Evaluation of the Application of Computer-Aided Shape-Adapted Fabricated Titanium Mesh for Mirroring-Reconstructing Orbital Walls in Cases of Late Post-Traumatic Enophthalmos

Yi Zhang, MD, PhD, DDS, Yang He, MD, PhD, DDS,†*
Zhi Yong Zhang, MD, PhD, DDS,‡
and Jin Gang An, MD, PhD, DDS§

Purpose: Computer-aided individually shape-adapted fabricated titanium mesh for the mirroring-reconstruction of the orbit is a promising method for the correction of post-traumatic enophthalmos. The purpose of this study was to evaluate the application of this technique and assess the treatment outcomes.

Patients and Methods: Twenty-one patients with delayed treatment of unilateral impure orbital fracture and post-traumatic enophthalmos were included in this study. Computed tomography–based mirroring-reconstruction images of the orbit were obtained for each individual to fabricate anatomically adaptive titanium mesh by computer-aided design and computer-aided manufacturing techniques. After exposing the areas of orbital defect and reducing the herniated soft tissue, the titanium mesh was inserted to reconstruct the internal orbit with a mean deep extension of 29.33 mm. Measurements were performed to assess the change in the degree of enophthalmos and orbital volume before and after surgery. Paired samples t test and Pearson correlation coefficient were employed for statistical analysis.

Results: Follow-up examinations revealed that the degree of enophthalmos decreased to less than 2 mm in 11 patients, 2 to 4 mm in 9 patients, and remained greater than 7 mm in 1 patient. Statistical analysis revealed that post-traumatic enophthalmos in this series was 4.05 ± 2.02 mm, which was associated with an orbital volume increment of 6.61 ± 3.63 cm^3, with a regression formula of enophthalmos = $0.446 \times$ orbital volume increment + 2.406. Orbital reconstruction effected a orbital volume decrease of 4.24 ± 2.41 cm^3 and enophthalmos correction of 2.01 ± 1.46 mm, the regression formula being enophthalmos = $0.586 \times$ orbital volume decrease + 0.508. After surgery, the degree of unresolved enophthalmos was 2.03 ± 1.52 mm, and the retained orbital volume expansion was 2.23 ± 2.86 cm^3, and the regression formula was enophthalmos = $0.494 \times$ orbital volume expansion + 1.415.

Conclusion: Application of the individual fabricated titanium mesh for orbital reconstruction reduced the trauma-induced orbital volume increment by 65% and corrected 50% of severe late enophthalmos. Additional augmentation of orbital contents was required for further correction. The related treatment parameters were suggested.

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*Professor.

†Postgraduate Student.

‡Chief Resident.

§Associate Professor.

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Address correspondence and reprint requests to Dr Zhang: Department of Oral and Maxillofacial Surgery, Peking University, School and Hospital of Stomatology, Haidian District, Beijing 100081, China; e-mail: zhangyi2000@263.net

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Impure orbital fractures are defined as those simultaneously involving the orbital rim and walls and are reported to account for 76% of all orbital fractures.[1] Because these injuries are often accompanied by life-threatening brain or body injuries that require immediate management, the treatment of impure orbital fracture is delayed, resulting in post-traumatic enophthalmos with or without diplopia. The volume discrepancy between the orbital cavity and orbital contents has been documented in the literature as the physical mechanism underlying the pathogenesis of post-traumatic enophthalmos.[2-5] The outcome of late correction of post-traumatic enophthalmos by the insertion of the sliced bone chips or alloplastic implants into the orbit to reduce the volume of the expanded orbital cavity cannot be usually predicted or may be unfavorable. In recent years, surgeons have been using the individually performed titanium mesh for mirroring-reconstruction for unilateral orbital fracture. This advanced technique showed great promise because it afforded a high accuracy of reconstruction with an error of 1 mm and improved treatment outcomes.[6,7] The purpose of this study was to evaluate the application of this technique for the correction of severe post-traumatic enophthalmos.

Patients and Methods

PATIENTS

After obtaining informed consent, 21 consecutive patients who were treated at the Department of Oral and Maxillofacial Surgery, Beijing University School and Hospital of Stomatology from September 2004 to April 2008 were included. Patients included 12 men and 9 women, ranging in age from 20 to 54 years, with a mean age of 35 years. All patients had sustained unilateral impure orbital fractures. In all cases, the original treatment was delayed because of the presence of concomitant injuries or delayed transfer to Beijing University. The interval between injury and surgery was 111 days on average, being 4 weeks in 5 cases, 4 to 12 weeks in 8 cases, and longer than 12 weeks in 8 cases. Complications of enophthalmos with or without diplopia and cosmetic disfigurement became the indications for secondary orbital surgery.

In most included cases, injuries were the result of car accidents (n = 13, 51.91%); in others, the causes were industrial accidents (n = 4, 19.01%), aggressive assaults (n = 2, 9.52%), explosions (n = 1, 4.76%), and height falls (n = 1, 4.76%). Combined orbital floor and medial wall fracture was the most common type of injury (n = 15, 71.43%), whereas the incidences of sole orbital floor and medial wall involvement were the same (n = 3, 14.29% for each).

