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Accuracy and clinical evaluation of computer-aided surgery in management of maxillofacial fractures after trauma

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ABSTRACT

Management of maxillofacial fractures is a challenging situation for surgeon. This clinical study aimed to evaluate management of various types, involving complex fractures in the face and head region, in terms of accuracy and clinical outcomes. Included patients were treated using CAD/CAM techniques. A voxel-based analysis was carried out to evaluate the pre-/postoperative accuracy for each patient by superimposing the preoperative planning with the data for the postoperative CT. The distances between the preoperative, virtually planned, and postoperative positions of the screw holes of custom plates were compared. Additionally, various specifics, such as number of reduction guides/plates and surgical accesses, operating times, and perioperative complications were evaluated. Nine patients were included. The median accuracy, measured in millimeters by superimposing the planning with postoperative CT results, was 1.420 (standard deviation 0.425). The surgical times ranged between 100 and 620 min. Complications were seen in three patients; these included preoperative breakage of one reduction guide, and difficulty in intraoperative positioning of the plates in two patients. In conclusion, CAD/CAM techniques in the treatment of a variety of maxillofacial fractures can be beneficial; however, there is a lack of information in the literature, and more studies are needed to confirm these results.

1. Introduction

In the context of pathologies of the cranio-maxillofacial region, trauma patients are predominant. The epidemiology of fractures of the maxillofacial complex is extremely variable, and mostly depends on various factors such as: geographical area, cultural/lifestyle differences, and socioeconomic status. An analysis of results in oral and maxillofacial surgery departments in Europe shows that the most common causes of facial fracture are accidents (traffic, falls, sports injuries, and work-related injuries), and the average age of incidence is between 30 and 39 years, with a male:female ratio of 3.6:1 (Boffano et al., 2015).

The most frequently observed fracture is that of the jaw, followed by fractures of the orbito-malar-zygomatic complex (OMZ), the orbit, the nose, and Le Fort II. Less common fractures are those of the frontal sinus and the naso-orbito-ethmoid complex (NOE) (Boffano et al., 2015; Brusati and Chiapasco, 1999; Fonseca et al. 2005).

Facial fractures usually do not need immediate treatment (within 24–48 h), unless there are major traumas involving hematomas and cerebrospinal fluid (CSF) fistulas or open and comminuted fractures, due to the high risk of infection. The treatment is usually delayed for 10–12 days, which allows for better planning of the intervention, following resolution of inflammation in most parts (Brusati and Chiapasco, 1999).

The main goals of treatment include good bone healing, normal eye functions, and the restoration of occlusion/speech/deglutition with aesthetic results (Hupp et al., 2015). The main surgical aims are the restoration of bone segments in their correct anatomical position, and fixation. Additionally, it is important that the preoperative occlusion is restored, and that any risks of infection are prevented in such patients

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(Hupp et al., 2015).

Reconstruction surgery after trauma in the maxillofacial region is challenging, due the complex anatomy of the facial features and significant aesthetic and functional demands. Developments in modern biomedical technology offer the surgeons alternative protocols, such as intraoperative real-time navigation, computer-assisted planning, and computer-assisted manufacturing (CAD/CAM) methods, which use patient-specific bio-models and surgical plates (Martelli et al., 2016; Brito et al., 2016). Currently, even the most complex fractures in the facial and cranial regions can be restored aesthetically and functionally by means of digitalized preliminary planning and individualized skull, orbital, and zygomatic implants, as well as total temporomandibular joint prostheses (Gellrich et al., 2021; Alagarsamy et al., 2021).

Especially since the mid-1990s, computer-assisted surgery (CAS) has progressed dramatically, leading to a remarkable improvement and optimization of the global approach to reconstructive craniofacial surgery (Scolozzi, 2017; Scolozzi and Schouman, 2012; Taylor et al., 1996; Gellrich et al., 2002; Lauer et al., 2006; Bell and Markiewicz, 2009; Pohlenz et al., 2009; Scolozzi and Terzic, 2011; Terzic and Scolozzi, 2011; Austin and Antonyshyn, 2012; Liu et al., 2016). Today, there is increasing interest in computer-aided design/computer-aided manufacturing (CAD/CAM) techniques and intraoperative navigation systems, because they represent the most adaptable, supportive, and attractive alternatives to the traditional freehand approaches (Scolozzi, 2017).

CAS techniques help the surgeon to plan the surgery before the operation (3D virtual surgical planning); the results can be transferred to the operating room by means of patient-specific implants (PSI) and/or surgical drilling/cutting guides (Scolozzi, 2017; Aboul-Hosn Centenero and Hernandez-Alfaro, 2012; Wilde et al., 2014; Ernoult et al., 2015).

Images captured with computed tomography (CT) or magnetic resonance imaging (MRI), in Digital Imaging and Communications in Medicine (DICOM) format, are processed using specific programs to create three-dimensional data sets in stereolithographic (STL) format. Major progress in the improvement of virtual system performance, in terms of obtaining more accurate and symmetric facial reconstructions, has been achieved through the incorporation of specific software that allows a 'mirroring' technique (Scolozzi, 2017; Taylor et al., 1996; Gellrich et al., 2002; Lauer et al., 2006; Pohlenz et al., 2009; Liu et al., 2016). Mirroring is a technique that can be used both in the context of model stereolithography and, in more recent methods, with surgical navigation and CAD/CAM systems. This method involves projecting the unaffected bone part of the subject (opposite the fractured side), with the aim of making the face as symmetrical as possible and, therefore, obtaining a result that is as close as possible to the condition prior to facial trauma.

Although there is a growing interest in exploring the potential application of CAD/CAM technology in the management of fractures of the maxillofacial region, there is a very limited number of published studies in this area. Furthermore, the majority of these studies are case reports or technical descriptions (Wang et al., 2018; Duran-Rodriguez et al., 2022; Sinha et al., 2018; Cornelius et al., 2015; Elegbede et al., 2018; Marschall et al., 2019; Brito et al., 2016; Novelli et al., 2014). The literature reveals a continuing lack of research papers evaluating the results of treatment modalities based on the management of maxillofacial fractures by CAS techniques, with even fewer studies evaluating the correspondence between virtual reconstruction and surgical result (Novelli et al., 2014).

The aim of our study was to evaluate outcomes of CAD/CAM techniques in the treatment of a variety of maxillofacial fractures. The primary objective was to evaluate the accuracy of a custom-made system applied to the management of trauma of the facial area, based on the results obtained from the applications of this method in oncology and in orthognathic surgery (Zavattero et al., 2019, 2021; Karanxha et al., 2021).

Secondary objectives involved clinical evaluation of the patient to assess the correct symmetry of the face and functional restoration of occlusion. Additionally, costs were compared with the free-hand technique. The accuracy was calculated using a voxel-based overlay of the postoperative CT images with the surgical treatment plan STL files.

2. Materials and methods

This multicentric, retrospective, non-randomized, case-control study aimed to evaluate outcomes of CAD/CAM technique in the treatment of maxillofacial fractures.

The subjects were collected, according to the inclusion criteria, from the databases of two maxillofacial surgery centers of the University of Milan (Maxillofacial Surgery and Odontology Department of the IRCCS Cà Granda Foundation Ospedale Maggiore Policlinico of Milan, and the Galeazzi Orthopedic Institute of Milan) over the period from September 2021 to May 2022. The study followed the principles laid down in the Declaration of Helsinki on medical protocol and ethics. Signed, informed consent was obtained from all participating patients prior to the procedures. The study was approved by Ethics Committee 3 of the Lombardy Region on December 13, 2023 (authorization number OSMAMI-03/01/2024-0000287U, ID 4279).

