine the occlusion splint with a laser surface scan, thus providing a completely non-invasive registration method (Maurer et al., 1995; Maurer et al., 1998). The surface scan can compensate small misalignments of the splint. The splint in turn would lessen the effect of soft tissue decongestion. Unfortunately, to this date the VectorVision2® system does not accommodate for such a combined registration technique.
CONCLUSIONS

An occlusal splint is sufficient for navigation of the mid-face but yields poor precision beyond that. The precision can be increased by combining an occlusal splint with just two percutaneous bone implants inserted bilaterally on the lateral orbital rim. In a clinical setting it is essential to carefully evaluate what level of precision is required and select the appropriate registration method accordingly. Our recommendations for registration method selection in cranio-maxillofacial surgery are detailed in Table 2.
ACKNOWLEDGEMENTS

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Maurer CR, Jr., Maciunas RJ, Fitzpatrick JM: Registration of head CT images to physical space using a weighted combination of points and surfaces. IEEE transactions on medical imaging 17: 753-61, 1998.


Figure 1: Skull model with mounted maxillary occlusal splint. Additional screws have been inserted as independent referencing markers (arrows). The 170 drilled landmarks for regional precision assessment are numbered.
Figure 2: Three-dimensional view of the skull model in the preoperative planning software (iPlan, BrainLAB). Both referencing fiducials and multiple landmarks have been digitized.
Figure 3: Screenshot of the navigation software with probe’s eye, coronal, sagittal and axial views. The pointer tip is manually directed into the drilled landmark on the skull model and the target registration error read off the navigation system’s display. Note the slight deviation in the lower right screen.
Figure 4: Average target registration error for each registration method. Registration with the splint alone produces the worst results. Splint combined with two orbital screws is significantly more precise than the occlusion splint alone.
Figure 5: Correlation between target registration error and distance from reference marker polygon. The most accentuated deterioration is found when registering via splint alone. Spreading the registration markers over a wider area by using multiple fiducial screws or a combination of two techniques improves the precision to distance correlation. The overall z-touch® precision is however overestimated in vitro as soft tissues are not accounted for.
Figure 6: Target registration error mapped onto the 3D surface model. Registration only via occlusal splint results in a rapidly deteriorating precision. The error increases with distance from the reference markers’ plane (maxillary row of teeth). Green: <1.5mm, yellow 1.5 to 2.5mm, red >2.5mm target registration error.
### TABLES

#### TABLE 1

Target registration error in mm for various registration techniques

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<th>Periorbital</th>
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<th>Splint &amp; lat.orb.</th>
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Splint: Occlusal splint

Z-Touch: Laser surface scanning

Screws: Bone implants as landmarks

Splint & lat.orb: Splint and two bone implants, one on each lateral orbital rim
### TABLE 2

Clinical recommendations for registration method in cranio-maxillofacial surgical navigation.

<table>
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<th>Registration method</th>
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<td>- Acute trauma with soft tissue edema</td>
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<td>Laser surface scanning</td>
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<td>- Backup strategy (when other methods fail)</td>
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<td>Combination of splint and bone implant markers on lateral orbitae</td>
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<td>- Skull base surgery (trauma and tumor)</td>
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<td>- Fronto-orbital advancement with or without skull forming procedures</td>
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