By incorporating three-dimensional (3D) imaging and computer-aided design and manufacturing techniques, 3D computer-assisted technology has been applied widely to provide accurate guidance for assessment and treatment planning in clinical practice. This technology has recently been used in orthognathic surgery to improve surgical planning and outcome. The modality will gradually become popular. This study reviewed the literature concerning the use of computer-assisted techniques in orthognathic surgery including surgical planning, simulation, intraoperative translation of the virtual surgery, and postoperative evaluation. A Medline, PubMed, ProQuest, and ScienceDirect search was performed to find relevant articles with regard to 3D computer-assisted orthognathic surgery in the past 10 years. A total of 460 articles were revealed, out of which 174 were publications addressed the topic of this study. The purpose of this article is to present an overview of the state-of-art methods for 3D computer-assisted technology in orthognathic surgery. From the review we can conclude that the use of computer-assisted technique in orthognathic surgery provides the benefit of optimal functional and aesthetic results, patient satisfaction, precise translation of the treatment plan, and facilitating intraoperative manipulation.

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Introduction

Conventional treatment planning for orthognathic surgery uses two-dimensional (2D) cephalometric analysis, dental casts mounted in the articulator with face-bow transfer, and model surgery to predict the direction and extent of jaw movement. This approach, however, has drawbacks for accurate simulation of real bony movement based on 2D radiographic evaluation and dental models. The presentation and analysis of a complex three-dimensional (3D) maxillofacial structure in two dimensions have limitations, such as landmark identification and overlapping of anatomic structures, especially for patients with facial asymmetry. High-tech digital imaging technology and computer software have been increasingly used for the diagnosis and treatment planning, which may integrate different image data sets, such as 3D computed tomography (CT) image and 3D surface scanning. In particular, low-dose cone-beam computed tomography (CBCT) allows reconstruction of a 3D craniofacial skeletal model for accurate presentation of the complex 3D shape and position, and has been applied widely in the field of orthognathic surgery. Numerous proprietary software programs have been developed and applied to formulate the surgical plan on 3D skeletal models extracted from the CT images, to simulate the surgical procedures on a virtual environment, as well as to predict the final outcome. In recent years, a few articles proposed the 3D computer-assisted orthognathic surgery (CAOS) systems that incorporated advanced imaging, computer software, computer-aided design and manufacturing (CAD/CAM) technique, and image-guiding system to provide high level of precision necessary for translation of the virtual planning to actual surgery. 

In general, the 3D CAOS systems involve the steps shown in Fig. 1. The first step is image acquisition and diagnosis, in which the diagnosis of dentofacial dysmorphology is established based on physical examination and extraction of clinical information from 3D presentation of the anatomy. From the evaluation, a surgical plan can be made. The second step is to perform the virtual surgery on a 3D CT image model and predict surgical outcome using a proprietary software program, and then the intraoperative guidance such as surgical splints, positioning guides, and preoperative navigation plan are digitally designed and prepared for use in the operation. The third step is translation of the virtual surgery planning to the patient in the surgery using the intraoperative guidance. The final step is postoperative assessment for accuracy evaluation of the treatment plan transfer, and the surgical outcome.

In this study, we conducted a review of the literature concerning the state-of-the-art computer-assisted techniques in orthognathic surgery and provided the clinicians with contemporary information for successful and predictable treatment outcome.

Materials and methods

To identify relevant articles for this review, Medline, PubMed, ProQuest, and ScienceDirect searches were performed for English-language literature published in the past 10 years. The search items used in this article were three-dimensional, 3D, cone beam computed tomography, 3D cephalometry, 3D cephalometric analysis, computer aided, computer assisted, surgical simulation, navigation, CAD, CAM, and splint, in combination with maxillofacial, craniofacial, and orthognathic surgery. A total of 460 articles were found from 2004 to present, out of which 232 publications were considered potentially relevant; 58 duplicate articles were removed. The remaining reference articles were hand-searched and an additional 21 articles identified.

Results

In total, 195 articles were selected for full text analysis describing the various methods in relation to 3D CAOS system. Fig. 2 shows the search results. An overview of the characteristics of the reviewed articles was shown in Table 1.

