Case series

Late treatment of orbital fractures: a new analysis for surgical planning

Trattamento tardivo delle fratture orbitarie: una nuova analisi per la programmazione chirurgica

M. PAGNONI[1], M. MARENCO[1], V. RAMIERI[1], V. TERENZI[1], D. BARTOLI[1], G. AMODEO[1], A. MAZZOLI[2], G. IANNETTI[1]

[1] Maxillo-Facial Surgery Department, Policlinico "Umberto I", Sapienza Università di Roma, Roma, Italy;
[2] Department of Materials and Environment Engineering and Physics, Technical University of Marche, Ancona, Italy

SUMMARY

Surgical treatment of orbital fractures should be performed without delay; in some cases acute management is not possible due to general conditions and might be delayed for weeks or months. In the latter case, the fractured fragments can consolidate improperly, causing secondary deformities of the orbital region with aesthetic and functional alteration. Surgical planning of secondary deformities is critical for adequate pre-operative planning. In the last decade an increasing number of dedicated software applications for surgical planning have been developed. Standard computed tomography (CT) or the relatively new cone beam CT can be used for diagnostic purposes, pre-surgical visual treatment outcome and virtual surgery. In this report, the authors propose their pre-operative planning analysis for surgical correction of secondary deformities of orbital fractures. The treatment of orbital fracture must, in fact, analyse not only the bone structures but the soft tissue and surrounding periorbital region. The position of the orbit in the space should be determined in relation to the surrounding structures compared to the contralateral side, if this is not affected by the trauma or pre-existing malformations.

KEY WORDS: Orbital fracture outcomes • Surgical planning • Two-dimensional analysis • Three-dimensional analysis

RIASSUNTO

Il trattamento chirurgico delle fratture orbitarie dovrebbe essere teoricamente effettuato il più precocemente possibile; in molti casi tuttavia l'intervento deve essere rimandato per qualche settimana o mese a causa delle condizioni generali del paziente. In questo ultimo caso è possibile che i frammenti fratturati si consolidino in posizioni errate causando deformità secondarie alla regione orbitaria con alterazioni funzionali ed estetiche. Un adeguato ed attento programma chirurgico delle deformità secondarie diventa quindi di fondamentale importanza per una perfetta riuscita del trattamento sia da un punto di vista di integrità delle strutture ossee che per quanto riguarda gli aspetti estetici. Nell'ultimo decennio si è sviluppato un numero sempre maggiore di software per la programmazione chirurgica. Sia tramite TC che tramite la nuova tecnologia Cone Beam è possibile ottenere file da poter utilizzare per scopi diagnostici, di previsualizzazione chirurgica o di chirurgia virtuale. In questo lavoro gli Autori propongono la loro metodica di programmazione pre-chirurgica nella correzione delle deformità secondarie alle fratture orbitarie. La valutazione e, di conseguenza, il trattamento di queste fratture deve essere basato non solo sulle strutture ossee ma anche, e soprattutto, sui tessuti molli della regione periorbitaria. È fondamentale quindi analizzare la posizione dell'orbita nello spazio in relazione alle strutture che la circondano ed alla regione controlaterale, se scevra da esiti traumatici o da malformazione pre-esistenti.

PAROLE CHIAVE: *Risultati nelle fratture orbitarie • Programmazione chirurgica • Analisi bidimensionale • Analisi tridimensionale*

