Advanced Concepts of Orbital Reconstruction

A Unique Attempt to Scientifically Evaluate Individual Techniques in Reconstruction of Large Orbital Defects

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Introduction

In most, if not all, clinical research papers and presentations on novel techniques in orbital reconstruction, combinations of different techniques have been used to highlight technological progress and increased quality of surgical outcomes in terms of predictability and reliability. 1–6 In the Amsterdam University Medical Centers, The Netherlands, a comprehensive research started in 2014 with the development of a human cadaver model for assessment of orbital reconstruction. This model was used in sequence to evaluate every single technological step in the process of orbital reconstruction. This article is a resume of this series of investigations and publications in which the additive value of individual steps used in computer-assisted surgery, including various intraoperative navigation techniques, in orbital reconstruction has been assessed.

KEYPOINTS

The use of a cadaver model allows assessment of the effect of individual steps of computer-assisted surgery on orbital implant positioning.

The accuracy and consistency of implant positioning without computer-assisted surgery are low, which emphasizes the need for intraoperative control.

3D virtual surgical planning leads to a better implant position through enhanced insight in anatomy and fracture details, and detailed knowledge on the ideal implant position.

Deviations from the ideal implant position can be identified with intraoperative imaging and the implant’s position can be improved accordingly.

Real-time navigation proves to be the safest, fastest and most accurate method of intraoperative navigation for orbital reconstruction.

The interventions evaluated were as follows:

1. Conventional transconjunctival reconstruction (baseline) 7
2. Reconstruction with transsinusoidal endoscopy 7
3. Reconstruction with virtual surgical planning 8
4. Reconstruction with intraoperative imaging 9
5. Reconstruction with intraoperative image-guided navigation 10
6. Reconstruction with intraoperative marker-based navigation 11
7. Reconstruction with intraoperative real-time navigation 12

Materials and methods

Materials and methods of assessment were almost identical in all studies. Fixed human cadaver heads were obtained from the Department of Medical Biology, Section of Clinical Anatomy and Embryology of the Amsterdam University Medical Centers. Computed tomography (CT) scans of the cadaver heads were performed at baseline (with intact orbits, T0) (SOMATOM Sensation 64; Siemens Healthineers, Erlangen, Germany). Scan parameters included collimation of 20 × 0.6 mm, 120 kV, 350 mAs, pitch 0.85, field of view 30 cm, matrix 512 × 512, reconstruction slice thickness of 0.75 mm with overlapping increments of 0.4 mm, bone kernel H70s, and bone window W1600 L400. The orbital floor and medial wall were fully exposed through a standard transconjunctival incision and retroseptal preparation. Following the
Jaquière classification, complex orbital defects (class III–IV) were created with piezoelectric surgery (Mectron SpA, Carasco, Italy).13 After creation of the orbital defects (T1), and postoperatively after implant placement (T2), consecutive CT scans were acquired using the aforementioned scanning protocol. After T2 imaging was acquired, the orbital reconstruction plates were removed, and the screw holes were covered with dental filling material (DuraLay; Reliance Dental Mfg Co, Worth, IL, USA) to make them invisible. In all studies, preformed orbital titanium mesh implants (KLS Martin, Tuttlingen, Germany) were used; the stereolithographic models (STL files) of these implants were imported in the iPlan Cranial software environment (version 3.0.5; Brainlab AG, Munich, Germany). The optimal position of the implant was virtually planned and served as the target position during reconstruction. The faces of the human cadaver heads were covered to prevent recognition in consecutive studies, and the various studies were carried out with time intervals of several months to years.

Validation studies were performed to investigate the accuracy and precision of different methods for orbital reconstruction. The acquired implant position was compared with the target implant position of the planning. For this purpose, a reference frame for the preformed orbital implant was created (Fig. 1).14 This reference frame made quantification of the difference between acquired and planned implant position possible: the individual rotational (roll, pitch, and yaw, in degrees) and translational (in millimeters) deviations served as the outcome parameters for all studies. In studies 1 to 5, 19 orbits were reconstructed by 2 surgeons; 10 orbits were reconstructed by 1 surgeon in study 6, and 20 orbits (of another cadaver group) were reconstructed by 2 surgeons in study 7. The results of studies 2 to 5 were compared with the baseline results (study 1). Studies 6 and 7 were compared with the results of study 5, because image-guided navigation could be considered the reference method for evaluating these enhanced navigation methods.

