Three-Dimensional Treatment Planning of Orthognathic Surgery in the Era of Virtual Imaging

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Purpose: The aim of this report was to present an integrated 3-dimensional (3D) virtual approach toward cone-beam computed tomography-based treatment planning of orthognathic surgery in the clinical routine.

Materials and Methods: We have described the different stages of the workflow process for routine 3D virtual treatment planning of orthognathic surgery:

1) Image acquisition for 3D virtual orthognathic surgery;
2) Processing of acquired image data toward a 3D virtual augmented model of the patient’s head;
3) 3D virtual diagnosis of the patient;
4) 3D virtual treatment planning of orthognathic surgery;
5) 3D virtual treatment planning communication;
6) 3D splint manufacturing;
7) 3D virtual treatment planning transfer to the operating room; and
8) 3D virtual treatment outcome evaluation.

Conclusions: The potential benefits and actual limits of an integrated 3D virtual approach for the treatment of the patient with a maxillofacial deformity are discussed comprehensively from our experience using 3D virtual treatment planning clinically.

To reach the present stage in which an integrated approach of 3D orthognathic surgery has become feasible, a lot of problems had to be solved. First, 3D imaging of the patient in the natural head position (NHP), capturing the hard and soft tissues and teeth, had to be possible at a low radiation dose. All conventional tools for planning of orthognathic surgery such as cephalometry, anthropometry of the face, dental model analysis, plaster dental model surgery, and soft-tissue simulation had to be developed and implemented in a single software platform.

The aim of the present study was to report a workflow process (Fig 1) for routine 3D treatment planning of orthognathic surgery in the era of virtual imaging consisting of:

1) Image acquisition for 3D virtual orthognathic surgery;
2) Processing of the acquired image data toward a 3D virtual augmented model of the patient’s head;
3) A 3D virtual diagnosis of the patient;
4) 3D virtual treatment planning of the orthognathic surgery;
5) 3D virtual treatment planning communication;
6) 3D splint manufacturing;
7) 3D virtual treatment planning transfer to the operating room; and
8) 3D virtual treatment outcome evaluation.

We have not intended to provide evidence but to discuss comprehensively the benefits and the potential, but especially the actual, limits as determined from our experience with 3D virtual treatment planning of orthognathic surgery clinically. We have
therefore referred, in particular, to our work and have credited all other research groups in this field. Finally, 3D virtual treatment planning requires a good understanding of the patient’s needs, a good clinical examination, and clinical experience.

**Image Acquisition for 3D Virtual Orthognathic Surgery**

To enable proper planning of orthognathic surgery, the patient should undergo imaging in the NHP with relaxed facial soft tissues. The introduction of cone-beam computed tomography (CBCT) scanners with the potential to vertically scan the patient with a low radiation dose and a scanned volume large enough to capture the entire face (triad of hard and soft tissues and teeth) will revolutionize how orthognathic surgery will be planned in the future. CBCT is a volumetric image acquisition technique that offers unique accessibility because of its low costs compared with multislice CT (MSCT) and the potential for in-office imaging. The ideal CBCT apparatus for 3D virtual treatment planning of orthognathic surgery, however, is not yet available. A number of problems will be encountered in the routine clinical situation. First, the scanned volume of CBCT scanners is currently too small to capture all types of maxillofacial deformities (Fig 2). Depending on the type of CBCT scanner, the field of view is too short in height and does not allow scanning of the patient from the upper limit of the thyroid up to 2 cm above the superior orbital rim. Other CBCT scanners have a field of view that is too short in depth and do not allow capturing both porions and the tip of the nose with a sufficient free margin. The image volume of CBCT is dependent on the shape of the x-ray beam and the size of the flat panel detector. Owing to the relatively small detector size of the available CBCT apparatus, the scanned volume is limited. With the fast evolution in detector technology, it is expected that CBCT with larger detectors will become available and eliminate this limitation in the near future. Second, because of the limits in the scanned volume, accurate positioning of the patient in the NHP in the CBCT apparatus is sometimes difficult or not feasible. Because of the long scan times (e.g., 40 s with the Iluma CBCT, Imtec, Ardmore, OK) or 2 scan times (e.g., 2 × 20 s with the classic iCAT CBCT, Imaging Sciences International, Hatfield, PA), patients might move during image acquisition, resulting in movement artifacts and useless data. Improvements in CBCT hardware and software to allow larger scanned volumes and decreased scan times are expected to solve these problems in the near future. Furthermore, in-office CBCT imaging by experienced personnel is key for good-quality data. Third, the higher noise level, lower contrast, higher