2.1. Inclusion criteria

- Adult patients aged between 18 and 90 years, who were treated for management of maxillofacial fractures, including zygomatic, mandibular, condyle, orbital, Le Fort I, anterior cranial base, nose, maxillary, or any mixed fractures, as well as partial fractures or complete displaced fractures, including multifocal and multi-fragmented fractures.
- Patients who were able to understand the study requirements and comply with the instructions and appointment plan, as well as giving their approval to participate in the study through a written informed consent form prior to treatment,
- Patients who were otherwise healthy, based on their medical history and physical examination.

2.2. Exclusion criteria

- Oncological patients.
- Patients being treated with any of the following medications: anticoagulant drugs (INR greater than 2), intravenous bisphosphonates and anticonvulsants, steroid therapy, immunosuppressive drugs.
- Patients who underwent radiotherapy, chemotherapy or who have undergone radiotherapy within the past 5 years.
- Patients with history of drug or alcohol abuse; suffering from psychosis; with endocrine disorders.
- Patients with other uncontrolled systemic conditions that cannot be operated.
- Patients who are unable to maintain reasonable standards of home hygiene, in accordance with the requirements of the study.
- Patients who are pregnant or breastfeeding at the time of recruitment.

2.3. Material characteristics of the custom-made system

- Reduction guides: polyamide or titanium.
- Plates: titanium (cpTi) or titanium alloys (Ti_6A1_4V) or cobalt-C alloys with a thickness of 0.7 mm.
- Fixing screws: 1.5 mm diameter for the midface and 2.0 mm diameter for the lower jaw (unlike reduction guides and plates, which were customized for the patient, the screws used were from DePuy Synthes (Johnson & Johnson Medical S.p.A., Pomezia Roma, Italy) maxillofacial surgery sets.

2.4. Preoperative planning

All the traumatized patients were subjected to a computed tomography (CT) scan of the facial mass in thin layers (0.625 mm). The DICOM files of the CT scans were extracted and sent to the biomedical engineering company (SINTAC s.r.l., Trento, Italy), where the data were extracted and processed as STL files, to create models of the skulls of each patient (showing fracture lines and bone segments). Subsequently, each case was discussed in an online meeting between surgeons and engineers.

The fracture reduction Author query: virtual fracture reduction was performed, and custom-made guides with pre-drilling holes for reduction and fixation, and associated plates, were designed and planned. Once the project was approved, guides, plates, and anatomical 3D models were produced in the company's laboratories within 5 working days. The entire preoperative planning procedure was carried out in 6–7 days (from the time of the planning to the day of the intervention). The pre-operative planning of one the patients can be seen in Figs. 1 and 2.

2.5. Surgical procedure

All the patients were operated under general anesthesia. The surgical approach started with mucosal or skin incision and exposure of the fracture. The patient-specific surgical drilling guides were positioned on the fractured extremities and drilling performed, with the holes on the pre-drilling guides corresponding to those on the patient-specific plates that had been designed, using virtual methods, from the patient's CBCT data (Fig. 3 shows intra-operative representative view of drilling guide of one of the patients).

Subsequently, the drilling guides were removed and the patient-specific fixation plates applied in order to obtain ORIF (open reduction internal fixation) of the fracture (Fig. 4: Pre-operative view of fixation plate and Figs. 5 and 6: Intra-operative view of fixation plates). At this point, perfect correspondence between the plate holes and the drilling holes was carefully confirmed before the screws were tightened, to obtain optimal three-dimensional reduction. Once direct control of the stability of the fragments had been achieved, and depending on the nature of the fracture, mandibular function, including individual occlusion, was checked (Figs. 7–11: Pre-operative virtual planning steps of fracture reduction). Finally, the surgical wounds were sutured.

No patients required freehand surgery, since no mismatch between planning and the patient's anatomical condition was experienced. No complications were noted pre-, intra-, or postoperatively.

2.6. Postoperative regimen

Prophylaxis with antibiotics included augmentin (amoxicillin + clavulanic acid; 1 g dose (1 tablet every 8 h for 7 days, starting from the evening before the surgery)). In cases of allergy to penicillin, azithromycin 500 mg was prescribed for 3 days. Patients were hospitalized for 1–2 days following surgery.

Analgesic, anti-inflammatory, and gastroprotective medications comprised ibuprofen 600 mg (one sachet every 8 h for 7 days) and pantoprazole 40 mg (1 tablet per day for 10 days).

Postoperative CT scans were performed to checking the correct positioning of the plates and the reduction of the fractures. DICOM data sets were sent to the engineers for evaluation of accuracy using preoperative (virtual) and postoperative DICOM measurements.

Two follow-up appointments were organized. First, the general clinical situation was checked at 7–10 days after surgery to evaluate morphological positioning, symmetry, projection of the prominences, mandibular function, extrinsic eye movements (EEM), diplopia, dysesthesia, possible paresis, and occlusion. Wound healing was assessed, and sutures were removed.

Then, 1 month after the intervention, the same parameters were evaluated.

2.7. Data collection, measurements, and evaluation of accuracy

As a primary objective of this study, a voxel-based analysis was carried out to evaluate the pre-/postoperative accuracy for each patient by superimposing the preoperative planning with the data from the postoperative CT. show representative preoperative data from CBCT scans for one of the patients for see whom planning was performed virtually. In , the details of accuracy measurements are shown for a representative patient. For this study, mainly the level of accuracy of the reduction system was assessed. For this reason, evaluation was based on discrepancies between drilling holes.

In brief, the DICOM files were loaded onto the Mimics Medical software (Materialize, Belgium) to obtain both the models of the anatomical parts analyzed and those of the plates, which were transferred to the 3-Matic Medical software (Materialize, Belgium).

After importing all the elements, a volumetric base alignment was performed between the 3D models obtained from the postoperative CT and the preoperative plan models. Once the models were aligned, spatial analysis of the plates was performed using Geomagic Freeform© software (Figs. 12–17). The distances between the preoperative virtually

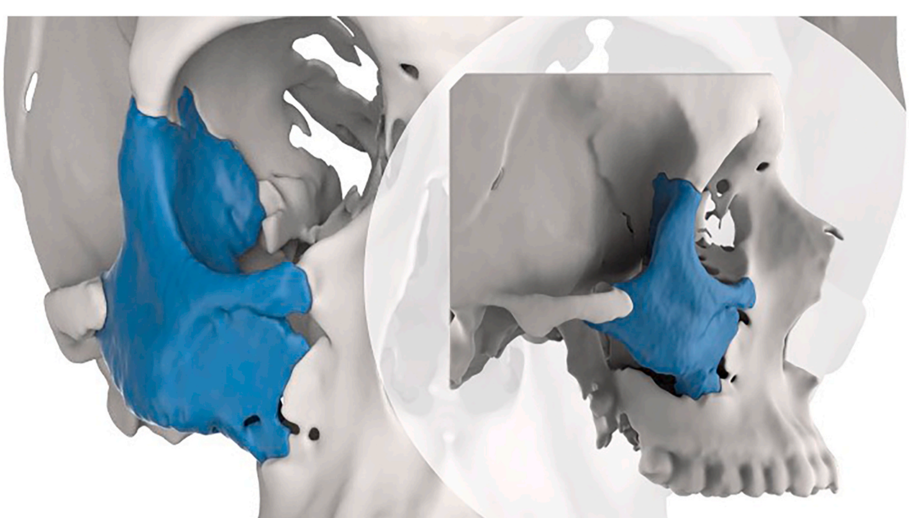

Fig. 1. Representative figure from one of the patients, showing the preoperative situation, with the fracture highlighted. Extraction of data from the CBCT was performed virtually.