Conventional transconjunctival reconstruction (study 1)

In the first surgical session, all orbits were reconstructed without further technological additions, with a transconjunctival approach. Preformed orbital implants were positioned according to the best judgment of the surgeon and fixed with osteosynthesis screws. It is important to know that the surgeon had no access to information on the preoperative virtual planning, but only to a multiplanar visualization and 3-dimensional (3D) reconstruction of the CT scan acquired after creation of the orbital defects (T1). The information available to the surgeon and hardware used are visualized in Fig. 2. This study acted as a baseline study for comparison of implementation of the technologies evaluated.

Reconstruction with transsinusoidal endoscopy (study 2)

The orbital reconstructions in this surgical session were performed with the additional use of a transsinusoidal endoscope. The standard transconjunctival approach was again used to position the implant. To facilitate inspection with an endoscope, a gingivobuccal incision and a 5-mm antrostomy were created in the canine fossa concavity using a Piezotome (Mectron SpA). The sinus mucosa was removed, so the defect and position of the implant could be visualized from the maxillary sinus with a 30° endoscope (KARL STORZ SE & Co KG, Tuttingen, Germany). In Fig. 3, the available information during surgery and the hardware used are visualized. The results of this session were compared with the baseline study (study 1).
Fig. 3  Additional information at hand in reconstruction with transsinusoidal endoscopy (left), and hardware used (right). The multiplanar reconstruction and 3D reconstruction from study 1 (see Fig. 2) were accessible as well. (Courtesy of Ruud Schreurs, MSc, Alfred G. Becking, MD, DMD, PhD, FEBOMS, Jesper Jansen, MD, DMD, PhD, and Leander Dubois, MD, DMD, PhD.)

Fig. 4  The virtual surgical planning for reconstruction that was visible to the surgeon during reconstruction in study 3. No hardware tools were used in the workflow. (Courtesy of Ruud Schreurs, MSc, Alfred G. Becking, MD, DMD, PhD, FEBOMS, Jesper Jansen, MD, DMD, PhD, and Leander Dubois, MD, DMD, PhD.)

Fig. 5  Intraoperative scanning feedback. The result of intraoperative imaging is visualized on the screen (the necessary hardware is also shown). Based on these images, the surgeon could decide whether adjustment of the implant position was necessary. (Courtesy of Ruud Schreurs, MSc, Alfred G. Becking, MD, DMD, PhD, FEBOMS, Jesper Jansen, MD, DMD, PhD, and Leander Dubois, MD, DMD, PhD.)
Reconstruction with virtual surgical planning (study 3)

In the third session, the surgeons had access to a 3D virtual computer environment and to virtual planning tools in iPlan Cranial, such as segmentation and mirroring. Information on the ideal position of the orbital implant, which had been planned with the help of a skilled and experienced technical physician, was available during reconstruction (Fig. 4). The surgeons were challenged to put the implant in the best position according to the virtual plan. The results of reconstruction with preoperative 3D virtual planning were compared with the baseline results (study 1).

Reconstruction with intraoperative imaging (study 4)

An intraoperative CT scan was made after reconstruction of the orbits in this study. A scanning protocol identical to the T0, T1, and T2 studies was used for intraoperative imaging. The implant position was verified by the surgeon on the information seen in Fig. 5 and, if required, the orbital implant position was corrected. The procedure and the scans were repeated until the surgeon was satisfied with the resulting implant position. The results were compared with baseline (study 1).

Reconstruction with intraoperative image-guided navigation (study 5)

All orbits were reconstructed with assistance of intraoperative image-guided navigation (Kolibri; Brainlab AG). The preoperative virtual surgical plan was linked to the intraoperative position of the cadaver head (registration). The cadaver head was tracked using a skull reference marker array (Brainlab AG). After a stable position of the orbital implant was achieved intraoperatively, the navigation pointer was moved along the implant. The result was verified on the multiplanar views: the surgeon could compare the trajectory of the pointer with the contour of the planned position of the implant, which was shown as an overlay (Fig. 6). Results were compared with the baseline study (study 1).