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Introduction

Orbital fractures, like all fractures of the maxillo-facial skeleton, require early surgical treatment, at most within a week after the trauma. Sometimes however, surgical treatment needs to be delayed for weeks or even months, either for general reasons or due to the occurrence of life-threatening injuries. In these cases, the fractured fragments can consolidate improperly [1 2]. Orbital fractures can be isolated, part of an extended fracture (such as Le Fort III fracture) or part of comminute fractures of the midface. The success of delayed trauma surgery depends on diverse aspects of the preoperative evaluation of the defect. Computed tomography (CT) and cone-beam CT (CBCT) is widely used to support the surgical planning process. Three-dimensional (3D) visualisation techniques can also be used in order to facilitate surgical planning. Moreover, diverse image-reformatting software packages have been developed for the this purpose (e.g. Analyze; Mayo Clinic, Jacksonville, FL; Mimics; Materialise NV, Leuven, Belgium; 3-D Doctor; Able Software Corporation, Lexington, MA; SliceOmatic; TomoVision, Montreal, Quebec, Canada). These tools supply the surgeon with a 3D analysis and measurements, and some also provide a surgical simulation platform. Solid free-form fabrication (SFF) technologies, originally developed for industry, have been receiving a great deal of attention in the medical sector in the past few years. SFF-manufactured anatomical models find applications particularly in oral, maxillofacial and neurological surgery to assist diagnosis, planning treatment and manufacturing implants. The effectiveness of SFF models has been shown in various surgical procedures [3 4]. Currently, the SFF techniques used in medical applications are 3D printing (3D-P), stereolithography (SLA), selective laser sintering (SLS), fused deposition modelling (FDM) and electron-beam melting (EBM). In the present paper, the authors propose their pre-operative analysis for the correction of secondary post-traumatic orbital deformities. Three-dimensional graphic rendering was done using the Dolphin Imaging Plus 11 software (Dolphin Imaging and Management Solutions, Chatsworth, CA).

Clinical examination

The first phase of objective examination includes aesthetic evaluation of the patient, highlighting any change of appearance and facial expressions, bipupillary line alignment, enophthalmos, eye movement alterations, the position and movement of the eyelids and the inclination of the palpebral fissure with its symmetry and direction. Palpebral ptosis can often appear simply due to loss of upper eyelid support from the displaced eyeball (false ptosis). It is important to distinguish this form of ptosis from a true one, which is caused by damage to the elevator palpebrae superioris muscle or damage to the 3rd cranial nerve. In the latter case, there is also a defect of ocular motility of the four recti muscles. With simple inspection, it should be possible to locate the region affected by the trauma, to identify any losses of hard or soft tissue substance and evaluate the integrity or possible involvement of the optic nerve, of the 3rd, 4th, 6th and 7th cranial nerves. In normal conditions, the eyeball protrudes from the orbital frame by between 18 and 20 mm and a regression of 2 mm is considered the limit beyond which surgical correction is advised. Evaluation of diplopia is fundamental for therapeutic strategy. Diplopia is closely connected to enophthalmos and can occur in primary gaze or habitual position. The red glass test should be performed for diplopia and/or the Parks 3-step test and/or Bielschowsky's test in the case of vertical diplopia along with the Hess screen test. The forced duration test is an objective method for examining extrinsic ocular motility; a positive result allows the exclusion of secondary paralysis of the oculomotor muscles due to orbital fractures. In orbital trauma, in addition to basic examination with visual acuity test, ophthalmological evaluation also includes split lamp, ophthalmoscopic examinations including careful evaluation of ocular motility and binocular visual field, and electromyography to assess muscular function and of course CT and MR.

Surgical planning

Computed tomography provides analysis of the orbit on the axial, coronal and sagittal planes. CT images should be of a maximum thickness of 1 mm; the axial scans should be parallel to the Frankfurt plane on the lateral (the plane passing through the porion and lower orbital point). The acquired images should be oriented according to a standardised model referred to as reslicing, which can be performed either by the technician or by the treating physician, thanks to the introduction of software which allows both two-dimensional analysis on axial, coronal and sagittal reconstructions as well as on three-dimensional views (Dolphin Imaging®).

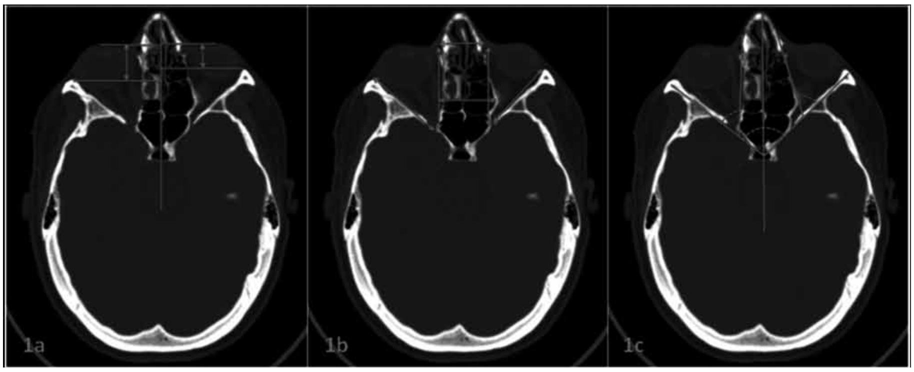

Fig. 1. a. A line from the nasion and passing through the nasal septum and the sphenoidal sinus; a line through the most retruded point of the lateral wall of the orbit; a line tangent to the corneal apex; position of the zygomatic bones and the nasion; analysis of optic nerve curvature. **b**. Inter-dacryl distance; transverse dimension of the ethmoid; length of the medial and lateral walls. **c**. The angle subtended to the extensions of lines passing through the lateral walls of the two orbits; the angle subtended to the extensions of lines passing through the medial and lateral wall of an orbit.