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**FIGURE 1.** Workflow process for 3D virtual treatment planning of orthognathic surgery. Note, the different steps of the 3D workflow process are illustrated using a clinical case other than the case discussed in this article.

Parallel to the volumetric data acquisition by CBCT, 3D surface information can be acquired for a more natural and realistic visualization of the patient by obtaining the color and texture of the facial soft tissues. The major advantage of 3D photography is the short acquisition time compared with laser surface scanning of the face. The latter, however, is more accurate if the scanned patient is not moving.

**Processing of Acquired Image Data for 3D Virtual Augmented Model of Patient’s Head**

The aim of 3D virtual imaging for orthognathic surgery is to create one virtual anatomic model of the patient, including the triad of the facial soft mask, underlying bony structures, and teeth. To enable 3D virtual treatment planning of orthognathic surgery, the acquired volumetric CBCT image data are segmented by semiautomated thresholding. The resulting surface representations of the patient’s anatomy are then drawn (rendered) on the computer screen, given a viewing direction of the virtual camera, called “surface rendering.” A tetrahedral soft-tissue mesh can subsequently be built to enable fast soft-tissue simulation using a biomechanical model. Although surface representations of the hard and soft tissues and teeth can be rendered and visualized in the 3D viewer of the software, some problems are still present.

Probably the most important obstacle was the inaccurate visualization of the interocclusal relationship; however, this issue has been resolved. Gateno et al.\(^6\) should be credited for developing the first method applicable to the clinical routine of orthognathic surgery to integrate accurate dental information into the patient’s skull. After a long odyssey,\(^7-11\) our research group has succeeded in developing an innovative technique\(^12\) to augment the 3D virtual model of the patient appropriate for orthognathic surgery treatment planning without the use of plaster dental models or markers and without deformation of the facial soft-tissue mask (Figs 3A,B). The method, consisting of a “triple” CBCT scan procedure with “triple” voxel-based rigid registration,\(^12\) has been validated and used clinically in more than 200 cases in our department. The protocol\(^12\) consists of 1) a first CBCT scan of the patient in the NHP with central occlusion and relaxed lips; 2) a second low-resolution and low-dose CBCT scan of the patient with a double impression tray in the mouth; and 3) a high-resolution CBCT scan of the impression tray. After the “triple” CBCT scan procedure, a 3D virtual model of the patient with accurate occlusal and intercuspidation data is made using a
To improve 3D soft-tissue simulation algorithms (see below), it was essential to integrate accurate interocclusal data without any soft-tissue disturbances into the 3D patient model of the head to secure an unbiased virtual preoperative setting before virtual simulation. The next challenge is to further augment the patient’s CBCT model of the head with detailed visualization of the dental roots. “Surface rendering” is based on thresholding and currently leads to improper visualization of certain anatomic structures (eg, sella turcica, condyles, orbital walls) owing to the inherent inhomogeneity of the CBCT gray value data. However, a volume of voxels can be rendered with “volume rendering.” For each voxel, a color and opacity can be assigned, and a projection image according to the viewing direction of the virtual camera can be computed and presented on the computer screen. “Volume rendering” of the acquired image data provides beautiful anatomic images and is useful for 3D virtual diagnosis of the patient’s anatomy. Because “volume rendering” is still computationally complex and it is expensive to manipulate the image data, it is not yet suitable for 3D virtual treatment planning of orthognathic surgery. Therefore, mixing “surface”
and “volume” rendering probably will allow one to combine the benefits of both rendering techniques and is a very promising approach. It is expected that this “mixed” visualization approach will become possible in the near future.