Reconstruction with intraoperative marker-based navigation (study 6)

In this study, intraoperative navigation was again used, but feedback was obtained by indicating orientation markers in the implant design. Three markers were embedded in the preformed implant design, in a triangular fashion (Fig. 7). The markers were indicated as landmarks in the virtual surgical planning, which allowed comparison between the current position of the marker (indicated with the navigation pointer) and the planned position. This feedback was both visual, to obtain information about the direction of displacement, and quantitative, on the amount of displacement (as seen in Fig. 8).
implant-guided navigation workflow results were compared with the results of the image-guided navigation workflow (study 5).

Reconstruction with intraoperative real-time navigation (study 7)

For this study, a real-time navigation workflow was developed and used. An instrument (Titanium Orbital Positioner) was designed that attached to the preformed orbital implant and was compatible with tracking by the navigation system. The cohesion between implant, instrument and navigation tracking allowed calculation of the implant position from the instrument’s position, even during positioning of the implant. Real-time feedback on the current implant position in comparison to the planned position was provided, both visually and quantitatively, and the surgeon could be steered to the correct implant position under navigation guidance. The instrument attachment to the preformed implant and the feedback obtained during positioning are shown in Fig. 9. The reconstruction was compared with reconstruction with implant-oriented navigation (study 6).

Results

The results are all presented in later discussion in the same manner; statistical workflows, however, differed in some situations because of study design or scientific insights over the years. The outcome of the Orbital Implant Positioning Frame (shown in Fig. 1) parameters (roll, pitch, yaw, and translation) are provided in tables, and graphic representation of the mean obtained implant position with each technique (in relation to the planned position) is provided in the figures.

Conventional transconjunctival reconstruction (study 1)

The rotational and translational deviations of the acquired implant position in relation to the planned implant position are provided in Table 1. The mean and standard deviations of the positioning parameters show that there is minimal control in positioning of the orbital implant: the mean rotation around the z-axis (yaw) is larger than 15° and the mean translation is 5 mm. A maximum value of 47.6° is seen for the yaw. Precision, the consistency of positioning, is also low, as seen by the large standard deviations. Visual appraisal of the average acquired position of the implant (Fig. 10) illustrates the size of the quantitative deviations found. These results underline the need for intraoperative control during reconstruction.
Reconstruction with transsinusoidal endoscopy (study 2)

The rationale behind endoscopic-assisted orbital reconstruction is that a bidirectional view is created for the surgeon: the implant’s position may be visually assessed both transconjunctivally and, with the aid of an endoscope, transsinusoidally. The resulting implant positions are quantified in Table 2 and visualized in Fig. 11. The results suggest that there is no significant improvement with the use of an endoscope compared with the baseline. Although there are some unrelated advantages regarding exhibition of the procedure for training surgeons, accuracy and consistency of implant placement are again low.

Reconstruction with virtual surgical planning (study 3)

With virtual surgical planning available, the surgeon is able to check the information in the planning during the reconstruction of the orbit. In Table 3, the results are compared with the baseline study: roll, yaw, and translation are significantly more accurate with 3D virtual surgical planning. The standard deviations are smaller than in the baseline reconstructions as well, demonstrating improved precision. The addition of 3D virtual planning is considered to be superior to conventional reconstruction with multi-planar reconstruction information from a CT scan. Additional anatomic landmarks of the preoperative 3D planning, enhanced insight in the extent of the fracture, and the detailed knowledge of the ideal implant position help the surgeon to achieve a better reconstruction result (in terms of implant position). The mean acquired implant position is visualized in Fig. 12.

Reconstruction with intraoperative imaging (study 4)

With intraoperative imaging, major deviations from the ideal position can be identified and may be altered intraoperatively, to avoid a second procedure and potential complications. The position of the orbital implant improves significantly in terms of roll, yaw, and translation compared with the baseline study (Table 4), showing the advantageous effect of an intraoperative imaging during reconstruction. In Fig. 13, the improvement on implant positioning yielded by intraoperative imaging is shown. Significant improvement in yaw, the parameter with the largest deviation, is also recorded if the position after the first reconstructive attempt and the final CT scan are compared (Table 5), demonstrating the learning effect of intraoperative imaging and the guidance it provides.