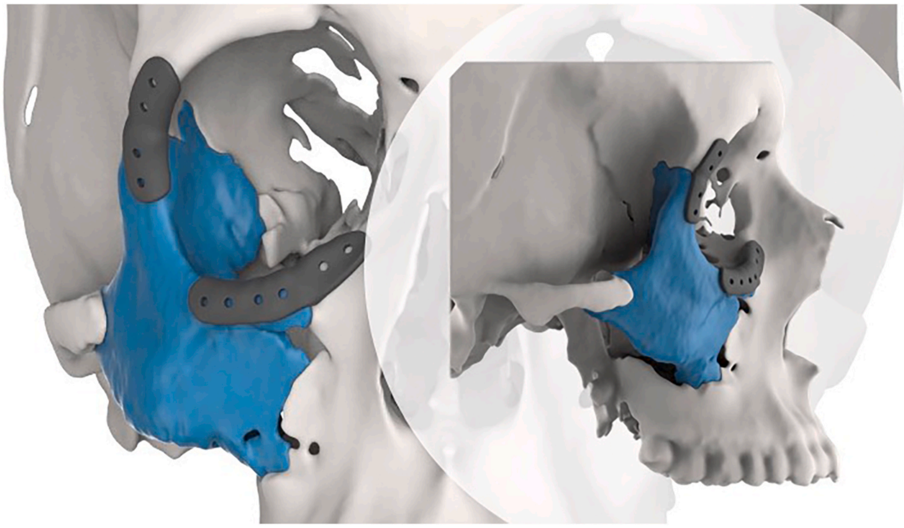

Fig. 2. Representative figure from the same patient, showing two pre-planned surgical drilling guides.

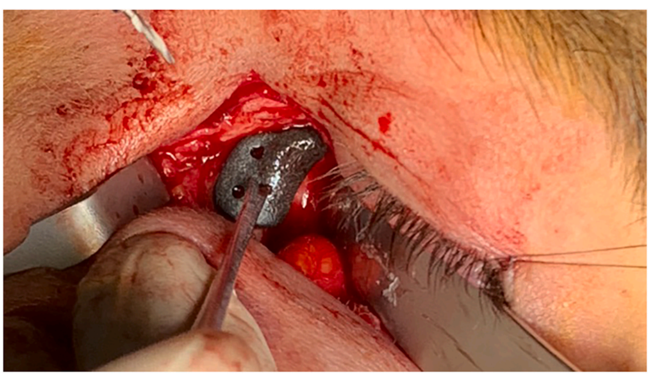

Fig. 3. Intraoperative photo from the same patient, showing placement of the pre-planned surgical drilling guide.

planned positions of the screw holes in the custom plates were compared with those in the plates obtained after surgery (extracted from a post-operative CT), and the differences measured.

Initially, these elements were spatially distant, and therefore it was necessary to perform rotational translations to reduce the distances. For matching, only the 3D models obtained from the postoperative CTs were

Fig. 5. Intraoperative photo from the same patient, showing placement of the pre-planned surgical reduction plates.

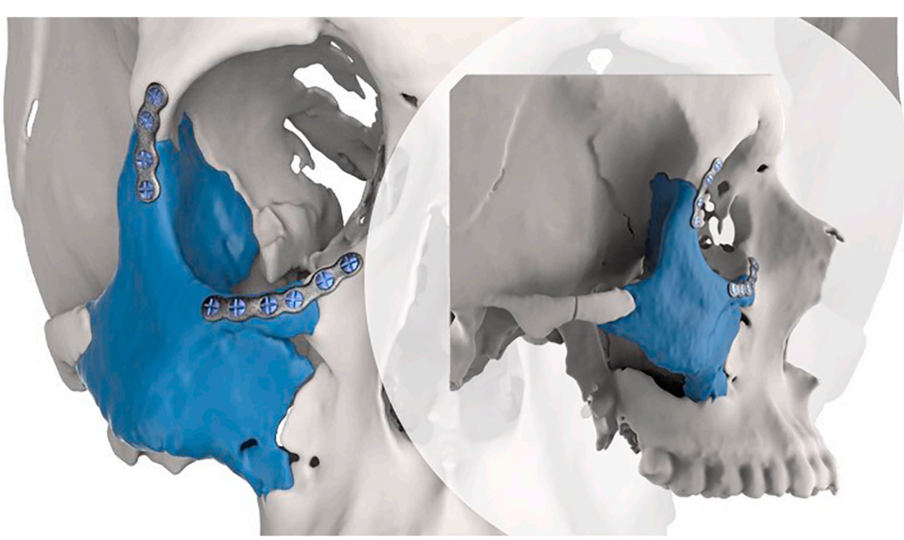

Fig. 4. Fracture reduction was planned in consultation with the surgeon. This representative figure shows development of the two pre-planned surgical reduction plates. All holes were 1.5 mm in diameter.

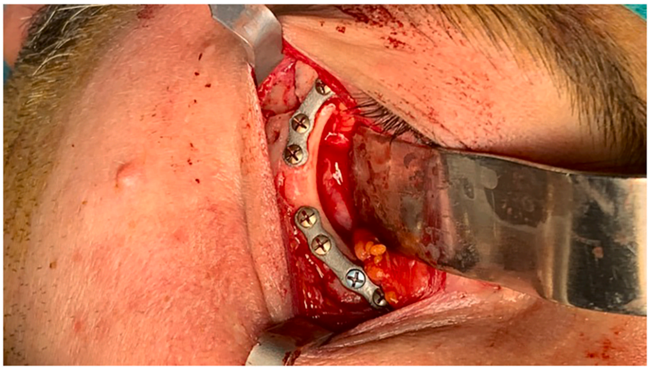

Fig. 6. Intraoperative photo from the same patient, showing placement of the pre-planned surgical reduction plates.

rotated, while those for the plans maintained their spatial position. This operation was performed before the actual alignment, and was essential, since in some cases, due to the spatial distance between the models, the software was unable to complete the alignment operation correctly. By manually superimposing the models, it was then possible to have the software carry out the actual alignment on a volumetric basis.

Once the alignment was complete, a 'zebra-like' image was observed, which confirmed that the process had been performed correctly. The circumferences of the screw holes were utilized to obtain disk-shaped surfaces. Since the radius of each screw was known, the distance from the center of a disk on a plate to the center of the same disk on the corresponding plate was measured. As a result, the individual distances between the holes on plates were calculated. The arithmetic average for each plate and the arithmetic mean for the entire study were obtained. These results were compared with those obtained in the literature, where CAD/CAM methods had been applied to oncological and orthognathic surgeries (Zavattero et al., 2019, 2021; Karanxha et al., 2021).

As a secondary objective, data collection also included various specifics that allowed evaluation from several points of view. These included the number of reduction guides and plates (on which the volumetric analyzes were made), the number of surgical accesses, operating times, and perioperative complications.