Two-dimensional evaluation axial plane

A line projected from the nasion and passing through the nasal septum and the sphenoidal sinus represents the plane of symmetry. Selection of axial images that best represent the equator of the eyeball is then made. (Fig. 1a).

Linear measurements

- Protrusion or intrusion of the eyeball expressed as exo- or enophthalmos (normal values are 10-14 mm for children and 15-

19 mm for adults). Two lines are drawn perpendicular to the median. The first represents the reference plane and passes through the most retruded point of the lateral wall of the orbit, while the second represents a projection of the eyeball and is at a tangent to the corneal apex (Fig. 1a). The projection of these two lines on a sagittal median plane corresponds to the quantification of the exophthalmos or enophthalmos in relation to the values codified by Hertel for exophthalmometry.
- Position of the zygomatic bones (Fig. 1a).
- Position of the nasion (Fig. 1a).
- Analysis of optic nerve curvature (Fig. 1a).
- Inter-dacrial distance (the distance between the two anterior lacrimal crests, dacryon) (Fig. 1b). The normal range of measurements for this distance is about 18 mm in newborn infants and 25 mm in adults. Hypertelorism is classified as slight (30-34 mm), moderate (35-39 mm) or severe (greater than 39 mm). This value can also be evaluated in coronal reconstructions.
- Transverse dimension of the ethmoid (Fig. 1b).
- Length of the medial and lateral walls (Fig. 1b).

Angular measurements
- The angle identified by the lines passing through the lateral walls of the two orbits (normally 90°). (Fig. 1c).
- The angle identified by the lines passing through the medial and lateral wall of an orbit (approximately 45°) (Fig. 1c).

Two-dimensional evaluation coronal plane

A line projected from the crista galli to the anterior nasal spine and passing through the nasal septum (if not deviated) represents the plane of symmetry (Fig. 2c).

Linear measurements
- Interdacrial distance (select the coronal section in which both anterior lacrimal crests are visible and measure the most cranial portion) (Fig. 2a).
- Transverse dimension of the ethmoid (Fig. 2c).
- Vertical dimension of the orbit (Fig. 2b).
- Position of the superior and inferior orbital margins in relation to the contralateral orbit or reference planes (occlusal plane, maxillary plane, interzygomatic plane and median sagittal plane) (Fig. 2c).
- Position of the orbital floor and roof (Fig. 2c).

A posterior coronal section where the superior orbital margins are both visible at the same time and helps determining the orbital parameters, the angle of the orbital floor in relation to median reference plane; if reference points are unavailable, a linear measurement system can be adopted based on a plane passing through the palatine shelves of the maxillary bones. Projections of the reference points used on the sagittal median plane can be made to evaluate any discrepancy.

Two-dimensional evaluation sagittal plane

Linear measurements

Select sagittal sections parallel to the sagittal median plane. Some reference points should be defined tangent to

