Advanced Diagnostics and Three-dimensional Virtual Surgical Planning in Orbital Reconstruction

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KEYWORDS
- Computer-assisted surgery • Orbit • Orbital trauma • Orbital reconstruction • Virtual surgical planning

KEY POINTS
- The first step in advanced diagnostics and virtual surgical planning is the generation of a virtual patient model.
- Information can be added to the virtual patient model through image manipulation for advanced diagnostic purposes.
- The virtual surgical planning is used preoperatively, but can also be used intraoperatively and postoperatively.

Introduction

The principles and limitations of orbital reconstruction have triggered technological developments in the past 2 decades. Because of the complex anatomy of the orbit and limited exposure during surgery, computer-assisted surgery (CAS) is of great added value.5–8 Several studies have shown that CAS assists the surgeon in achieving a better and more predictable treatment outcome.1,3,6–8 CAS consists of several preoperative, intraoperative, and postoperative components. Advanced diagnostics and three-dimensional (3D) virtual surgical planning (VSP) ensure a better inspection of the problem and the possible solutions during the preoperative phase.9,10 This article explains the preprocessing steps required to start VSP, the benefits of advances in diagnostics, and the tools used in VSP.

Imaging and preparation

Several modalities may be encountered in imaging of the orbit and orbital contents: MRI, ultrasonography, and two-dimensional (2D) or 3D radiologic imaging (eg, radiographs or computed tomography [CT]).11–13 MRI is seldom used as the primary imaging modality after trauma: soft tissue structures can be excellently distinguished, but sensitivity for hard-tissue trauma is low.11–13 MRI is contraindicated if metallic foreign bodies may be present. Ultrasonography may provide fast evaluation of the globe, but should not be used if a rupture of the globe is suspected because of the pressure exerted on the globe during image acquisition. This pressure may lead to further acute decompensation of the eye and/or intraocular content extravasation.11–13

CT is the modality of choice in orbital traumatology.14–16 CT has higher sensitivity for fracture detection than plain radiography and offers the additional possibility of internal hemorrhage detection. The problem of superimposition on 2D radiographic imaging and missing information of one of the dimensions is overcome by the 3D nature of the data that are produced with CT: the imaging volume is reconstructed and built up in voxels (3D pixels), each with a gray-scale value (Hounsfield unit [HU]) corresponding with the x-ray absorption within the voxel. From the image data, several planes can be reconstructed: a typical multiplanar view is made up by axial, coronal, and sagittal slices. In order to be able to distinguish existing bony ledges of the thin orbital floor and walls in the advanced diagnostics and virtual planning phase, it is recommended to use a maximum slice thickness of 1 to 1.5 mm.17–19

An important preparation step in CAS in orbital reconstruction is to create a virtual 3D model of the bony structures and soft tissue of the patient from the basic CT slices. Typically, volume rendering is used to create a fast 3D overview. The original anatomy and fractured orbit can be easily visualized. For planning purposes, a volume render is not sufficient because it cannot be manipulated; a surface model needs to be created for this. Surface rendering is a technique that generates this virtual surface model: voxels belonging to the same anatomical structure can be selected in the image volume (segmentation) and a 3D virtual object is generated based on the selection made. Surface models can be modified and manipulated and are therefore required for VSP. Typical surface models used in the preparation step include at least a surface model of the bony structures (Fig. 1) and the soft tissue exterior.

The generated surface models provide the same fast 3D overview as the volume renders and accurately represent the patient’s orbital anatomy and disorder. If required, CT images from different time points or 3D images from different imaging...
modalities (eg, MRI, intraoral scans, cone-beam CT, 3D stereophotogrammetry) can be combined with the CT data using (multimodality) image registration techniques. In this way, a CT base image can be augmented with additional 3D data to create a complete and detailed virtual representation of the patient: the virtual patient model (Fig. 2). The integration of accurate dental information from an intraoral scan might, for example, be useful to create a dental splint for navigation guidance during surgery. After the creation of the virtual patient model, advanced diagnostics and VSP can be performed.