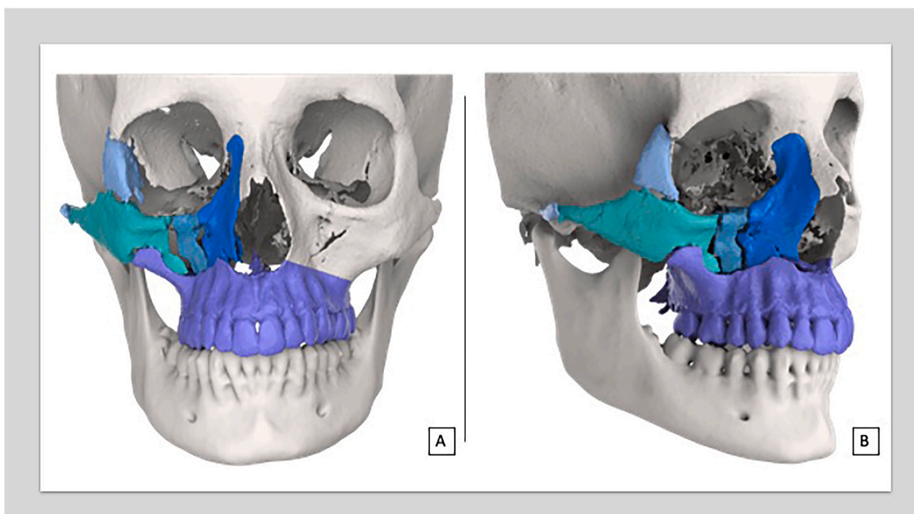

Fig. 7. Preoperative extraction of a patient's CBCT data for planning. The figure shows representative views of (A) the frontal view and (B) the right-side view), revealing fractures in the orbito-malar-zygomatic complex (OMZ).

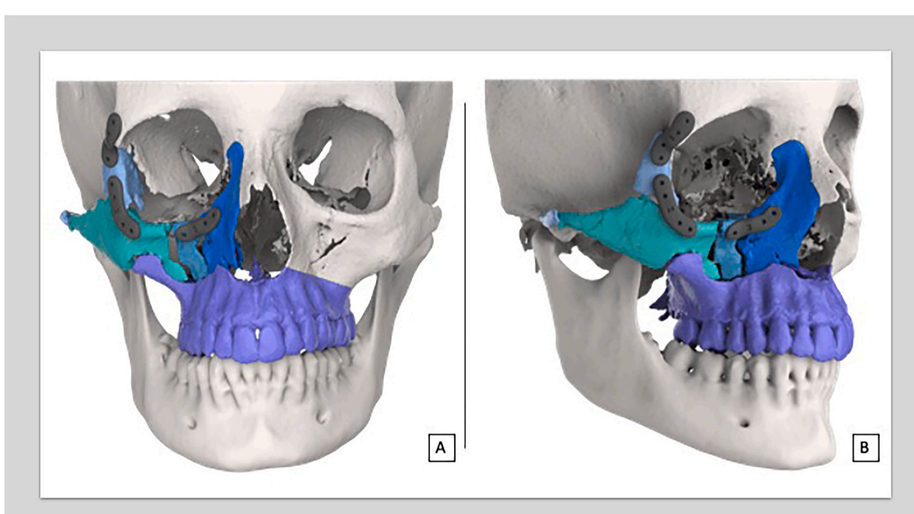

Fig. 8. Preoperative planning of the drilling template design in titanium for the same patient: (A) frontal view, (B) right-side view. The drilling templates were numbered and were equipped with guidance holes for fixation screws.

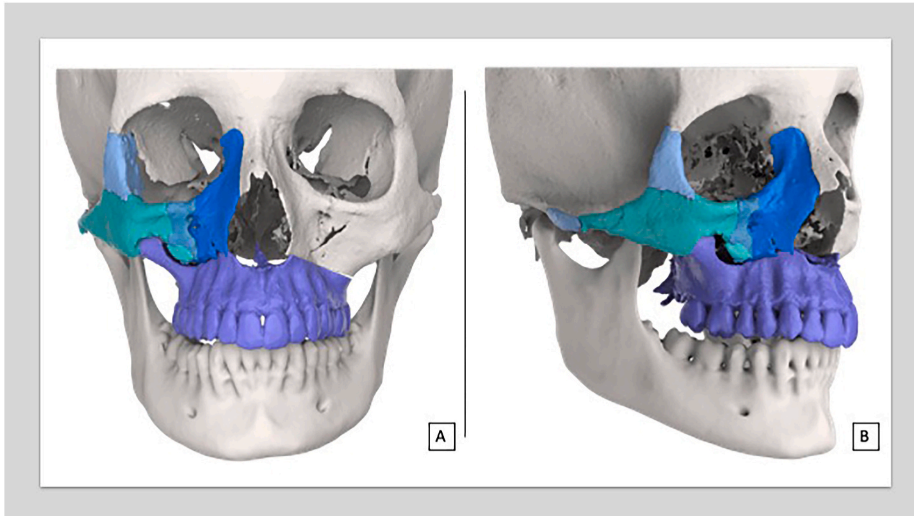

Fig. 9. Preoperative virtual planning of fracture reduction with the surgeons: (A) frontal view, (B) right-side view.

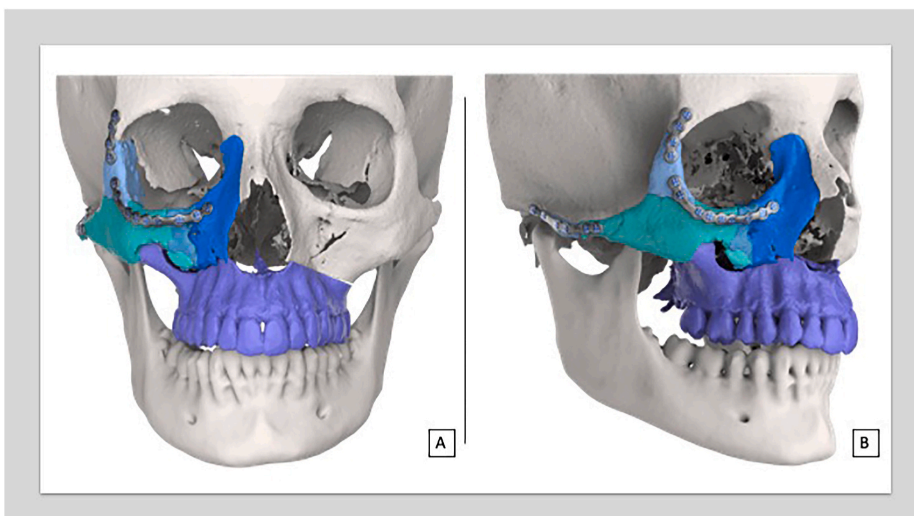

Fig. 10. Preoperative planning of the polished-surface titanium plates with 1.5 mm-diameter screw holes: (A) frontal view, (B) right-side view.

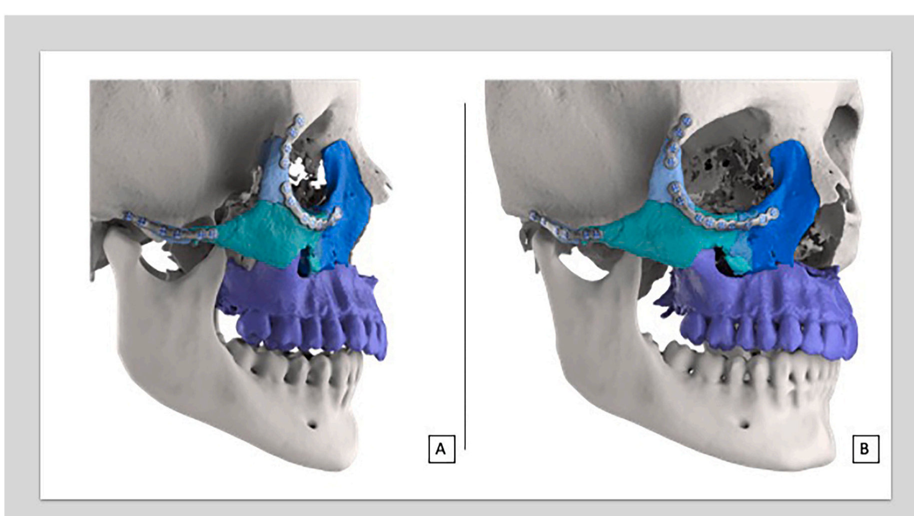

Fig. 11. The reduction plates were designed with a thickness of 0.7 mm and a width of 3 mm: (A) sagittal view, (B) right-side view).