Reconstruction with intraoperative image-guided navigation (study 5)

Image-guided navigation feedback may be generated immediately after the implant is first positioned. From comparison of the pointer’s trajectory with the implant’s contour in the

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Table 1 Rotational and translational deviation in conventional reconstruction (baseline)

<table>
<thead>
<tr>
<th></th>
<th>Mean</th>
<th>SD</th>
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<tbody>
<tr>
<td>Roll (deg)</td>
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<td>3.1</td>
</tr>
<tr>
<td>Yaw (deg)</td>
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<td>9.1</td>
</tr>
<tr>
<td>Translation (mm)</td>
<td>5.0</td>
<td>2.2</td>
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</table>

The mean and standard deviations (SD) of the rotations (roll, pitch, yaw) and translation are given.

Abbreviation: deg, degrees.

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Fig. 10 Angulated, top, and frontal view of the mean acquired position of the orbital implant with conventional reconstruction (orange). The planned implant position is visualized in gray. A deviation in yaw can be best appraised in the top view, whereas roll is best seen in the frontal view. (Courtesy of Ruud Schreurs, MSc, Alfred G. Becking, MD, DMD, PhD, FEBOMS, Jesper Jansen, MD, DMD, PhD, and Leander Dubois, MD, DMD, PhD.)
Table 2  Quantification of endoscopic-assisted implant positioning, compared with conventional implant positioning

<table>
<thead>
<tr>
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<th>Conventional</th>
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<th>Endoscope</th>
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<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
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<tr>
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<td>-9.8</td>
<td>9.1</td>
<td>-7.1</td>
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<tr>
<td>Pitch (deg)</td>
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<td>-0.3</td>
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<td>Yaw (deg)</td>
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<tr>
<td>Translation (mm)</td>
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<td>2.2</td>
<td>4.2</td>
<td>2.1</td>
</tr>
</tbody>
</table>

Fig. 11  Mean acquired position with endoscopic-assisted orbital reconstruction (blue) compared to the planned position (grey). (Courtesy of Ruud Schreurs, MSc, Alfred G. Becking, MD, DMD, PhD, FEBOMS, Jesper Jansen, MD, DMD, PhD, and Leander Dubois, MD, DMD, PhD.)

Table 3  Results of reconstruction with virtual planning versus results of conventional planning

<table>
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<tr>
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<th>Virtual Planning</th>
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<td>SD</td>
<td>Mean</td>
<td>SD</td>
</tr>
<tr>
<td>Roll (deg)</td>
<td>-9.8</td>
<td>9.1</td>
<td>-4.5</td>
<td>3.5</td>
</tr>
<tr>
<td>Pitch (deg)</td>
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<td>Yaw (deg)</td>
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<td>10.9</td>
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<td>6.8</td>
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<tr>
<td>Translation (mm)</td>
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<td>2.2</td>
<td>2.6</td>
<td>1.7</td>
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</table>

Fig. 12  Average position of the implant for reconstruction with preoperative virtual planning (green). The planned position is visualized in gray. Compared with Figs. 9 and 10, the average obtained position resembles the planned position more closely. (Courtesy of Ruud Schreurs, MSc, Alfred G. Becking, MD, DMD, PhD, FEBOMS, Jesper Jansen, MD, DMD, PhD, and Leander Dubois, MD, DMD, PhD.)
Table 4  Quantification of orbital implant position obtained with intraoperative imaging

<table>
<thead>
<tr>
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<th>Intraoperative Imaging</th>
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<td>SD</td>
<td>Mean</td>
<td>SD</td>
<td></td>
</tr>
<tr>
<td>Roll (deg)</td>
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<td>9.1</td>
<td>–2.5</td>
<td>4.2</td>
<td>.01</td>
</tr>
<tr>
<td>Pitch (deg)</td>
<td>–1.3</td>
<td>3.1</td>
<td>–1.8</td>
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<td>.37</td>
</tr>
<tr>
<td>Yaw (deg)</td>
<td>17.8</td>
<td>10.9</td>
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<td>&lt;.01</td>
</tr>
<tr>
<td>Translation (mm)</td>
<td>5.0</td>
<td>2.2</td>
<td>3.0</td>
<td>1.4</td>
<td>&lt;.01</td>
</tr>
</tbody>
</table>

Compared with conventional reconstruction, significant improvements for all parameters but pitch are seen.