Summary of reports

3D image acquisition and diagnosis

3D image acquisition

The rapid growth of use of 3D imaging technique, such as medical CT and CBCT scans, provides a more accurate presentation of anatomic structures than 2D imaging to assist clinicians in diagnosis, treatment planning, and evaluation of treatment outcome for orthognathic surgery. CBCT is a volumetric image acquisition technique allowing high quality 3D reconstruction model that offers several advantages over the conventional CT imaging with lower radiation dose, shorter scanning time, and lower cost. It has become widely used as a valuable technique of dentofacial imaging for orthognathic surgery. Parallel to the volumetric CT data, texture and color information of the facial surface can be obtained for a natural and realistic visualization via two classes of stereo surface imaging systems, namely stereophotography and laser surface scanning.

Then, a virtual model of combination of skin surface and
CT reconstructed osseous volume can subsequently be built to enable soft-tissue simulation and prediction.\(^4\)

Creation of a skull–dental composite 3D model

In the presence of metallic dental restoration and orthodontic brackets, the CT images show streaking artifacts and impede precise identification of the teeth. The dentition need to be replaced for optimized simulation of occlusal relationship between the maxilla and mandible, and the implementation of a treatment plan. Conventional plaster models have been used to provide an accurate presentation of the dentition and fabricate surgical splints. A number of studies have reported the methods of integration of the maxillofacial CT bone model and the digital dental models, enabling simultaneous 3D presentation of the skeletal structure, teeth, and occlusion. The methods of Gateno et al,\(^4\) Uechi et al,\(^5\) and Nairn et al\(^6\) used the fiducial markers, such as titanium spheres, ceramic balls, softened gutta-percha, acrylic, or facebow to produce an accurate method of replacing the distorted dental image without accounting for flawed imaging effects acquired by CBCT. Swennen et al\(^7\) used a double CBCT scan procedure with a modified wax bite wafer and gutta percha as markers to augment the 3D virtual skull model with a detailed dental surface that did not use plaster dental models and did not deform the facial soft tissue mask to avoid the distortion of lip morphology and posture due to the use of the titanium spheres. Swennen et al\(^8\) also presented the triple CBCT scan methods that the fiducial markers are unnecessary for registration when the participants have undergone CT scanning more than once. However, this approach involved undesirable, additional radiation exposure. Nkenke et al\(^9\), Kim et al,\(^10\) and Noh et al\(^11\) proposed the different surface-based methods using the iterative closest point algorithm, with the errors evaluated by measuring the 3D Euclidean distances between the surface points on the two original images based on manual selection of the corresponding areas. Recently, Lin et al\(^12\) provided an artifact-resistant surface-based registration method that was robust and clinically applicable and that did not require markers. Liao et al\(^13\) used a free-hand method to reposition and reorient the dental model to the surface-best-fit with CT teeth images. However, outliers still existed and could compromise clinical results. As such validation of the registration is recommended after each task using this manual 3D superimposition technique.

Setting up virtual facial reference planes

For correct diagnosis, the setting of the reference plane is a critical factor in cephalometric analysis. The virtual facial reference planes must be set up for construction of a unique 3D reference system and orientation of the skull–dental composite model. Some horizontal reference planes have been be defined by landmark points or head position. For head position, most research studies used either a laser scanning device or digital orientation device to record and reproduce the natural head position in three dimensions and transfer it into a 3D CT model.\(^14\) For a landmark-based reference plane, previous studies used different coordinate systems and the standardized reference plane first selected by the researcher determined the remaining reference planes. In some studies, the horizontal plane was established as the standard plane\(^15\) and the midsagittal and coronal planes followed and formed a 3D reference system.

Diagnosis

After the composite skull model is positioned in the 3D reference system, the cephalometric analysis can be performed. Combining the clinical examinations and 3D cephalometric analysis of the virtual model, the diagnosis of the maxillofacial deformity was carried out, checking the occlusion, bipupillary lines, maxillo–mandibular contour angle, mandibular sulcus contour angle, the soft tissue angles, and dental exposure during smile.\(^26\) The diagnosis using a 3D model can be shown to patients for better understanding. A preliminary plan is developed by combining the conventional planning and 3D digital model. For patients with facial asymmetry or complex cranio-maxillofacial deformity, modification of plan is often required.