Another issue is that the facial soft-tissue mask obtained by CBCT imaging looks unnatural and is not a realistic view of the patient. Sophisticated registration algorithms to further augment the patient’s CBCT model of the head with skin texture and color information to enable a more natural looking rendering are already available. Using a 3D photograph or an arbitrary set of 2-dimensional photographs of the patient with the same facial expression as during CBCT scanning, highly detailed texture information can be added to the skin, segmented out of the CBCT scan (Fig 3C).

3D Virtual Diagnosis of Patient

The combination of a good clinical examination and 3D inspection of the virtual model of the patient’s head has an unprecedented potential toward the diagnosis of the patient with a maxillofacial deformity. Both “volume rendering” and “surface rendering” offer a thorough in-depth 3D virtual inspection of the patient’s anatomy in the 3D virtual scene. Both viewing methods also incorporate the original axial CBCT slices and coronal and sagittal reconstructions, which allow 2-dimensional inspection of the patient’s anatomy in the 3 standard planes (axial, sagittal, coronal) and multiplanar planes. A large amount of relevant clinical information with regard to the patient with a maxillofacial deformity can be gleaned from these slices (eg, condylar anatomy, maxillofacial bony and dental pathologic features, maxillary sinus pathologic features, nasal septum deviation, hypertrophic inferior turbinates, a restricted airway, dentoalveolar bone support to the teeth, and the pathway of the inferior alveolar nerve; Fig 4). Volume rendering is currently the most appropriate for 3D virtual assessment of the roots of the teeth, the temporomandibular joints, and the airway (Fig 5; see also Fig 12). Surface rendering offers great potential to implement the related data in the 3D virtual viewer such as virtual measurement and osteotomy tools and virtual surgical devices (eg, virtual surgical splints). Using surface rendering (Fig 6), 2 innovative virtual approaches were developed and subsequently combined by our research group. First, a new virtual approach was developed in which virtual lateral and frontal cephalograms were calculated from the CT (CBCT or MSCT) data set of the patient and linked with the hard and soft-tissue surface-rendered representations. This approach allowed us to bridge conventional cephalometry with 3D cephalometry of the facial soft-tissue mask and underlying bone and teeth with a common 3D cephalometric reference frame. Second, the “triple CBCT scan protocol” was developed and validated and allows one to augment the virtual model of the patient’s head to be appropriate for orthognathic surgery planning without the use of markers and plaster dental models. The latter developments were key toward the presented 3D virtual approach of treatment planning of orthognathic surgery. A current disadvantage of the 3D virtual approach is the static diagnosis of the patient. The virtual dynamic diagnosis (four dimensions) of the patient (eg, smile esthetics, habits) has recently been introduced and will probably be integrated in the future.

3D Virtual Treatment Planning of Orthognathic Surgery

One of the important advantages of 3D virtual planning compared with conventional treatment planning of orthognathic surgery is that the clinician inherently has more information on the patient’s anatomy during planning. Moreover, 3D virtual treatment planning allows one to focus more on 3D facial harmonization, rather than on the facial profile. A standardized approach toward 3D virtual treatment planning of orthognathic surgery, which includes 4 consecutive virtual planning steps (VPSs) (Fig 7), is used in our clinical practice: VPS1, 3D Bruges cephalometric analysis for the ideal facial soft-tissue mask; VPS2, 3D Bruges 3D soft-tissue analysis; VPS3, 3D virtual osteotomies; and VPS4, 3D virtual surgery toward the ideal facial soft-tissue mask. VPS1 consists of 3D cephalometric analysis (11 angles, 7 linear distances, and 2 facial proportions) of the hard and soft tissues and teeth using conventional cephalometric analysis performed in the oral maxillofacial department of Bruges for clinical and scientific purposes. Moreover, 4 additional vertical and horizontal measurements (UMcusp $p_x$, UC $p_x$, UC $g_x$, UMCusp $p_x$) were included to verify the vertical position of the repositioned maxilla at 4 levels (both canines and both mesial buccal cusps of the first molars) during surgery (see below). VPS2 consists of additional 3D soft tissue cephalometric analysis (2 angles, 10 linear distances, and 4 facial proportions) using direct anthropometric analysis performed in the oral maxillofacial department of Bruges for clinical and scientific purposes. In VPS3, the most performed facial osteotomies (Le Fort I, bilateral sagittal split osteotomy, and chin) are routinely done virtually, which creates the potential to virtually conduct different surgical treatment plans. Finally, VPS4 consists of virtual surgery toward the ideal facial soft-tissue mask, including virtual occlusal definition. The latter consists of a best fit between the dental arches