**Advanced diagnostics**

In a dedicated software environment, further manipulation and analysis of the patient model can be performed. Advanced diagnostics is the expansion of the information that is readily available in the image data. This additional information can be obtained through image manipulation. Segmentation, mentioned earlier in relation to the generation of a surface model, is such a technique: voxels belonging to the same tissue type or anatomical structure are annotated within the image volume. This process may be done manually (coloring of the image set) or through thresholding, in which voxels greater than a certain gray-scale value (HU) are selected. This thresholding is, for instance, used in differentiating the bony structures from the soft tissues before a surface model of these bony structures is generated.

The paper-thin orbital floor and medial wall hamper the accuracy of threshold segmentation: more elaborate segmentation algorithms may be used to acquire an accurate

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*Fig. 1* Multiplanar views of a cone-beam CT scan and the generated hard-tissue surface model. (*Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)*

*Fig. 2* Combining different imaging modalities to generate an extended virtual patient model. In this example, a cone-beam CT scan, intraoral scan and 3D stereophotograph are registered. (*Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.*)
segmentation of the orbit and its contents (Fig. 3). One example of this is atlas-based segmentation, in which an atlas consisting of a patient model with presegmented anatomical structures is registered to the current patient scan (Fig. 4).\textsuperscript{5,15,18} Atlas-based segmentation can provide reliable segmentation, even when CT image quality is suboptimal. Small manual adjustments might be needed to optimize the segmentation result (Fig. 5), especially in the case of deviating anatomy or disorder.\textsuperscript{2,18} Because accurate segmentation of the orbit is a prerequisite for many advanced diagnostic and virtual planning processes, much research has been performed on improvement of accuracy or user-friendliness of segmentation techniques for orbital anatomy.\textsuperscript{15,22–24}

A virtual 3D model of the segmented structures can be reconstructed similar to the process which is used to generate a hard-tissue patient model from the bony tissue segmentation. Of particular interest are the bilateral orbits, orbital contents, and, for an orbitozygomatic complex fracture, the zygomatic complex. The 3D shape of an object may be analyzed, and the volume of the object can be measured within the software. This method enables comparison of the orbital content between affected and unaffected orbits and thus quantification of the enlargement of the affected orbit. The segmented structures can subsequently be manipulated in the virtual environment in the ongoing process of adding diagnostic information to the virtual patient model. In unilateral orbital fractures, mirroring provides exact insight into the displacement of the affected orbital walls (Fig. 6).\textsuperscript{3,5–7} In orbitozygomatic fractures (Fig. 7), segmented anatomical structures, obtained through different segmentation workflows, may be combined to obtain a complete template of the unaffected side before mirroring (Fig. 8). This way, the displacement of the orbital floor, zygomatic arch, and prominence (relative to the unaffected contralateral side) can be seen from 1 mirrored object (Fig. 9).\textsuperscript{6,18,25,26}

Virtual surgical planning

The indication for surgery is established on clinical findings, possibly supported by findings in the advanced diagnostics process. The goal of VSP is to reconstruct the pretraumatized anatomy as closely as possible.\textsuperscript{27–29} The VSP continues on information acquired from the advanced diagnostics process. This information in itself may comprise the surgical planning: the mirroring of the zygomatic complex provides a reconstruction of the premorbid anatomy of the affected structure. The mirrored orbit provides an adequate reconstruction for the affected orbit as well, but reduction of the dislocated bony parts is infeasible: alloplastic materials are frequently necessary to reconstruct the orbital floor and/or medial wall. The surgical planning is therefore more elaborate than mirroring alone: the optimal position of the reconstruction material (eg, a preformed titanium orbital implant) is also planned.

If a preformed titanium orbital implant is used, a virtual stereolithographic model (STL) of the implant is imported in the planning environment. The position of the implant can be manipulated in the virtual patient to find an optimal position for the implant in the current patient (Figs. 10 and 11).\textsuperscript{6,10,31} Several parameters are taken into account in the positioning process: covering of the defect, support on the dorsal ledge, fixation possibility on the orbital rim, prevention of interference with existing bony structures, reconstructing the contour as closely as possible to the mirrored orbit, and bony support at the medial tip of the implant (Fig. 12). The virtual patient offers the possibility to perform virtual surgery and evaluate the outcome within the patient model. Multiple possible implant positions for the imported implant can be evaluated before coming to a decision on the desired position. If necessary, additional implants, with different sizes or from other manufacturers, may be imported to compare their fit and find the implant with the optimal size and shape for the individual reconstruction (Fig. 13).\textsuperscript{6,10,28}

A suboptimal virtual implant fit of a preformed implant and clinical indication (and/or the surgeon’s preference) may lead to the decision to perform the reconstruction with a premolded or patient-specific implant (PSI) (Fig. 14; see Fig. 18). The basis for the design of the implant is, again, the extended virtual patient model with all information that has been added in the advanced diagnostics and preliminary planning phase (Fig. 15; see Fig. 19). Information can be extracted from the virtual patient model for additive manufacturing (eg, 3D printing).