Virtual surgery

Surgical simulation

Once the skull–dental composite model has been generated, the surgeon can perform a patient-specific virtual
surgery on the composite model according to the preliminary plan as if it is the real surgery in a 3D environment using a feasible developed software system. Common software currently used for virtual surgical simulation in orthognathic surgery include Mimics (Materialise N.V., Leuven, Belgium),\(^{27}\) SimPlant OMS (Materialise),\(^{27}\) Dolphin Imaging (Dolphin Imaging and Management Solutions, Chatsworth, CA, USA),\(^{28}\) and Maxilim (Medicim, Mechelen, Belgium).\(^{29}\) These computer simulation programs provide multiple functions, such as image segmentation for conversion of DICOM files to a 3D model by identifying and delineating the anatomic structures of interest in CT image, 3D cephalometric analysis, simulation of common osteotomy procedures, relocation of bony segments according to planned surgical movement, and prediction of soft tissue changes. Additionally, Dolphin\(^{30}\) and Maxilim\(^{18,34}\) can also map texture information of a 2D and 3D photograph onto the CT skin surface (registration) utilizing surface matching algorithm to provide a color photo-realistic rendering of soft tissue changes. The 3D virtual surgery provides the surgeon with a better understanding of the surgical situation, and involves several steps depending on the initial plan. Modification of the preliminary plan could be made if surgeons have concerns on facial symmetry, skeletal harmony, or collision of ramus segments.

**Design and preparation of intraoperative guidance**

After establishment of the final treatment plan and completion of 3D surgical simulation, the results need to be transferred to an actual operation with the aid of intraoperative guidance for optimization of operative accuracy and efficiency. In CAOS, three commonly used intraoperative guidelines for translation of the virtual planning to actual surgery are surgical splints, repositioning guides, and real-time navigation system.

- **Surgical splints.** For a long time, conventional plaster models have been the only way to establish the occlusion and fabricate surgical splints accurately. A virtual surgical plan can be an alternative approach for design and fabrication of computer-generated surgical splints without conventional model surgery which is time-consuming and imprecise. Once the surgical simulation has been completed, the result in a stereolithography format is imported into the CAD software, such as 3-Matic (Materialise),\(^{27}\) Geomagic Wrap (3D System, Rock Hill, SC, USA),\(^{32}\) and Tizian Creativ RT (Schütz Dental, Rosbach vor der Höhe, Germany).\(^{23}\) The splints are digitally designed based on the intermediate and final tooth positions, essentially by performing a Boolean operation and trimming to the virtually planned specifications. The obtained digital splint files are prepared for manufacturing in a rapid prototyping machine (3D printer). The reliability and accuracy of these CAD/CAM generated splints have already been validated for reproducing 3D virtual surgical planning in the operating room; and the results are similar to that of conventional splints (intermediate and final splints).\(^{1,6,34,35}\)

- **Repositioning guides.** When 2-jaw surgery is planned, it is critical to correctly position the maxilla using an intermediate surgical splint. The maxilla cannot be positioned independently and the task of repositioning the maxilla may require complex movements and rotations. Therefore the intermediate surgical splint is required when one is relating it to the mandible. The instability of the mandible may directly interfere with the placement of the maxilla in its designed position, especially in the vertical direction. A number of studies have evaluated the efficacy of using the 3D CAD/CAM repositioning guides (surface template) as an alternative to the use of intermediate surgical wafer for transferring the virtual surgical plan to the operation. Bai et al\(^{39}\) proposed a pair of surface templates fabricated by CAD/CAM technique to decrease efforts and possible errors from the conventional approach, and to reduce operation time. Zinser et al\(^{8}\) reported a virtual planning method incorporating a specially designed surgical splint, which could avoid 2D planning and arbitrary splints. Bai et al\(^{37}\) presented another procedure that used CAD/CAM locating guides and pre-bent titanium plates to position the maxillary segment in a fast and accurate way for 2-jaw orthognathic surgery. Shehab et al\(^{38}\) proposed a tooth/bone supported virtual splint design to guide the maxillary position during the operation. Li et al\(^{36}\) presented a CAD/CAM model to guide the osteotomy and the bone movement that did not require traditional model surgery. Polley and Figueroas\(^{1}\) introduced the use of an occlusal-based “orthognathic positioning system” to translate the virtual plan to actual operation.