Fig. 13  Obtained implant position after reconstruction with intraoperative imaging (yellow). The mean of the final implant positions is visualized. (Courtesy of Ruud Schreurs, MSc, Alfred G. Becking, MD, DMD, PhD, FEBOMS, Jesper Jansen, MD, DMD, PhD, and Leander Dubois, MD, DMD, PhD.)

Table 5  Comparison of first result and final result in the cadaver group with adjustments after the first intraoperative image

<table>
<thead>
<tr>
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<th>First Intraoperative CT</th>
<th></th>
<th>Final Intraoperative CT</th>
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<th>P Value</th>
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<td>SD</td>
<td>Mean</td>
<td>SD</td>
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<tr>
<td>Roll (deg)</td>
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<td>8.2</td>
<td>–1.5</td>
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<td>.78</td>
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<td>Pitch (deg)</td>
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<td>13.2</td>
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<td>1.4</td>
<td>2.9</td>
<td>1.0</td>
<td>.16</td>
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</table>

Table 6  The effect of image-guided navigation on translation and rotation of the resulting implant position

<table>
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<th>Image-Guided Navigation</th>
<th></th>
<th>P Value</th>
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<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>SD</td>
<td>Mean</td>
<td>SD</td>
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</tr>
<tr>
<td>Roll (deg)</td>
<td>–9.8</td>
<td>9.1</td>
<td>–2.3</td>
<td>4.8</td>
<td>&lt;.01</td>
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<tr>
<td>Pitch (deg)</td>
<td>–1.3</td>
<td>3.1</td>
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<td>.77</td>
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<td>Yaw (deg)</td>
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<td>&lt;.01</td>
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<tr>
<td>Translation (mm)</td>
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<td>2.2</td>
<td>3.3</td>
<td>1.6</td>
<td>&lt;.01</td>
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</table>

The baseline results, conventional reconstruction, are used for comparison.
Table 7  The effect of image-guided navigation on translation and rotation of the resulting implant position

<table>
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<th>Image-Guided Navigation</th>
<th>Marker-Based Navigation</th>
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<td>Mean  SD</td>
</tr>
<tr>
<td>Roll (deg)</td>
<td>$-2.3$  $4.8$</td>
<td>$-2.3$  $3.1$</td>
</tr>
<tr>
<td>Pitch (deg)</td>
<td>$-1.1$  $2.2$</td>
<td>$-2.2$  $2.8$</td>
</tr>
<tr>
<td>Yaw (deg)</td>
<td>$8.8$  $8.1$</td>
<td>$6.0$  $8.1$</td>
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<tr>
<td>Translation (mm)</td>
<td>$3.3$  $1.6$</td>
<td>$1.4$  $0.7$</td>
</tr>
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</table>

The baseline results, conventional reconstruction, are used for comparison.
multiplanar views, the surgeon is able to evaluate the need for adjustment of the position of the implant. After adjustments are made, their effect is again assessed directly afterward. This short feedback loop for control and improvement of implant position yields significant improvement in acquired implant position in comparison to the baseline reconstruction (Table 6). Roll, yaw, and translation are further improved through image-guided navigation. Fig. 14 demonstrates the mean position with image-guided navigation and the planned position of the implant.

Reconstruction with intraoperative marker-based navigation (study 6)

Although image-guided navigation provides direct feedback after positioning and leads to better outcome in terms of positioning, the feedback itself could be improved: moving of the probe along the implant means that the surgeon needs to evaluate the implant’s position through interpretation of continuously shifting multiplanar views. The thought behind marker-based navigation is that more static, and quantitative, feedback is obtained from the marker positions; the triangular fashion makes interpretation of the 3D position feasible. Marker-based navigation is compared with image-guided navigation (study 5) and proves to be significantly more accurate in positioning an orbital implant in translation and yaw (Fig. 15, Table 7). The precision is improved as well, as seen from the smaller standard deviations. With marker-based navigation, intraoperative handling thus becomes more intuitive.

