Purpose: To gain insight into the methodology of different computer-aided design–computer-aided manufacturing (CAD-CAM) applications for the reconstruction of cranio-maxillo-facial (CMF) defects.

Methods: We reviewed and analyzed the available literature pertaining to CAD-CAM for use in CMF reconstruction.

Results: We proposed a classification system of the techniques of implant and cutting, drilling, and/or guiding template design and manufacturing. The system consisted of 4 classes (I–IV). These classes combine techniques used for both the implant and template to most accurately describe the methodology used.

Conclusions: Our classification system can be widely applied. It should facilitate communication and immediate understanding of the methodology of CAD-CAM applications for the reconstruction of CMF defects.

Key Words: Additive manufacturing, CAD-CAM, cranio-maxillo-facial, implant, rapid prototyping, template

(J Craniofac Surg 2015;00: 00–00)

Computer-aided design (CAD) and computer-aided manufacturing (CAM) techniques allow reconstructive surgery to be planned accurately, thereby increasing the likelihood of obtaining predictable aesthetic results. These features make these techniques attractive tools for surgery involving reconstruction of cranio-maxillo-facial (CMF) defects, because predictability is essential for symmetric and aesthetically pleasing results.

When reviewing the literature concerning CMF reconstruction using CAD-CAM, we noticed that different approaches were used to plan surgery and implant design. To create transparency and facilitate clear communications with colleagues, scientists, industry, and others, a common classification system of CAD-CAM techniques is required. In this report, we propose a classification system of the methodology of CAD-CAM applications used for the reconstruction of CMF defects. This classification aims to bring clear and easy to understand order to the seemingly disorderly array of workflows used to obtain a CAD-CAM implant or template for CMF reconstructive surgery. The use of this classification will facilitate understanding of research reports in this field.

From the European Face Centre, UZ Brussel, Brussel, Belgium.

Received December 16, 2014.

Address correspondence and reprint requests to Lauri D.J. Wauters, European Face Centre, UZ Brussels, Jette, 1090 Brussel, Belgium; E-mail: lauri.wauters@uzbrussel.be

The authors report no conflicts of interest.

Copyright © 2015 by Mutaz B. Habal, MD

ISSN: 1049-2275

DOI: 10.1097/SCS.0000000000001845
To clarify our classification system, we have included examples (with illustrations) from the literature.

Class I
Figure 1 depicts the general class I workflow. This involves CAD design of the implant and/or template and direct CAM using additive manufacturing (AM) or a computer numerical controlled (CNC) machine. Wang et al described a patient who had developed a unilateral mandibular ramus defect after contouring surgery (Fig. 2). The authors used a class I workflow with direct manufacturing of a titanium implant. The implant was designed with CAD software using a mirrored image of the unaffected side to restore symmetry. Subsequent CAM of the titanium implant was performed using a Laser Prototyping System.

Mertens et al used a class I workflow to reconstruct a complex midface craniofacial defect (resulting from a tumor resection), using a titanium implant and scapular flap (Fig. 3). Using computed tomography (CT)-digital imaging and communications in medicine (DICOM) images for 3-dimensional (3D) reconstruction, the unaffected side was mirrored digitally to reconstruct the defect. 3D data of the scapula were matched to fit the reconstruction of the alveolar ridge and palate as precisely as possible. Computer-aided design of a titanium implant was performed on these data to obtain satisfactory support of the facial and orbital structures, reconstructing these structures, and supporting the scapular graft. Computer-aided manufacturing of the titanium (KLS Martin Group, Tuttingen, Germany) implant was subsequently performed.

Class II
Figure 4 depicts the general class II workflow. This involves CAD design of the implant and/or template followed by indirect CAM of all implant and/or template material. Tang et al reconstructed an orbital wall defect making use of the class II workflow (Figs. 5 and 6). A computer-assisted volumetric analysis was performed on both the affected side and the unaffected side. According to the ideal orbital volume reconstructed using digital mirroring, the operation was simulated and CAD of titanium mesh was performed. An RP model of the reconstructed skull was manufactured to mold the titanium mesh on the model.
A class II workflow was also used by Zhou et al during their correction of hemifacial microsomia using digital mirroring and an RP model to design a patient-specific mandibular border implant (Fig. 7). CAD of the implant was performed making the use of the digitally mirrored unaffected side. An RP of this implant was subsequently constructed and used to manually sculpt a block of implantable material manufactured from linear high-density polyethylene (Medpor, Porex Corporation, Fairburn, GA).