- **Real-time navigation system.** In CAOS, a real-time navigation system can be applied as a definitive tool to determine the final bone position in the absence of positioning guides, or act as an additional instrument to guide the osteotomies and check the bone movement. The real-time navigation system has been applied currently in various surgical specialties such as spinal surgery,\(^{40}\) orthopaedics,\(^{41}\) neurosurgery,\(^{42}\) endoscopic surgery,\(^{43}\) dental implant surgery,\(^{44}\) and several craniomaxillofacial surgery techniques, such as repair of posttraumatic defects,\(^{45}\) temporomandibular joint motion analysis,\(^{46}\) and tumor resection.\(^{47}\) but seldom employed to improve the accuracy of complex 2-jaw orthognathic surgery, especially for the facial asymmetry. Prior to surgery, a preoperative navigation planning should be established for intraoperative guidance. Several steps are required. First, the CT DICOM data and virtual surgical plan are imported into the navigation planning software. The preset fiducial markers or identifiable bone and teeth landmarks are indicated on the 3D reconstructed image for the reference points. The reference points are used for intraoperative registration in order to establish a connection between the virtual images and the patient. The osteotomy points are indicated on 3D model based on virtual surgery for guiding the osteotomy during surgery. Finally, intraoperative validation points were determined on virtual surgical image for guiding and checking the movement of skeletal segments.

Translation of the virtual planning to actual surgery

Before surgery, the occlusal splints and repositioning guides are sterilized and ready for use in the operating room, and
the preoperative navigation planning is imported into the commercially available navigation system if it is to be used. During surgery, patients are put under general anesthesia with nasotracheal intubation, and draping is performed to expose the whole face from forehead to neck.

Surgical splints and repositioning guides

At the time of surgery, following Le Fort I osteotomy or bilateral sagittal split osteotomy (BSSO), the maxilla or mandible is brought into relation with the opposing dentition via the CAD/CAM intermediate or final surgical splints. In addition, the CAD/CAM repositioning guides can provide reliable approach that is an alternative to the use of arbitrary surgical splint for transferring the virtual plan into the operating room. Finally, the maxilla and mandible are repositioned according to the surgical splints or repositioning guides and fixed by miniplates and screws.

Real-time navigation system

The common commercial navigation systems used in craniofacial surgery include Instatrak (GE Health Care, Little Chalfont, Buckinghamshire, UK), Stealth Station (Medtronic-Xomed, Jacksonville, FL, USA), Stryker Navigation System (Stryker-Leibinger, Kalamazoo, MI, USA), BrainLAB Kolibr (BrainLab, Heimstetten, Germany), and VoNaviX (IVS Solutions AG, Chemnitz, Germany). Recently, the navigation system has been used to accurately translate the virtual plan to actual operation. Tsuji et al presented an optical tracking system for navigation uses charged-coupled device video cameras and light-emitting diodes that provided sufficient accuracy and precision. Mazzoni et al evaluated the reproducibility with the assistance of the eNlite Navigation System by Stryker (Freiburg, Germany) with the iNtellect Cranial Navigation platform, and reported a higher accuracy compared with the non-navigated group. Bell described the using of Intellect Cranial Navigation System (Stryker) for intraoperative guidance and found it particularly useful for correcting the facial asymmetry in general and hemimandibular hyperplasia in particular. Shim et al reported the successful treatment in orthognathic surgery with the assistance of real-time eNlite Navigation System by Stryker. Zinser et al compared the using of the Navigation system VectorVision (BrainLab) with an image-guided visualization display (IGVD), CAD/CAM splints, and classic intermaxillary splints respectively in orthognathic surgery, and found that the CAD/CAM splint and the navigation system had higher accuracy. Yu et al explored the indication and application of computer-assisted navigation system (Stryker) in oral and maxillofacial surgery, and showed the value of improving the accuracy for maxillofacial surgery, reducing the operation risk and postsurgical morbidity, and restoring facial symmetry. The intraoperative navigation systems incorporated a computer digitizer to track the location of patient and instruments in space. When using the real-time navigation system, a reference star (tracker) is fixed to patient’s skull to mark the location of the patient in the navigation system. Then, the patient is registered to the navigation system using marker-based or surface matching registration modalities to represent the mathematical relationship that links the patient’s CT imaging space coordinates to the physical space coordinates of a patient. Registration errors are a potential problem in a real-time intraoperative navigation system. Previous studies have indicated that the surface matching registration method is inadequate for image-guided bimaxillary surgery because the using of nasotracheal intubation might cause skin surface distortion and shifting. Besides, Marmulla et al pointed out that a facial skin shift between lying and sitting could impact the mean target registration error. To meet the clinical requirement, landmark registration was reported as the more reliable method. Despite this, there were still reports showing a large target registration error because of insufficient definable landmarks on the facial bone. To overcome the problem, some reported using specific markers as registration points, for example, fiducial markers or inherit stable landmarks that can be identified on both the virtual model and real patient. The markers were identified by placing a surgical probe in the same location on the actual patient. Either bony or skin surface landmarks can be used. Clinically, skin surface landmarks are most common. With an accurate registration method, the navigation system could be a powerful tool for image-guided surgery. During surgery, common osteotomy such as LeFort I, BSSO, and genioplasty can be performed safely following the osteotomy points that were prepared in the preoperative navigation planning. The intraoperative validation points help to augment the virtual planning and the real-time bone position, because the position of the original and new bone positions are shown on the computer screen, and the distances between the probe and the validation point are observed readily.