Fig. 12. The anatomical replicas of (A) the fracture and (B) the fracture reduction.

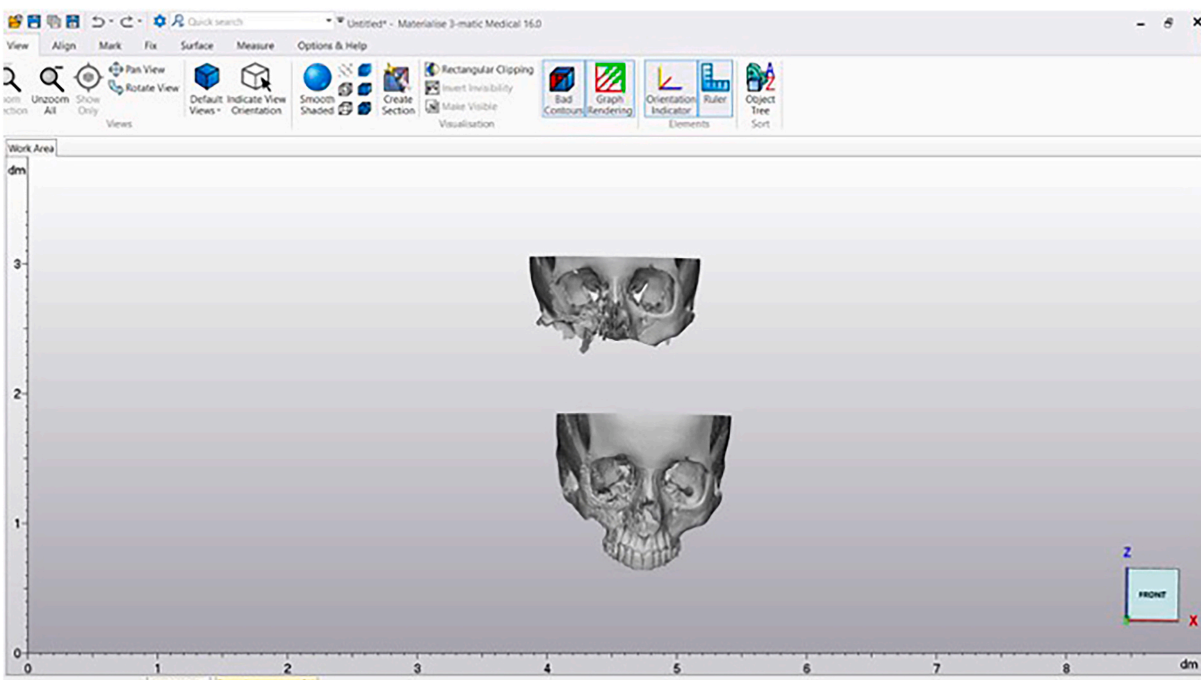

Fig. 13. Importing anatomical models to 3-Matic Medical from CBCT of the same patient.

Statistical analysis was not applied for evaluation due to the small sample size and, above all, the absence of a control group, which would have allowed us to apply a parametric test (e.g. a *t*-test). The results were instead presented as descriptive data, for qualitative and not quantitative analysis. The Shapiro-Wilk test was used to check the normality of the distributions.

3. Results

This study included nine patients — six men and three women — aged between 22 and 88 years (average age 45 years). Types of trauma that caused the fractures were as follows: street accident (six patients), falling accident (one patient), and fighting injuries (two patients).

Table 1 lists the types of fracture, distance measurements for the screw holes expressed in millimeters, and the accuracy (mean displacement distance, with standard deviation).

Table 2 shows details of the descriptive statistical analysis, including median (Q2), mean, first (Q1) and third (Q3) quartiles, and maximum and minimum values.

The pre-/postoperative accuracy values for each patient were found by superimposing the preoperative planning with the data for the postoperative CT. The results in millimeters were as follows: maximum 2.168, mean 1.518, median 1.420, standard deviation 0.425. On a plate basis, these results were calculated in millimeters as follows: maximum 3.133, mean 1.733, median 1.215, standard deviation 0.678.

Symmetry evaluation showed the median of the distribution to be more shifted towards the first quartile (Q1) than the third quartile (Q3), and therefore the distribution was slightly asymmetrical. Symmetry was identified by comparing the mean and median values; in this case the mean was greater than the median, which suggested positive asymmetry (a tendency to have higher values than the median). The Shapiro-Wilk test confirmed the hypothesis that distribution was normal (Gaussian

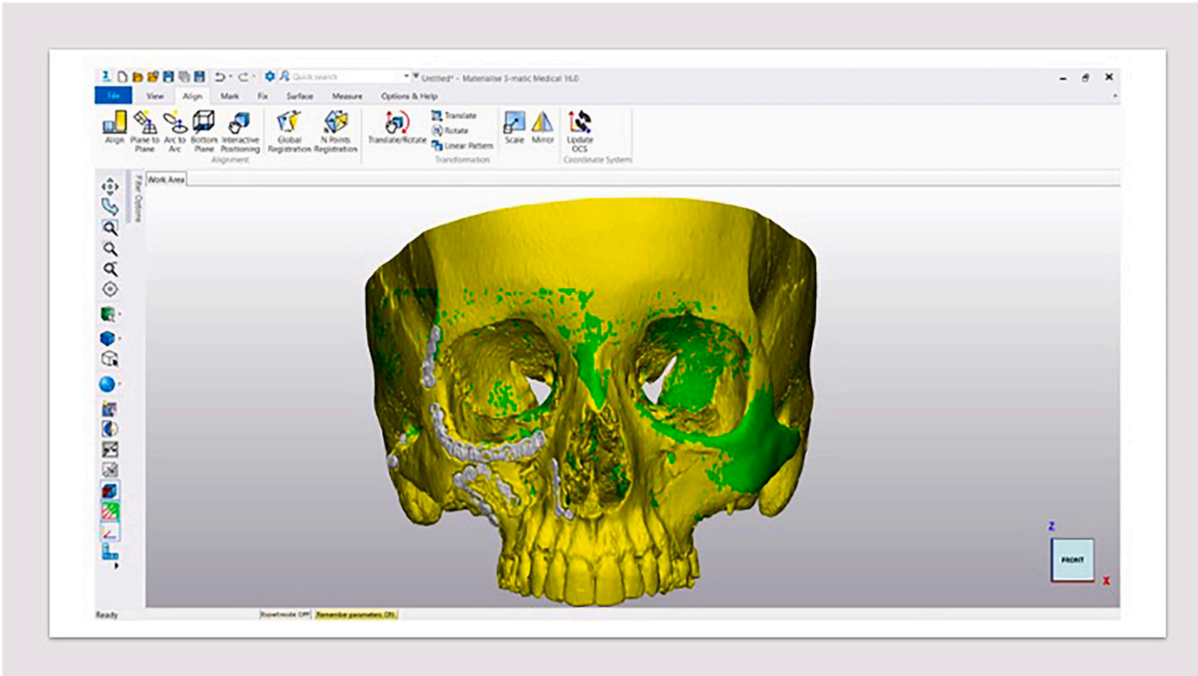

Fig. 14. Volumetric-based alignment of the design models (yellow) and of the models extracted from the postoperative CT (green). The 'zebra' pattern between the models (mixture of yellow and green) confirmed the correct execution of the alignment. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