![Fig. 3](https://example.com/fig3.png) Hard-tissue model and multiplanar views of patient 1. The 3D surface model is acquired from a threshold segmentation process. The orbital contents are not segmented accurately enough for further analysis. (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)
In the case of premolding an implant, a template of the mirrored, unaffected orbit may be printed to mold an implant before, or during, surgery. Additional information may be embedded in the 3D print, or in separate 3D prints; for instance, the defect itself or desired boundaries of the implant. Generation of a PSI is also based on exported virtual models from the patient model. In this case, the process of generating the implant’s shape is virtual rather than physical: the exported information serves as a digital template for the virtual design of the PSI. The exported models may be manipulated beforehand; for instance, to create an overcorrection of the orbital volume in a designated area (see Fig. 20). An STL of the PSI, or a preliminary design, can be imported in the software to check that it meets all parameters on implant shape and positioning, and to see whether the design will provide a unique fit to the designated position (see Fig. 21). Possible screw-hole positions for implant fixation can be evaluated in the virtual planning environment as well. In a secondary reconstruction, the position of existing osteosynthesis fixation can be indicated in the virtual patient model.

Fig. 4  Atlas-based segmentation of the unaffected contralateral orbit (patient 1). The atlas-based segmentation was performed in Brainlab iPlan Cranial (Brainlab AG, Munich, Germany). (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)

Fig. 5  Small manual adjustments of the resulting atlas-based segmentation. These small adjustments might be necessary in a small number of cases, especially if the anatomy differs greatly from the anatomy in the template. (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)
Fig. 6  Mirroring of the unaffected orbit, to obtain additional diagnostic information about the affected orbit (patient 1). (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)

Fig. 7  Hard-tissue model and multiplanar views of patient 2. A naso-orbitoethmoid type I fracture and comminuted orbitozygomatic complex fracture can be seen. (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)
Fig. 8  Threshold segmentation of bone (yellow) and atlas-based segmentation of orbit (green), to be combined into 1 template (patient 2). (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)

Fig. 9  Template consisting of segmentations from Fig. 8 are combined in the purple template, and mirrored to the contralateral side (cyan) to obtain information about the zygomatic displacement and the orbital fracture (patient 2). (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)
Fig. 10  VSP (patient 2). A preformed implant has been virtually positioned to reconstruct the orbit as closely as possible to the template obtained in Fig. 9. (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)

Fig. 11  VSP (patient 1). A preformed implant has been virtually positioned to reconstruct the orbit as closely as possible to the template obtained in Fig. 6 keeping the details in Fig. 12 in mind. (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)
Fig. 12  Positioning parameters (patient 1). Support on the ledge (top) and fixation possibility on the orbital rim (bottom) is seen in the coronal and sagittal views. (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)

Fig. 13  Small implant (red) versus large implant (blue) (patient 1). The medial wall extension of the large implant interferes with the unaffected bony structures of the medial wall, and cannot be positioned without cutting the implant. Because the small implant follows the contour of the mirrored orbit adequately (Fig. 11) and does not interfere with existing bony structures, the small implant was selected in this case. (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)
Fig. 14  Hard-tissue model and multiplanar views of patient 3. (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)

Fig. 15  Desired shape of the orbit after reconstruction (patient 3). (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)
(see Fig. 22). This way, the fixation of the PSI can be designed to overlap with the existing screw positions from the primary reconstruction, for additional feedback during positioning.33