guided by virtual elastics and subsequently visualized by a color scale. The present study has not reported in detail on the different VPSs. Moreover, especially regarding VPS1 and VPS2, different surgeons and orthodontists have their proper measurements they prefer. Unpublished data, however, from a prospective study of 50 patients, showed that VPS1 to VPS3 can be performed within a clinically acceptable period (VPS1, 11.46 ± 0.23 minutes; VPS2, 3.46 ± 0.18 minutes; and VPS3, 5.38 ± 0.33 minutes). VPS4 was still very time-consuming (23.17 ± 1.31 minutes) because of the virtual occlusal definition (15.45 ± 0.87 minutes) and can be improved by increasing the learning curve and, especially, software improvements. Particularly for nonharmonized orthodontic dental arches or segmental surgery, virtual occlusal definition is still very demanding. Improvements in software are therefore mandatory and could solve this problem. The routine clinical use of 3D virtual planning also showed that 3D soft-tissue simulation still requires a number of improvements and cannot be relied on, especially for patients with long faces and asymmetries. One should, therefore, be very careful with the setup of the ideal virtual 3D soft-tissue planes (eg, ideal modified Burstone profile plane, ideal modified Ricketts lip plane), because these planes are determined by the subnasal and lip soft-tissue landmarks, which are inherently modified by 3D soft-tissue simulation that is not yet reliable.

Despite the latter disadvantages, some major advantages were experienced using 3D virtual treatment planning in the clinical routine compared with conventional orthognathic surgery treatment planning. First, the occlusal plane cant in the frontal plane can be accessed much more accurately (and subsequently transferred to the patient using a 3D surgical splint) in 3 dimensions just as done conventionally (eg, wooden spatula, face bow transfer). The correction of the frontal occlusal plane cant has an important effect on the paranasal area, gonial angles, lower mandibular borders, and chin. Second, the upper dental midline is often clinically misjudged, because it is often determined in a clinical setting for the esthetic collumellalipillium unit, which can be deviated (Fig 8; eg, in the case of frontal occlusal plane tilting, deviated anterior nasal spine, or nasal floor asymmetry). The upper dental midline can be assessed more accurately toward the facial midline (and also subsequently transferred to the patient using a 3D surgical splint) in 3 dimensions, just as conventionally. The upper dental midline can be corrected by a rotation, translation, or combined rotation and translation of the maxilla toward the skull base. This will have an important effect on the symmetry of the lower face and facial harmony (Fig 9). Third, the chin position and anatomy can be assessed much more accurately in 3 dimensions in the frontal (transverse and vertical asymmetries) and base

FIGURE 5. Volume rendering showing 3D visualization of tooth roots and volume quantification of airway (Dolphin Imaging 11.0 Premium, Chatsworth, CA).

(transverse deviations, exostoses, and so forth) planes. Fourth, because the proximal virtual fragments of the mandible remain stable and thus the condyles remain seated (if the initial data acquisition was well done) during virtual surgery, the amount of mandibular movement (advancement or setback, clockwise or counterclockwise, and medial or lateral deviation) can accurately be measured on both sides. Finally, different virtual surgical treatment plans (eg, bimaxillary rotation clockwise vs counterclockwise) can be evaluated. An important issue that remains is to determine 3D virtual mandibular autorotation, especially in the case of maxillary extrusion.

3D Virtual Treatment Planning Communication

One of the major disadvantages of conventional orthognathic surgery planning is communicating the treatment plan of a patient determined using the combination of a good clinical examination, clinical experience, and a broad variety of diagnostic information such as lateral and frontal cephalograms, clinical standardized photographs, a profile prediction tracing, dental models, and model articulator surgery.