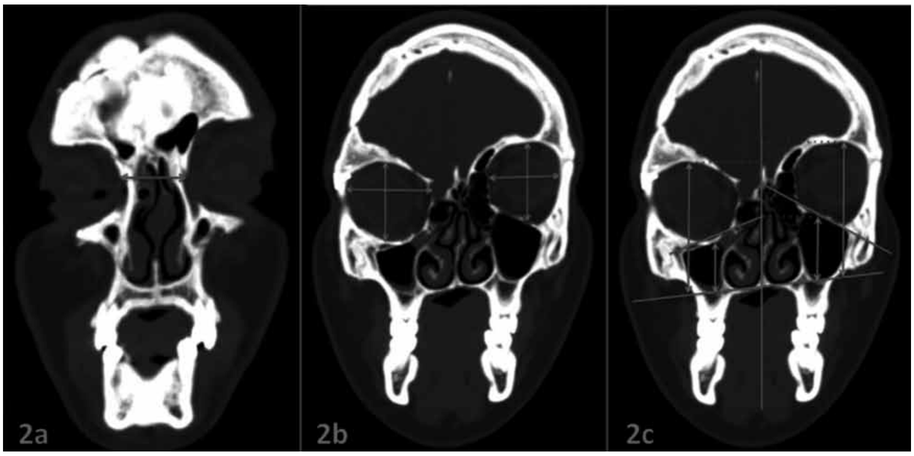

Fig. 2. a. Interdacryl distance. **b.** Vertical dimension of the orbit. **c.** A line from the crista galli to the anterior nasal spine and through the nasal septum; position of the superior and inferior orbital margins in relation to the contralateral orbit or reference planes; transverse dimension of the ethmoid; position of the orbital floor and roof.

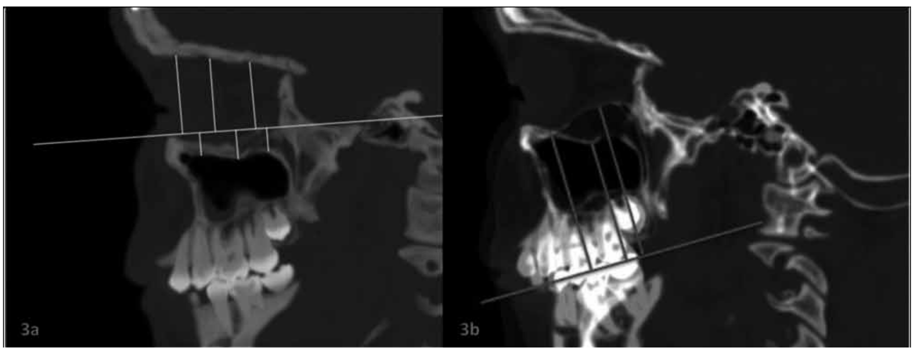

Fig. 3. a. Heights of the orbital cone. **b.** Distances of the floor and roof from a reference plane.

the sections to be measured in order to achieve symmetry between the two sides. It is suggested to use the plane at a tangent to the lacrimal sac at its most lateral point, the plane passing through the exit point of the optic nerve and a plane passing through the medium section of the eye. The measurements can be repeated on multiple slices.

- Heights of the orbital cone (Fig. 3a).
- Distances of the floor and roof from a reference plane (occlusal plane, Frankfurt plane) or in relation to the values of the superimposed healthy orbit (Fig. 3b).

Three-dimensional evaluation

Craniometric routine includes initial evaluation of the individual parts of the orbit on a frontal view of a three-dimensional bone window CT image. Next, the vertical diameter of the eye area is measured, taken between the most concave points of the superior and inferior orbital margins. The transverse diameter is then measured from the frontozygomatic suture to the frontonasal suture and, at a lower level, the maximum transverse diameter from the most concave points of the lateral and medial margins of the orbit. If any reference points is absent, other points, such as the mesiovestibular cusps of the first upper molars, may be used to obtain some absolute linear values (Fig. 4a). The soft tissue window is then superimposed to identify the lateral and medial palpebral canthi and palpebral fissure (Fig. 4b). Linear measurements are then made from certain skeletal points considered as references, such as the frontozygomatic suture for the lateral canthus and the lacrimal bone for the medial canthus. All these measurements should be made in relation to the planes perpendicular to the median axis (Fig. 4b).

The angle of the palpebral fissure and the line passing through the medial and lateral canthus can then be measured in relation to the median axis. Finally, orthogonal projections are made in relation to this latter axis to compare the position on the two- and three-dimensional reference planes with that of the healthy orbit. The values for the linear measurements are compared to highlight any discrepancies. Further analysis can be carried out using mirror-image superimposition of the image of the healthy orbit on the diseased one to graphically highlight asymmetries on both the skeletal and cutaneous planes.

Finally, certain programs can be used to evaluate orbital volumes. The analysis provides values in mm^3. Reference figures from large population samples are not yet available for this type of data, and thus the evaluation should be made in comparison to the healthy orbit (Fig. 5).