Reconstruction with intraoperative real-time navigation (study 7)

The real-time navigation workflow leads to very accurate positioning of the orbital implant, with small deviations compared with the planned position (Fig. 16, Table 8). Compared with the marker-based approach, positioning improves in terms of translation, roll, and yaw. This improvement may be explained by the real-time nature of the feedback. In image-guided or marker-based navigation, the surgeon can either obtain feedback or adjust the implant’s position and needs to switch between these processes. In real-time navigation, adjustment of the implant position is possible under navigation guidance. Feedback is presented in a true 3D fashion. Next to an improvement in implant position, surgery time is reduced and appraisal of the feedback by the surgeon is higher.

Discussion

These studies have been designed and executed to assess the relevance of individual parts of modern technologic advancements for orbital reconstruction, instead of the grouped results of computer-assisted surgery (3D virtual

**Table 8** Linear mixed model estimates for the effect of technique on the outcome parameters

<table>
<thead>
<tr>
<th></th>
<th>Marker-Based Navigation</th>
<th>Real-Time Navigation</th>
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<tbody>
<tr>
<td></td>
<td>Model Estimate</td>
<td>Model Estimate</td>
</tr>
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</table>
| Roll (deg)       | 3.2                     | 2.0                  | .03  
| Pitch (deg)      | 1.5                     | 1.3                  | .53  
| Yaw (deg)        | 3.4                     | 2.2                  | .01  
| Translation (mm) | 1.8                     | 1.3                  | <.01  

The P values are generated from Likelihood Ratio tests between a model with and without navigation.
planning, intraoperative imaging, and navigation). Significant progress in reliability and predictability has been achieved by introducing 3D virtual preoperative planning in which surgeons are thought to gain better insight in local anatomy, defect size, and complexity. This enhanced insight in turn generates helpful additional anatomic landmarks, leading to improvement in implant positioning.1,23,24 The same is true for traditional intraoperative imaging with CT, which also demonstrates a significant improvement in implant positioning, and it is hoped, decreases the need for secondary procedures.25,26

Three methods of intraoperative navigation have been assessed in combination with 3D virtual planning. Image-guided navigation significantly improves implant positioning compared with traditional reconstruction; however, marker-based navigation increases implant positioning even further and brings the mean translation within the calibration error. Using the Advanced Concepts of Orbital Reconstruction research protocol, the more user-friendly real-time navigation proves to be the safest, fastest, and most accurate way to place an orbital implant into the ideal position. The instrument for orbital implant positioning has not been clinically introduced yet: it is a proof of concept and in the process of further development.

The focus of the studies in this article, and of many other studies, is on orbital implant positioning.6,16,25,28,29 Outcome evaluation and presentation lead one to believe that implant positioning will be improved tremendously by using these novel technologies. Of course, the overarching goal for orbital reconstruction is not to improve surgical precision but to improve the quality of life for patients with orbital wall fractures. Surgery itself is an additional trauma to the orbit and its contents and should be well indicated and balanced with the anticipated outcomes of nonsurgical or less-invasive treatment options.30,31 Surgery and reconstruction with orbital implants have a distinct place in treatment of orbital wall fractures. When indicated, orbital implant positioning should be performed as accurately and precisely as possible, to improve bulb position, ocular movements, orbital volumes, and esthetic outcome.13,23,32,33

Clinics care points

- The effect of intraoperative navigation can be enhanced by providing more intuitive feedback on implant position. The more intuitive and user friendly the feedback is presented, the more accurate the implant is positioned.
- Translation of results from a preclinical setting to a clinical setting always warrants caution.
- The focus in these studies, and many other studies, is on implant position. However, the main goal in orbital reconstruction is not to improve surgical precision but to improve quality of life for the patient. Accurate implant positioning should be viewed as a means to achieve the goal, rather than a goal in itself.

Disclosure

In the submission process, in kind funding was declared. In all these studies, Brainlab provided the navigation equipment in kind, while KLS Martin provided the preformed orbital implants in kind. Additionally, for the real-time navigation, Brainlab provided the IGT link license in kind. KLS Martin provided the instrument in kind. This sub-project was supported by the S.O.R.G. Research Grant Award 2017.

References