Three-dimensional virtual orthognathic surgery planning has powerful potential as a communication tool because it offers the possibility to visualize an integrated treatment plan of the patient as a single virtual anatomic model including the hard and soft tissues and teeth. First, the 3D virtual treatment plan can be saved in a viewer format that can be sent by electronic mail to the referring orthodontist to communicate and discuss the patient’s treatment plan. Second, the 3D virtual treatment plan can be discussed with the patient and optimized and individualized to the patient’s needs. Third, the 3D virtual approach offers an excellent communication tool to teach contemporary treatment of maxillofacial deformity to residents in orthodontics and oral and maxillofacial surgery. Fourth, the surgeon or orthodontist can easily communicate the 3D virtual treatment plan of a difficult case to another colleague worldwide with more experience with a typical pathologic finding to obtain advice (electronic counseling). Finally, the 3D virtual approach could improve knowledge worldwide on maxillofacial deformities with electronic learning and electronic teaching (Fig 1).

Although 3D virtual treatment planning of orthognathic surgery offers an unprecedented tool in communication with patients and colleagues, it does have some disadvantages. First, the viewer format of the 3D virtual treatment planning necessitates a personal computer workstation with good graphic ability, which is currently not standard. Because recent commercially available personal computers have incorporated more and more powerful graphic ability, this problem will soon be eliminated. Also, because 3D soft-tissue simulation still requires improvement, one should be careful in communicating this infor-
FIGURE 9. Virtual correction of occlusal plane tilting and upper dental midline deviation by combined rotation and translation to right of maxilla showing A, effect on mandibular border gonial angle symmetry and chin position. Note, the mandible was put virtually into occlusion with the repositioned maxilla and the chin was not virtually repositioned. B, Isolated 3D virtual repositioning of the maxilla and visualization of the intermediate surgical splint to transfer virtual repositioning of the maxilla to the patient [Maxilim, version 2.2.2, Medicim NV, Mechelen, Belgium].

mation to the patient, especially for patients with long faces and facial asymmetries. It is clear that soft-tissue simulation algorithms will substantially improve in the future with the input of a large amount of 3D data.

3D Surgical Splint Manufacturing

Once the final 3D virtual treatment plan has been set up, the necessary 3D virtual surgical splints can be made (Fig 10). Subsequently, the 3D virtual surgical splints are processed using computer-aided design and computer-aided manufacturing techniques into surgical splints that can be used during the actual surgery. Gateno et al.19 have shown that stereolithographic surgical splints fit the same as conventional surgical splints. Our research group is currently evaluating and validating another process to produce surgical wafers by milling instead of stereolithography. Compared with conventional surgical splints, 3D virtually made surgical splints using our approach seem to have the following advantages: 1) the surgical splints are directly made using the 3D virtual augmented model of the patient without the intermediate of plaster dental models; and 2) the intermediate 3D virtually made surgical splint can incorporate more accurately the surgical treatment plan, especially in complex cases with combined leveling, rotation, and translation movements of the jaw. To use the 3D virtually made surgical splints in the clinical routine of orthognathic surgery, some important problems still exist. First, the base material for 3D surgical splint production must be medically approved. Second, the 3D surgical splints are still too bulky and need to be trimmed manually by the surgeon, which is time-consuming. It is expected that this will be solved by virtual trimming before processing and refinement of the computer-aided design and computer-aided manufacturing techniques. Finally, the manufacturing of the 3D surgical splints is still a time-consuming pro-

FIGURE 10. 3D virtual intermediate and final surgical splint (Maxilim, version 2.2.2, Medicim NV, Mechelen, Belgium).

FIGURE 11. Illustration of synthetic cadaver skull showing use of commercially available calipers to verify the vertical position of the repositioned maxilla at 4 levels (both canines and both mesial buccal cusps of first molars).
cess. The clinician must upload the virtual treatment planning data to be processed out of office, and the surgical wafer or wafers need to be shipped back to the clinician. Decreasing the time for out-of-office processing or in-office manufacturing could solve this problem. Finally, 3D surgical splints for segmental surgery are still very demanding in the presented 3D virtual approach, because virtual occlusal definition of the segmented jaws is still very difficult. Once again, improvements in software will solve this problem.