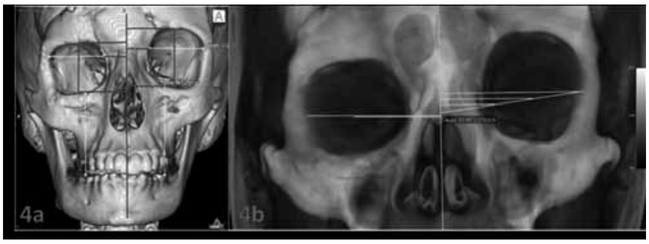

Fig. 4. a. Three-dimensional craniometric evaluation. **b.** Soft tissue craniometric evaluation.

Fig. 5. Software to evaluate the orbital volumes.

Clinical cases

Case 1

A 27-year-old female presented with sequelae of trauma involving the orbit and zygomatic maxillary region with avulsion of left eyeball. She was treated at another location for reduction of facial fracture. Despite this, left enophthalmos was evident (Fig. 6a-b). The patient underwent removal of the plate previously placed on the margin of left orbit through the same subpalpebral approach. Titanium mesh was positioned on the floor reaching the medial wall (Fig. 6d). The patient experienced minimal swelling postoperatively, which resolved in about two weeks. At two weeks follow-up, we observed that the left enophthalmos was no longer evident (Fig. 6c). Three years later, the patient showed very good facial aesthetic improvement.

Case 2

A 26-year-old female presented with right exophthalmos and diplopia following trauma that occurred three weeks before. Evaluation of ocular mobility revealed limited movement in the upper gaze of the right eye (Fig. 7a). She was diagnosed with fracture of medial wall of the right orbit (Fig. 7b). With a transcaruncolar endoscopic approach, biocompatible collagen membrane was placed between the medial wall and the orbital periosteum (Fig. 7d). The patient experienced minimal swelling postoperatively, which resolved in about one week. At two weeks follow-up, we observed with satisfaction that right exophthalmos and diplopia were no longer visible, and right ocular rotations improved with elimination of anomalous movements (Fig. 7c). Three years later, the patient showed excellent facial aesthetic and functional improvement.

Case 3

A 22-year-old male presented with outcomes of bilateral fracture of the orbital roof. He was treated in an emergency setting at another location for cerebral haematoma evacuation and bilateral exophthalmos with tarsorrhaphy. The patient came to our observation at one month after trauma. The evaluation of visual acuity revealed bilateral amaurosis that remained from the trauma. He underwent three sequential surgeries: orbital decompression, orbital expansion and finally medialisation of orbital walls with cranioplasty (Fig. 8d). Postoperative radiologic and clinical controls showed satisfactory results and the ophthalmologic examination revealed recovery of vision (visual acuity of 2/10 in the left eye and 3/10 in the right eye) and bilateral ocular bulb motility. The patient experienced swelling postoperatively, which resolved in about four weeks. At two months follow-up, bilateral exophthalmos was improved (Fig. 8c). Three years later, the patient showed very good facial aesthetic and functional improvement. Evaluation of visual acuity revealed a marked improvement (left eye: 4/10; right eye: 9/10).

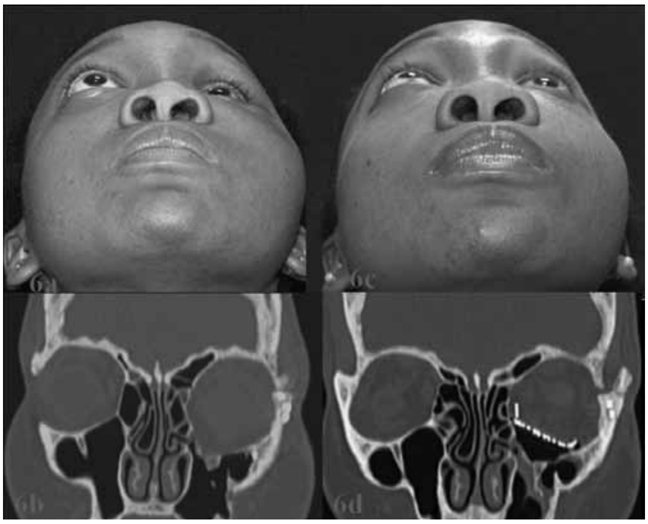

Fig. 6. Preoperative axial view (a) of the patient and pre-operative coronal CT scans (b). Left enophthalmos is evident. Postoperative axial view (c) of the patient and postoperative coronal CT scans (d). A titanium mesh was positioned on the left orbital floor to the medial wall, and left enophthalmos was no longer apparent.