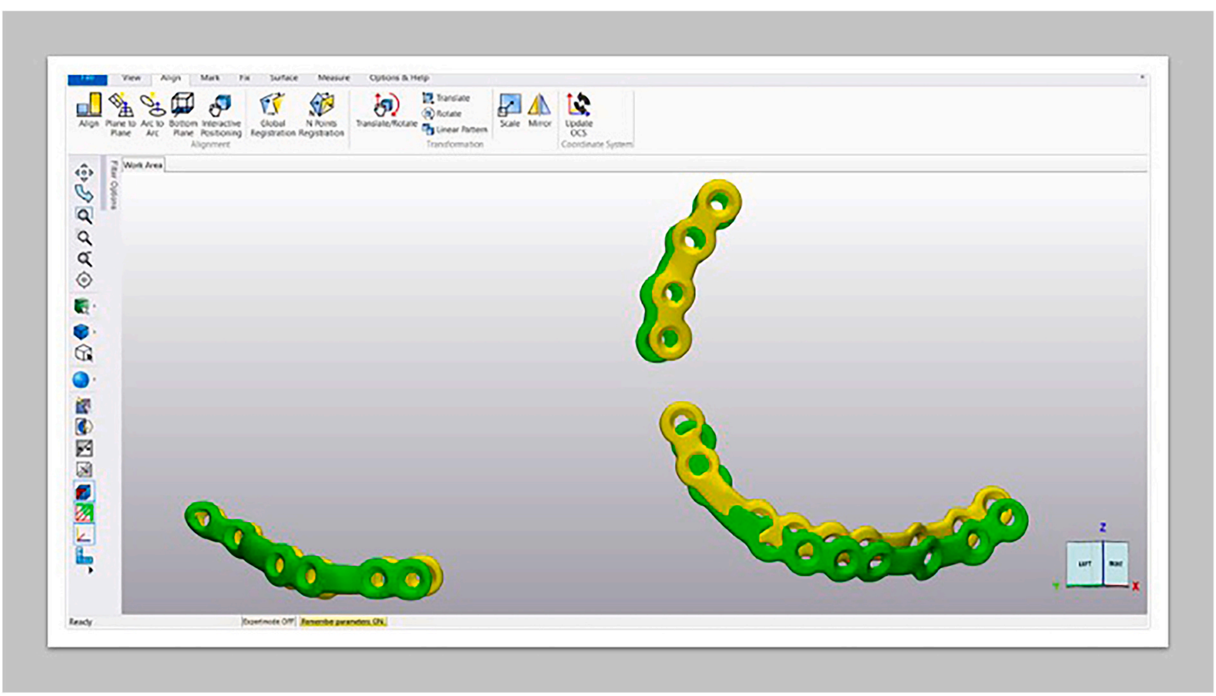

Fig. 15. 3D models of the plates created during the planning phase (yellow) and 3D models of the plates extracted from the postoperative CT scan (green). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

distribution).

Table 3 shows the distribution of data frequencies. The levels of accuracy were evaluated as high, intermediate, or low; their respective frequencies (as absolute and relative) are indicated.

On a patient basis, only in two cases out of nine was there displacement of the plates greater than 2 mm. On a plate basis, four plates out of 21 had displacements of more than 2 mm.

Table 4 gives details of surgical times, access, placement of incisions, and complications/problems encountered during surgery. In three patients, intraoperative problems were found in the positioning of one of the reduction guides and plates. However, operations were completed without any further problems. The surgical times ranged between 100 and 620 min (mean 206.1, SD 166.6). (In one case, the surgical time increased dramatically to 10 h and 20 min, due to a need for additional

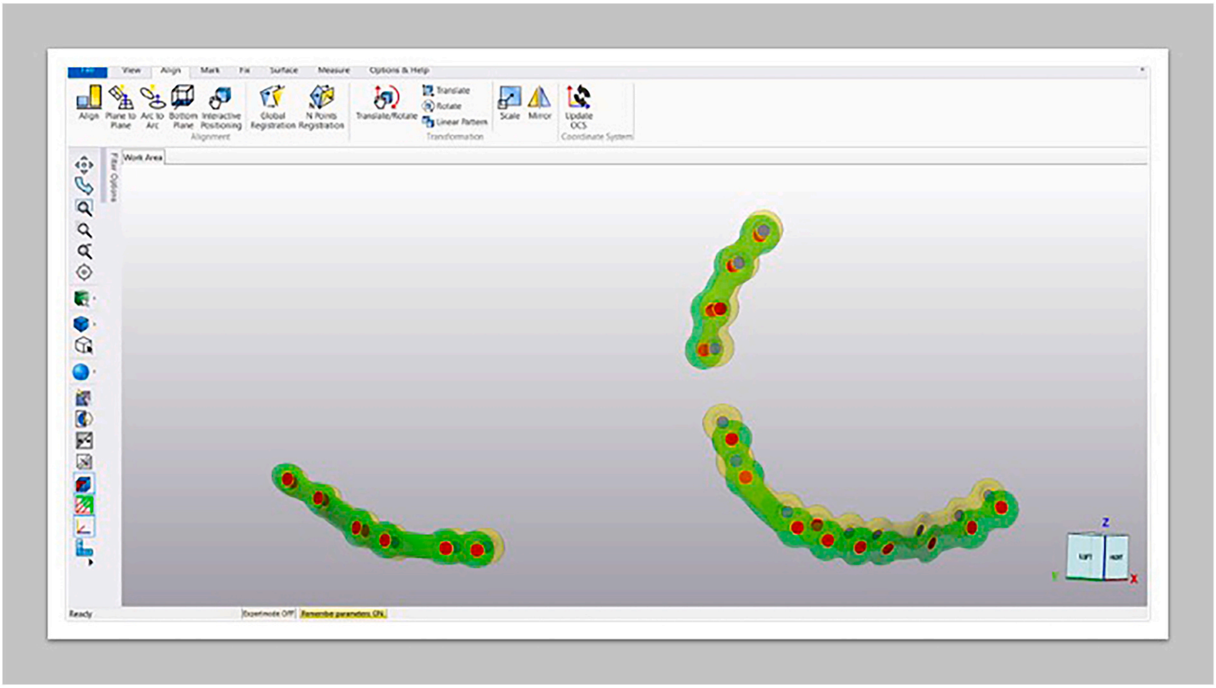

Fig. 16. The 'discs' obtained from the circumferences of the screw holes on the plates.

Fig. 17. The distance between the center of a hole on a plate and the center of the same hole on the corresponding plate was calculated. Once all the distances for a single slab were obtained, the arithmetic mean was calculated for accuracy.

neurosurgery).

4. Discussion

The application of CAD/CAM technology, together with VSP (virtual surgical planning) based on 3D imaging, has revolutionized oral and maxillofacial surgery, with the possibility of separating and moving structures and anatomical reproductions in three dimensions. The *accuracy* of virtually planned and *CAD/CAM*-guided *surgeries* is currently a great point of interest, and must be clearly defined to help surgeons provide safe treatment.