3D Virtual Treatment Planning Transfer to Operating Room

The 3D virtual surgical treatment plan can be easily transferred to the operating room in a viewer format. Surgeons, anesthesiologists, and nurses have access to the individualized 3D virtual treatment plan of the patient at any time during surgery. To transfer the individualized 3D virtual treatment to the patient, 3D surgical wafers and calipers are used in our approach. In our surgical approach, the maxilla is repositioned and osteosynthesized first during bimaxillary surgery in most cases. For maxillary repositioning, the 3D surgical wafer transfers the entire 3D virtual repositioning of the maxilla (including rotations, translations, and leveling), except for its vertical position to the cranial base. Theoretically, the vertical position of the repositioned maxilla should be verified at only one point. We currently use commercially available calipers to verify the vertical position of the repositioned maxilla at 4 levels (both canines and both mesial buccal cusps of the first molars) (Fig 11) using the patient’s 3D cephalometric data. For mandibular repositioning, the 3D surgical wafer incorporates the 3D virtual repositioning of the mandible; and for chin repositioning, calipers are used to transfer the 3D virtual plan. A prospective study is being conducted to evaluate the accuracy of this approach of transferring the 3D virtual treatment plan to the patient. If the results show that this approach is not accurate enough clinically, other techniques, such as guidance by intraoperative navigation, intraoperative imaging with C-arm CBCT, or prebent osteosynthesis plates, should be considered and investigated.
3D Virtual Treatment Outcome Evaluation

Probably the most powerful aspect of 3D treatment planning of orthognathic surgery in the era of virtual imaging is the unprecedented potential for the evaluation of the treatment outcome (Figs 12-15). The techniques of voxel-based rigid registration and superimposition on a 3D cephalometric reference system have been extensively described.² Cevidanes et al²⁰-²² have made a major contribution to the published data with their clinical research work. We suggest evaluating the treatment outcome using CBCT imaging in 3 stages. First, CBCT should be performed at 3 to 6 weeks postoperatively to evaluate the accuracy of the transfer of repositioning the bony parts. Because postoperative swelling of the buccal mucosa can interfere with occlusion, it is not recommended to perform CBCT in the first 2 postoperative weeks. In contrast, bony consolidation appears at 6 weeks postoperatively and will no longer allow for proper virtual identification of the osteotomy lines. Moreover, postoperative orthodontics has often been restarted at this point. Second, CBCT should be performed at 6 months to 1 year postoperatively (once the orthodontic brackets have been removed) to evaluate the soft-tissue response and the accuracy of the soft-tissue simulation. Finally, CBCT should be performed at 2 years postoperatively to evaluate the long-term treatment outcome.

Meticulous 3D evaluation of the pretreatment status, the 3D virtual treatment goal, and the actual treatment outcome will bring new insights and substantial information (eg, on long-term stability, airway stability, condylar resorption, facial harmony, and esthetics) and concepts in orthognathic surgery that will lead to better care of the patient with a maxillofacial deformity.

A large amount of basic laboratory and clinical research has been done by different research groups worldwide in the field of 3D virtual treatment planning of orthognathic surgery. The translation of this research into clinical practice (translational research²³,²⁴) has already shown an unprecedented potential toward the diagnosis, treatment planning, and evaluation of the treatment outcomes of maxillofacial deformity. However, to make the paradigm shift from conventional planning to 3D virtual planning, 3 basic require-
ments must be fulfilled: 1) the quality of care needs to improve; 2) the workflow process should become more efficient; and 3) the cost should decrease. No doubt exists any longer that 3D virtual planning definitely improves the care of the patient with a maxillofacial deformity. Efficiency difficulties still exist, however, in both computer hardware and software in the daily clinical routine. Moreover, both the CBCT apparatus and the virtual 3D software packages are too expensive. Hence, the challenge and common goal is to develop 3D virtual treatment planning of orthognathic surgery as an efficient and cost-effective clinical tool that improves the care of the patient with a maxillofacial deformity.

References