Postoperative assessment

Postoperative assessment is performed to evaluate the precision of treatment plan transfer. In general, there are two methods for validation of the translation of virtual planning, namely the color difference metrics and descriptive statistical analysis. CBCT is taken postoperatively. After the initial registration of the simulated and actual postsurgical images on the cranial base, a visual surface model superimposition was performed to compare the difference between the virtual surgical images and the postsurgical results. The model–fusion tool is commonly used for the automatic display of magnitude, direction, and location of disagreement between the two models by means of a color-scale plot. For advanced quantification analysis of accuracy and reliability, certain statistical analyses are chosen to compare whether there is a statistically significant difference between various cephalometric parameters of the virtual and actual postoperative images. In the meantime, inter- and intraexaminer reliability could be made for all methods for most of the measurements. In addition to the evaluation of the reliability of virtual plan transfer, postoperative assessment was used to evaluate the postoperative facial soft tissue and bone tissue changes, the treatment outcome, and the accuracy of digital prediction.

Discussion

Conventional surgical treatment planning applied in orthognathic surgery has limits for accurate simulation of
real bony movement based on 2D radiographic images and dental models. It may be clinically acceptable for some patients because the clinical outcome is not obviously affected by the minor inaccuracy in surgical planning. However, the accuracy of surgical planning can result in a less than ideal treatment outcome, especially for those with major facial deformity or asymmetry. For many patients, the 3D CAOS systems that incorporate advanced 3D imaging, computer simulation software, CAD/CAM technique, and image-guidance technology can improve the accuracy of treatment planning and the precision of surgical execution. This review reported the overview of the recently used 3D CAOS and was divided into four basic components including 3D diagnosis, surgical planning and simulation, intraoperative translation of the virtual surgery, and postoperative evaluation.

Three-dimensional imaging and computer simulation can be effectively used for planning office-based procedures. The system can be used to perform virtual surgery and establish a definitive and objective treatment plan for correction of facial deformity. The end result is improved patient outcome and decreased expense. Inclusion of 3D virtual model with cephalometric analysis in the diagnosis and treatment plan allows clinicians to perform comprehensive evaluation of maxillofacial structure and facilitate surgical planning. This modality has been proved to be superior to the 2D cephalometric analysis and plaster dental models mounted on the articulator. Three-dimensional virtual surgery allows the surgeon to precisely reproduce the treatment plan on the computer, provide an interactive manipulation to simulate different surgical procedures in real-time 3D virtual environment, to visualize the effect of simulation for the best possible outcome, and to establish a definitive and objective treatment plan for correction of facial deformity. The planning data and the simulated surgery on 3D models can be transferred with high precision to the operation room using appropriate intraoperative guidance, i.e., surgical splints, repositioning guides, and real-time navigation system. The intraoperative guidance helps surgeons to mobilize the skeletal segments to their planned position during surgery in a reliable and accurate way. Each patient is treated individually, so that the corresponding computer-aided procedures cannot be uniform.

In conclusion, the review reveals that 3D CAOS has gradually gained popularity in clinical practice. It helps to reduce surgical difficulty by problem detection and plan modification prior to the operation, simplify the positioning procedure, eliminate intraoperative human errors, possibly reduce the operating time, accurately transfer the virtual surgical planning to the actual surgery, achieve a satisfactory facial aesthetic outcome as well as dental occlusion, and improve patient care as well as decrease expense. With the advancement of computer hardware and software, the 3D CAOS will become more readily available and user friendly.

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