Today, voxel-based techniques are widely used to evaluate the accuracy of preoperative programming compared with results for various types of computer-assisted maxillofacial surgeries, such as reconstructive surgery with free flaps, either for oncological purposes or for rehabilitation of large defects (Gellrich et al., 2021; Geusens et al., 2019; Wu et al., 2021; Goormans et al., 2019; Foley et al., 2013), orthognathic surgery (Li, et al., 2021; Figueiredo et al., 2021), condylar fractures

Table 1
Types of fracture and distance measurements between the centers of the screw holes expressed in millimeters.

Patient	Type of fracture	Plate 1	Plate 2	Plate 3	Plate 4	Mean accuracy	Standard deviation
1	Zygomatic bone left and right + orbital frame + Le Fort I	1.130	0.960	2.080		1.390	0.604
2	Frontal sinus + anterior cranium base floor + right orbital frame + orbital pavement right and left + maxilla + nasal bone	–	0.664	0.940	1.393	0.999	0.368
3	OMZ right + nasal bone + Le Fort I	1.203	3.133	–	–	2.168	1.365
4	OMZ right	1.215	1.100	–	–	1.158	0.081
5	OMZ right	2.632	1.595	–	–	2.114	0.733
6	OMZ right	0.968	1.872	–	–	1.420	0.640
7	Bifocal mandible	1.743	1.615	0.978	–	1.445	0.410
8	OMZ right	1.398	0.665	–	–	1.031	0.518
9	OMZ right	2.910	0.968	–	–	1.939	1.374
						Mean total	**Total**
						1.518	0.450

OMZ: orbito-malar-zygomatic complex fracture.

Table 2
Descriptive statistics data in millimeters.

Parameters	Patient basis	Plate basis
Distribution of the mean displacement of plates in the population	9	21
Minimum	0.999	0.665
Maximum	2.168	3.133
Average	1.518	1.733
Median (Q2) (mean displacement of the prosthesis in the observed population)	1.420	1.215
Standard deviation	0.425	0.678
Variance	0.180	
First quartile (Q1)	1.095	0.968
Third quartile (Q3)	2.027	1.808
Interquartile range (IQR)	0.932	0.840
Outliers	Absent	Absent
Asymmetry	0.369	–

Table 3
Frequency of data distribution in millimeters.

Patient basis	High	Intermediate	Low	Total
	(0–1.5 mm)	(1.5–2 mm)	(> 2 mm)	
Absolute frequency	6	1	2	9
Relative frequency	66.67 %	11.11 %	22.22 %	100 %
Plate basis	(0–1.5 mm)	(1.5–2 mm)	(> 2 mm)	**Total**
Absolute frequency	13	4	4	21
Relative frequency	61.90 %	19.05 %	19.05 %	100 %

(Duran Rodriguez et al., 2022), and orbital surgery (Scolozzi et al., 2017). However, the number of the studies on the management of fractures remains limited (Zavattero et al., 2019, 2021; Karanxha et al., 2021).

Reconstructive surgeries in the region include mandibular bone, oral cavity, maxillary bone, and temporomandibular joint, which represent major challenges for the clinicians due to critical and complex morphology, physiological function (including mastication, speech), and restoration of aesthetics. The accuracy of mandibular reconstructions with a fibula free flap utilizing CAD/CAM guided surgery was evaluated by Geusens et al. In their study, the fibular segments were compared postoperatively with the virtual surgical plans in 20 patients. Linear distances (superior and inferior borders) of 41 fibula segments and intercoronoid distances were also measured. According to the results, the mean difference was 3.11 ± 2.80 mm for superior borders (range 0.02–12.20 mm), and 2.75 ± 2.61 mm for inferior borders (range 0.22–13.58 mm). The mean intercoronoid difference was 3.57 ± 1.80 mm (range 0.91–6.11 mm) (Geusens et al., 2019). In a similar study, Goormans et al. tested the accuracy of computer-assisted mandibular reconstructions with free fibula flap in 26 patients, and found means for deviation of each osteotomy angle and fibular segment length to be 1.98° (SD 2.98) and 1.78 mm (SD 2.69), respectively (Goormans et al., 2019). In a more recent case report, Wu et al. applied a 3D-printed polylactic acid (PLA) surgical guide plate to reconstruct a mandibular defect with fibula flap, and evaluated its clinical effect and accuracy. As a result, when compared with the preoperative design, the maximum deviation of the actual postoperative registration was found to be 1.67 ± 0.63 mm (Wu et al., 2021).

A recent systematic review evaluated the accuracy of orthognathic surgery with customized titanium plates (Figueiredo et al., 2021). The best mean value for surgical accuracy achieved in the analysis of the maxillary dental region was 0.45 mm (Heufelder et al., 2017), and the worst was 1.3 mm (Kraeima et al., 2016). For the mandibular dentition, mean accuracy was found to be 0.82 mm in a single report (Li et al., 2017). For the maxillary bone surface, the best mean accuracy was 0.24 mm (Mazzoni et al., 2015) and the worst was 1.09 mm (Brunso et al., 2017), while for the mandible bone surface the best result was 0.61 mm (Brunso et al., 2016) and the worst was 0.69 mm (Li et al., 2017). According to the review, mean differences of up to 2.0 mm were acceptable, in accordance with previous reports in the literature (Xia et al., 2007; Marchetti et al., 2007; Proffit et al., 1987, 2007; Donatsky et al., 1997; Ong et al., 2001).

In a morphometric study, Zavattero et al. evaluated the accuracy of virtual planning in orthognathic surgery in 17 patients, and reported that the average linear differences for selected points were <1 mm in 12 patients out of 17 (Zavattero et al., 2019). In five patients out of 17, the average differences for selected points were <2 mm (Zavattero et al., 2019). Several authors have worked on evaluating the accuracy of the new techniques, and currently a discrepancy of no more than 2 mm (between preoperative planning and postoperative CT) is generally considered as a success criterion (Hsu et al., 2013; Stokbro et al., 2014; Stokbro et al., 2016; Kaipatur and Flores-Mir, 2009; Shehab et al., 2013; Xia et al., 2000). Furthermore, a discrepancy of less than 2 mm is considered clinically insignificant in the analysis of conventional lateral cephalometric measurements (Tucker et al., 2010; Xia et al., 2011; Shafi et al., 2013; Mollemans et al., 2007; Gliddon et al., 2006; Swennen et al., 2009).

With regard to the management of fractures following trauma in the maxillofacial region, there are no clinical reports that evaluate virtual surgery accuracy results. For this reason, in this study, outcomes of accuracy for different types of computer-assisted maxillofacial surgery (such as virtually guided orthognathic and reconstructive surgeries) were considered as comparisons against our results. A difference of 2 mm was taken as the limit for success when evaluating accuracy (anything above this value was considered a large discrepancy); this was supported by several previous reports (Xia et al., 2007; Marchetti et al., 2007; Proffit et al., 1987, 2007; Donatsky et al., 1997; Ong et al., 2001).

One systematic review analyzed 3D printing applications in surgery

Table 4
Surgical time, access, incisions, and complications.