**Evaluation**

Advanced diagnostics and VSP are the first, and arguably most important, steps in a CAS workflow for orbital reconstruction. The advanced diagnostics stage ensures that all available information is used in the decision-making process. The feasibility of the surgical intervention is assessed beforehand through the VSP, which rules out preventable surgical mismanagement such as the use of an unsuited implant for reconstruction, which was the case in the primary reconstruction of the patient in Figs. 18–22 (Fig. 23). The surgery may be simulated as many times as necessary to obtain the desired reconstruction of premorbid anatomy. An additional advantage of these simulations is that the surgeon is familiarized with the patient’s specific anatomy and disorder. For training surgeons, this provides an enhanced learning experience,

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**Fig. 16** Orbital floor corresponding with the shape in Fig. 15 (green), and existing bony structures (yellow) (patient 3). (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)

**Fig. 17** 3D printed template for bending the implant (patient 3), consisting of the structures visualized in Fig. 16 (left). An additional template extracted from the patient model, indicating the desired implant’s contour, was 3D printed (middle). Based on these templates, an implant was premolded (right). (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)
Fig. 18  Hard-tissue model and multiplanar views of patient 4. (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)

Fig. 19  Unaffected orbit and mirrored orbit, which serves as the basis for the PSI design (patient 4). (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)
Fig. 20  Possibility of overcorrection (patient 4). The cyan model is a 1 cm³ overcorrected model of the mirrored orbit. (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)

Fig. 21  Design of a PSI (patient 4). (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)
Fig. 22  Segmentation of existing osteosynthesis fixation (patient 4). The screw positions of the primary reconstruction are incorporated in the PSI design, to provide feedback on positioning. (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)

Fig. 23  Feasibility assessment of implant chosen for reconstruction (patient 4). If the contour of the mirrored orbit is followed, the implant has no support on the dorsal ledge. If support on the ledge were sought, the enlarged volume of the orbit would not be corrected properly. (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)
Fig. 24  Intraoperative imaging of patient 1. (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)

Fig. 25  Computer-assisted evaluation of surgical result (patient 1). The planned implant position was obtained and no adjustments are necessary. (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)
Fig. 26  Postoperative imaging of patient 2. (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)

Fig. 27  Computer-assisted evaluation of surgical result (patient 2). The zygomatic complex is repositioned according to the virtual surgical plan, but the acquired implant position deviates from the planned position. (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)
Fig. 28  Postoperative imaging of patient 4. (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)

Fig. 29  Computer-assisted evaluation of surgical result (patient 4). The planned implant position was obtained. (Courtesy of Ruud Schreurs, MSc, Cornelis Klop, MSc, and Thomas J. J. Maal, MSc, PhD.)
whereas experienced surgeons are able to anticipate intraoperative difficulties from the information in the virtual surgical plan.

The CAS workflow entails intraoperative feedback and postoperative evaluation after advanced diagnostics and VSP. The virtual surgical plan sets a target for the surgeon, but the feedback during the operation can be extended beyond just visualization in the CAS workflow. The shape of a premolded implant or PSI can guide the surgeon to the planned implant position. The planning may be imported in a surgical navigation system, which can provide dynamic feedback on implant position during surgery. These feedback mechanisms may aid surgeons in achieving the desired reconstruction result. Both feedback mechanisms are discussed in greater detail in Schreurs and colleagues’ article, “Intraoperative Feedback and Quality Control in Orbital Reconstruction: The Past, the Present and the Future,” in this issue. Image fusion of the intraoperative or postoperative imaging to the virtual surgical plan enables detailed comparison between planned and acquired implant position. This evaluation of the final surgical result (Figs. 24–29), combined with clinical outcome and difficulties encountered during surgery, yield feedback and possible improvements in any of the stages for the next patient who is treated using the CAS workflow.

Clinics care points

- An important preparation step for computer-assisted surgery in orbital reconstruction is to create a virtual 3D model from the CT data. This model can be augmented with additional 3D information to generate an accurate virtual patient model.
- The virtual patient model enables advanced diagnostics and 3D virtual surgical planning, which ensure a better inspection of the problem and the possible solutions during the preoperative phase.
- Virtual surgical planning is a valuable tool in orbital reconstruction in the preoperative setting, but it can also be utilized intraoperatively for feedback, and postoperatively for evaluation.
- Postoperative evaluation within the computer-assisted surgery workflow provides meaningful feedback for future cases.

Disclosure

The authors have nothing to disclose.

References