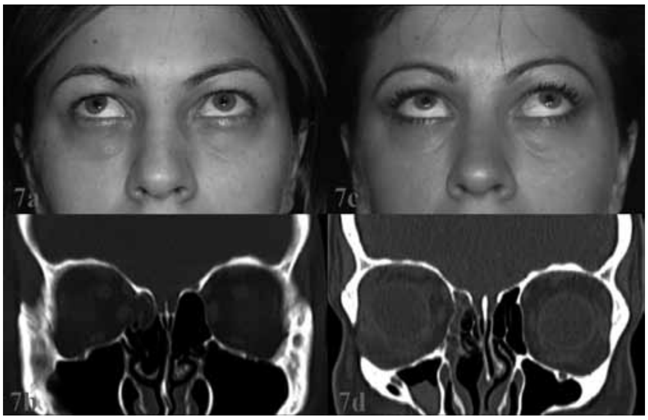

Fig. 7. Preoperative frontal axial view (a) of the patient and pre-operative coronal CT scans (b). Limited movement of the right eye in the upper gaze was evident along with fracture of right orbital medial wall. Postoperative frontal view (c) of the patient and postoperative coronal CT scans (d). A biocompatible collagen membrane was positioned on the right orbital floor to the medial wall;left enophthalmos and diplopia disappeared, and right ocular rotations improved.

Discussion

Sequelae of orbital fracture can be associated with aesthetic and functional defects such as enophthalmos, diplopia, facial asymmetry, hypertelorism and dystopia. Clinically, enophthalmos is defined as a backward and usually downward (hypoglobus) displacement of the globe into the bony orbit [1]. It is due to depression of the bony orbit, fat necrosis or atrophy, scar contracture of the retrobulbar tissue tethering the ocular globe in a posterior position, and/or entrapment or fibrosis of extraocular muscles [1]. It occurs more frequently after fracture of the lamina papyracea with herniation of the orbital content in the ethmoid. A study conducted on corpses by Hammerschlage in 1982 showed that 90% of observed enophthalmos cases were caused by fracture of the medial wall. In these cases, however, the enophthalmos does not always cause significant functional disorders, such as those occurring due to dislocation of the malar bone and entrapment of the inferior rectus muscle and the small oblique muscle. Clinical examination is fundamental to investigate the consequences of trauma. It can assess globe position in relation to orbital rim, eyelid rim, midline facial structures and lateral orbit. The instrumental exams to evaluate the enophthalmos consist of Hertel exophthalmometry, but it is accurate in defining the difference in globe position only if the area of the lateral orbital rim has been identified as being correctly positioned anteriorly and posteriorly, and is symmetric with the contralateral side. It can be useful to evaluate orbital volume, since some authors have found a correlation between enophthalmos and increasing orbital volume, even if these measurements are taken only 3-4 weeks after trauma [1].

In case of obsolete fractures, diplopia is usually second-

Fig. 8. Preoperative frontal axial view (a) of the patient and pre-operative coronal CT scans (b). Bilateral exophthalmos and bilateral fracture of the orbital roof were evident. Postoperative frontal view (c) of the patient and postoperative coronal CT scans (d). Bilateral exophthalmos was improved. Evaluation of visual acuity revealed a marked improvement.

ary to entrapment of one or more muscles (inferior rectus, medial rectus or inferior oblique) or of the adjacent fat. In this case, a forced duration test will have a positive result. The reconstructive principles for late reconstruction of the complex orbital fractures involve osteotomy, movement, reposition and fixation of all fractured bones, and repositioning of the globe. In order to correctly plan surgery, clinical and instrumental examination and radiological findings are both important. While image diagnosis is essential for defining the details of bone displacements and injuries to soft tissue, instrumental diagnosis is important for evaluating the functional damage caused by the trauma and is indispensable for assessing recovery following the surgical treatment [5].

Traditional radiological examination of the head in the four projections (axial, lateral, occipito-buccal and postero-anterior) is of little use, whereas panorex and x-rays are recommended in two projections (lateral and antero-posterior) when there is a fracture of the upper jaw. A CT scan with axial, coronal, sagittal and 3D reconstructions, however, is essential, not only for confirming orbital bone injuries but also for planning surgical treatment. Cone beam CT, which has recently been introduced, with a very brief exposure allows the reconstruction of the facial skeleton both in 3-D and three standard reconstructions [6]. Each reconstruction allows the study of several parameters to analyse. Due to the 3-D CT scans, however, it is possible to have an overall view of the various traumatic displacements and, together with the information acquired from the measurements of the other CT reconstructions, to define the surgical programme.