Class III

Figure 8 illustrates the general class III workflow. This involves manufacturing of an RP skull model, followed by manual molding and design of the implant and/or template on the RP model. The implant and/or template is subsequently scanned to perform adjustments using CAD software, and then prepared for direct CAM.

In our clinic (European Face Center, UZ Brussel, Belgium), a 16-year-old girl with Ehlers–Danlos-like connective tissue disease presented with a history of frequently recurring temporomandibular joint (TMJ) subluxation causing pain and dysfunction. To prevent recurring subluxation, we designed a custom bilateral tuberculum implant using a class III workflow (Figs. 9–12). An RP model of the skull was manufactured based on the CT-DICOM files. The goal was to produce an implant that prevented subluxation but allowed normal motion without interfering with the condyle at the extremes of motion. To assess normal range of motion of the condyle, wax bites were generated in all extremes, without causing subluxation. The wax bites were then fitted in the RP model to determine the condyle position at these extremes. The implant was designed on the RP using model wax. The tuberculum was heightened, taking into consideration the extreme condyle positions. The heightened tuberculum was fixed on the zygomatic arch and supported anteriorly against the temporal process of the zygomatic arch. It was designed in 2 pieces to allow implantation. The wax implant was then optically scanned, adjusted using CAD software for digitally planned screw
FIGURE 10. Wax modeling of the implant on the RP model. RP, rapid prototype.

FIGURE 11. The implant was optically scanned and screw holes were inserted digitally using CAD software (Geomagic Freeform, Rock Hill, SC). CAD, computer-aided design.

FIGURE 12. The implant was manufactured using direct CAM titanium printing. CAM, computer-aided manufacturing.

FIGURE 13. The surgeon traced the custom design on a custom patient model that was milled using the data from the preoperative CT scan. CT, computed tomography.

FIGURE 14. The completed patient-specific TMJ prosthesis on the custom model. TMJ, temporomandibular joint.

FIGURE 15. Class IV workflow: manufacturing of an RP skull model followed by manual molding and/or design of the implant and/or template on the RP model. RP, rapid prototype.

FIGURE 16. Manual preoperative planning: simulation of resection and reconstruction on stereolithographic model. (A) Planned resection (red lines). Frontal view. (B) Planned resection (red lines). Side view. (C) Prebending of the reconstruction plate (indirect CAM). (D) Planned grafts from the parietal bone. CAM, computer-aided manufacturing.
placement, and prepared for direct CAM titanium printing (Layerwise, Heverlee, Belgium).

In 1995, Mercuri et al. described their use of a class III workflow to construct a custom CAD/CAM total TMJ reconstruction system (Figs. 13 and 14). First, a CT scan was obtained with the teeth in occlusion, and Techmedica (Camarillo, CA) fabricated an RP model of the skull using CNC. The surgeon performed simulated surgery on this model, and used it to construct a custom design for the TMJ prosthesis. The model containing the surgeon’s design specifications was then used by Techmedica to develop CAD blueprints and templates of the prosthesis, which were approved by the surgeon. The prosthesis was then manufactured using direct CAM CNC titanium milling.

Class IV

Figure 15 depicts the class IV workflow, in which manufacturing of an RP skull model is followed by manual molding and design

of the implant and/or template on the RP model. Rohner et al. described a case of complex maxillofacial reconstruction with a fibula flap using the class IV workflow for both molding of a custom bent titanium reconstruction plate and cutting templates for the fibula flap reconstruction (Figs. 16–18). RP models of the patient’s skull and fibula were manufactured to manually plan the resection and reconstruction.

**DISCUSSION**

With the rapid, on-going evolution and the increasingly widespread use of CAD-CAM techniques for CMF surgery throughout the world, a clear method of classification has become necessary. Our classification system is a useful tool to facilitate clear communications with colleagues and industry regarding these techniques. This system covers 4 possible workflow options and can be broadly applied to both implant and template production. Using our classification system in further publications in this field will greatly improve the immediate understanding of the techniques used.

**CONCLUSION**

Our classification system should improve the immediate understanding and mutual communication between colleagues, scientists, and industry involved in CAD-CAM applications for the design and production of implants and templates in the field of CMF surgery.

**REFERENCES**