Patient	Surgical time	Number of guides	Number of plates	Surgical access	Surgical incisions	Complications/ Challenges
1	4 h 30 min	3	3	4	Right upper eyelid region, subtarsal region right, right preauricular region (facelift type with temporal and superior circum-vestibular extension)	None
2	10 h 20 min	4	4	5	Left submental region, notched coronal extending from the root of the right helix to the preauricular region left, bilaterally inferior subtarsal transpalpebral and circummaxillary of the superior vestibular fornix	Preoperative break of left zygomatic drilling guide, which caused problems with positioning of plate 1
3	3 h 15 min	3	3	3	Right subciliary region, right superior vestibular fornix and para-latero-nasal	None
4	1 h 40 min	2	2	3	Right subciliary region, right eyebrow, and vestibular fornix of the right upper jaw	None
5	1 h 30 min	2	2 + mesh	3	Right subciliary region, right eyebrow, and vestibular fornix of the right upper jaw	Difficulty in positioning of one of the reduction guides
6	3 h 30 min	2	2	4	Right subciliary, right eyebrow, upper vestibular fornix, and right parietal	None
7	2 h 30 min	2	3	2	Inferior vestibular fornix and retro- mandibular angle incision	None
8	2 h	2	2	3	Right sub-ciliary region and right frontal-zygomatic region and right vestibular fornix	None
9	1 h 40 min	3	3	3	Right subciliary region, reopening of the previous wound, torn/bruised in the right frontal-zygomatic region and right vestibular fornix	Presence of a broken bone fragment at the level of the lower orbital frame in correspondence with the positioning of the reduction guide (holes were drilled and plate was positioned equally)

and confirmed that the main advantages of this technology are the possibilities of preoperative planning, and better accuracy in less surgical time (Martelli et al., 2016). According to the results of our study, the surgical times ranged between 1 h and 30 min and 10 h 20 min (because of an additional neurosurgery that was performed in the same session). It is almost impossible to confirm that virtual surgery reduces surgical time in the management of maxillofacial region fractures, because in every patient the situation is different. There are several factors that might affect surgical time, such as complexity, type of fracture, and the general health condition of the patient.

According to the literature, one of the drawbacks in virtual planning and 3D printing methods in maxillofacial reconstruction surgeries seems to be the long wait for delivery of the titanium plates, which can take up to 21 days (Lichtenstein et al., 2025). This can create a major limitation for patients with fractures that need to be operated 1–2 weeks after the injury, which is the optimum time for repair once the initial swelling subsides. However, in our study, with proper communication between surgeons and engineers, it was possible to schedule the reconstruction surgeries after 7–10 days (since the 3D-printed plates were delivered in 5–7 days, and were sterilized a day before surgery). We can conclude that virtual planning and application of CAD/CAM protocols in trauma patients with fractures can simplify the surgical process and can help to minimize the surgical time in the operating room, while efficient production of 3D custom-made plates can be managed with collaboration of the team members.

According to our results, the mean accuracy was 1.52 mm, which was in accordance with several previous CAD/CAM surgery studies involving the maxillofacial region (Hsu et al., 2013; Stokbro et al., 2014; Stokbro et al., 2016; Kaipatur and Flores-Mir, 2009; Shehab et al., 2013; Xia et al., 2000). Since our study did not have a similar study with which to compare the accuracy of results for different types of fracture, it was almost impossible to label the outcomes as successful or not. However, the included subjects experienced a positive healing period with acceptable accuracy results, suggesting that virtual planning in complex fracture patients can be a valuable option.

One very recent study evaluated the feasibility of individualized plates that were produced via CAD/CAM methods for reconstruction of zygomatic bone fractures (Lichtenstein et al., 2025). For this purpose, the authors conducted their research using eight cadaver skulls with 16 zygomatic bones that were artificially fractured. Eight zygomatic bones were reconstructed with patient-specific plates and eight contralateral zygomatic bones of the same subject were reconstructed with standard osteosynthesis plates, in order to compare results. The virtual planning method used was similar to that employed in our study, since the 3D models were created using threshold segmentation tools, although with some possible minor variations due to the different software systems used. In the cadaver study, virtual reconstructions were performed, and 3D-printed, individualized titanium plates were used to fix the zygomatic bone fragments. A postoperative CBCT scan was taken to assess the deviation of bone fragments from the original position, and to evaluate the accuracy of the planning and the outcomes using a 3D coordinate system, which algorithmically matched reference points that had been defined by the operator for each cheek bone on the skull, with five measurement series for each fracture (Lichtenstein et al., 2025).

In our study, the accuracy evaluation was carried out using a different method, based on the discrepancies between the drilling holes on the plates instead of anatomical reference points on the skull that were defined by hand. In real-life scenarios, pre-trauma CBCT for comparison of accuracy of the positioning of anatomical points with postoperative CBCT is rarely available; therefore, reference points on reconstructive plates are a more feasible alternative for evaluating accuracy. Another option involves comparing the contralateral healthy side with the fractured side to assess symmetric and aesthetic outcomes. Although this approach was used in our study for virtual planning of positioning of the fractures and fixation of bone fragments, contralateral sides were not considered for accuracy calculations, since they can differ and be asymmetrical depending on each individual.

According to the results of the cadaver study, the discrepancy between the planned and postoperative situation was around 1 mm, while our research showed a similar but slightly higher value at 1.5 mm (Lichtenstein et al., 2025). In their cadaver study, it was concluded that a workflow involving individualized plates for trauma cases is clinically applicable. Although 3D-printed titanium plates showed no significant differences in terms of accuracy when compared with traditional plates, there might be an advantage in their use for heavily dislocated fractures (Lichtenstein et al., 2025).

Our study had some limitations, including the limited sample size, lack of a control group, evaluation of different types of fracture (making comparisons among them difficult), and the very limited number of studies (mostly case reports) relating to rehabilitation of fractures in the maxillofacial region with which to compare our results. However, this lack of reports in the literature guiding lead surgeons in reaching decisions regarding the benefits of virtually guided surgery is also a strong point of our study. Further randomized studies of CAD/CAM applications in the rehabilitation of fractures in the maxillofacial region, using larger samples of subjects, are needed in the literature. In addition, further research should be carried out to compare the accuracy of maxillofacial fracture reconstructions with traditional and individualized plates to understand their feasibility in routine post-traumatic maxillofacial reconstructions.

5. Conclusion

According to the results of our study, CAD/CAM techniques appear to be beneficial in the treatment of a variety of maxillofacial fractures. The accuracy of the custom-made system applied in this study for management of trauma of the facial area seems to be in accordance with results found in the literature relating to the application of this method in oncology and in orthognathic surgery. The postoperative clinical evaluation of the patients found that the correct symmetry of the face and functional restoration of occlusion had been achieved in all cases without any major complications.

Author contributions

Conceptualization: FG, CM, FR, AR, GB, MDF, ABG, CB, and AB. Data curation: FG, CM, FR, AR, GB, MDF, ABG, CB, and AB. Formal analysis: FG, CM, FR, AR, GB, MDF, ABG, CB, and AB. Investigation: FG, CM, FR, AR, GB, MDF, ABG, CB, and AB. Methodology: FG, CM, FR, AR, GB, MDF, ABG, CB, and AB. Project administration: FG, CM, FR, AR, GB, ABG, CB, and AB. Resources: FG, CM, FR, AR, GB, MDF, ABG, CB, and AB. Software: FG, CM, FR, AR, GB, MDF, ABG, CB, and AB. Supervision: FG, CM, FR, AR, GB, MDF, ABG, CB, and AB. Validation: FG, CM, FR, AR, GB, MDF, ABG, CB, and AB. Visualization: FG, FR, AR, MDF, ABG, CB, and AB. Writing — original draft: FG, CM, FR, MDF, CB, and AB. Writing — review and editing: FG, CM, FR, AR, GB, MDF, ABG, CB, and AB.

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