Advancements in computer technology have made it possible to accurately simulate the surgery and lead to precise surgical planning. In fact, these programs permit calculating orbital volume, and thus to compare the affected with the non-affected orbit. In particular, this comparison can be made both in absolute terms, in mm^3, and in relative terms by graphically superimposing the orbital margins and bone walls. These data are also relevant from a repositioning perspective and can be used to build three-dimensional digital models to create personalised implants for morphological recovery of the bone structures. Traditionally, medical sculptors employed their anatomical modelling expertise to manufacture implants using clay and wax [7].

Currently, however, shape reconstruction techniques for the skull surface involve both clay and spatulas as well as the use of Computer Aided Design (CAD) tools [8]. Previous studies have explored computer-aided implant design in the maxillofacial area [9 10]; these procedures are highly effective but time-consuming as they require a great deal of manual input, and the design process remains costly in terms of labour, materials and monetary resources.

Some software packages (i.e. MIMICS, Dolphin Imaging) simulate osteotomies and skeletal repositioning for reliable evaluation of surgical outcome. Diverse studies [11] have described the use of CAD/Computer-Aided Manufacture (CAD/CAM) for late reconstruction of orbital fractures, confirming increased surgical accuracy [2]. They have focused attention on orbital volume, and not considering linear and angular measurements as we described. From an aesthetic point of view, it is important to plan surgery in order to re-establish symmetry; the authors advocate the use of 3D CT-scan reconstruction to obtain mirror-image superimposition of the image of the normal orbit on the fractured one in order to graphically highlight asymmetry, both skeletal and cutaneous. Three-dimensional intraoperative navigation of previously acquired CT images represents a technical evolution in surgical planning and is used to verify the precision of the reconstruction during the operation [12]. A further field of application is pre-and post-surgical examination for a precise evaluation of the results of skeletal repositioning. Dimensional accuracy is a major concern for the clinical application of 3D medical models, and has been previously studied [13 14]. Whereas CT scans are useful for the study of bone structures, it is well known that MRI provides much more reliable indications on the parenchymatous structure. In our case, MRI with axial and coronal reconstructions, is useful for highlighting both morphological alterations and changes in the position of the orbital content, particularly the muscles, endo-orbital fat and optic nerve curvature. The three case studies herein highlight the successful results obtained in treating orbital fractures with this type of analysis. Each aspect is analysed in its totality, yielding a result that is suitable not only for the selected parameters, but also for the selected one in relation with the other. Compared to previous surgical treatment planning, this kind of analysis allows study of the orbit in every aspect, leading to perfect reconstruction of the bony orbit and the periorbital region.

Conclusions

In our experience, we believe that analysis of the orbit is a fundamental process in pre-operational planning and post-operative evaluation of traumas directly or indirectly involving the orbital and periorbital region. Compared to traditional analyses, this new one takes into account different aspects. The first, in fact, analysed linear measurements and bony tissues without evaluating the relationship of these with periorbital soft tissue, especially improving the bone, and not just the "aesthetic" aspects. This new analysis allows a more detailed study of the bony structures, which are analysed in several aspects and in most planes, but also and especially, the soft tissue periorbital region, which is responsible for the aesthetic appearance of the patient. The possibility to superimpose the healthy portion with that of the deficit also allows analysing in detail potential shortcomings and, therefore, how to resolve these. The diagnostic and instrumental accuracy achieved in recent years through the use of three-dimensional reconstructions and elaboration software allows the required surgical procedures to be planned with satisfactory precision and adapting treatment to each individual case. The position of the orbit in the space should be determined in relation to the surrounding structures compared to the contralateral side, if this is not affected by the trauma or pre-existing malformations. In the three cases described herein, we obtained successful results both in bony structures and in soft tissue aspects.

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Address for correspondence: Mario Pagnoni, Maxillo-Facial Surgery Department, Policlinico "Umberto I", Sapienza Università di Roma, viale del Policlinico 155, 00161 Roma, Italy. Fax +39 06 49979107. E-mail: mario.pagnoni@uniroma1.it