SURGICAL PROCEDURES

Spiral computed tomographic datasets with a 0.625-mm slice thickness were obtained before and 14 days after the operation. Serial computed tomographic images in multiple planes were obtained and analyzed to demarcate the defective orbital area. A 3-dimensional image of the orbit was rebuilt on a computer by mirroring the individually defined 3-dimensional segment from the unaffected side onto the affected side. The resulting subvolume file was transferred to computer-aided design and computer-aided manufacturing machines to produce an orbital resin model. On this resin model, an anatomical shape-adapted titanium mesh for orbital reconstruction and a guiding template for orbital rim realignment were fabricated. The basic experimental procedures were similar to those described by Metzger et al.[7]

A subciliary approach was used to expose the orbital rim and orbital floor. The coronal approach was used to expose the medial orbital wall and zygomatic complex. With a guiding template, the orbital rim and the zygomatic complex were first reduced and fixed using a 2.0-mm plate. Subperiosteal dissection was performed within the orbit, the herniated orbital soft tissue carefully reduced, and the entire wall defect widely exposed backward up to the posterior border of defect. The intraoperative insertion and positioning of the fabricated titanium mesh were performed with reference to the landmarks of the resin model. The implant extension in depth was 25.9 to 36.3 mm, with a mean of 29.33 mm.

MEASUREMENT AND STATISTICAL ANALYSIS

Quantitative analysis of orbital changes revealed the enophthalmos degree and the entire orbital volume of the affected side before and after operation, in addition to the eyeball proptosis degree and the entire orbital volume of the unaffected side. Computed tomographically based measurements were made with computer-assisted measuring and calculating tools. The methods used were as illustrated in Figures 1 and 2.

Paired samples *t* test was used to determine the difference in the degree of enophthalmos and orbital volume between the affected and unaffected sides and between the pre- and postoperative values of these parameters. Correlations between the degree of enophthalmos and values of the orbital volumetric extent, respectively, before and after operation were assessed using the Pearson correlation coefficient (the correlation was considered significant at 0.05). Data were processed using SPSS 1.30 (SPSS, Inc, Chicago, IL).

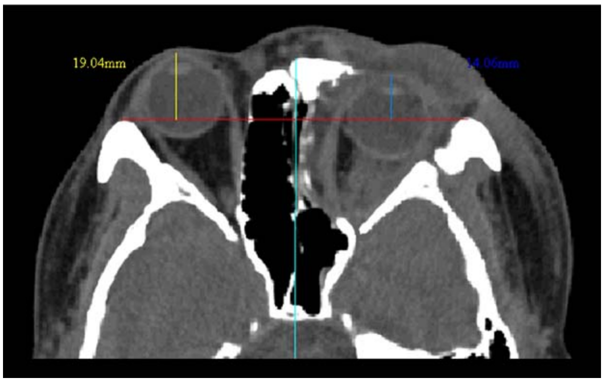

FIGURE 1. Illustration of enophthalmos measurement. A computed tomographic axial slice with the largest diameter of the eye globe was obtained. On it, a baseline was demarcated from the anterior point of the lateral orbital rim of the unaffected side inward perpendicular to the midline of the skeleton. The linear distance from the most projecting point on the corneal surface to the baseline was defined as the degree of eyeball proptosis on the measured side. The difference in values of the 2 sides was regarded as enophthalmos of the affected orbit.

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Results

The follow-up period was 3 to 6 months. Acceptable results were achieved in 11 patients (52.38%), with a decrease in the degree of enophthalmos to less than 2 mm. In 9 patients (42.86%), moderate improvement was achieved, with the degree of unresolved enophthalmos ranging from 2 to 4 mm. Only 1 patient (4.76%) had no significant improvement, and the degree of enophthalmos retained was 7 mm.

Preoperatively, mean degrees of eyeball proptosis were 15.89 ± 2.36 mm in the unaffected orbits and 11.83 ± 2.67 mm in the affected orbits. The difference between the 2 sides was 4.05 ± 2.02 mm (t = 9.179, P = .000), which could be regarded as the degree of preoperative pathologic enophthalmos of the fractured orbits. Postoperatively, the mean degree of proptosis of the eyeballs of the fractured sides increased to 13.85 ± 2.64 mm, which was 2.01 ± 1.46 mm higher than the corresponding preoperative value. The statistical difference (t = 6.306, P = .000) indicated a significant improvement in the degree of enophthalmos. However, it was still 2.03 ± 1.52 mm less than the degree of the proptosis of the eyeballs of the contralateral orbits. A statistically significant difference (t = 6.306, P = .000) implied unresolved enophthalmos.

Preoperatively, mean orbital volumes were 24.86 ± 3.05 cm^3 in the unaffected orbits and 31.47 ± 4.30 cm^3 in the affected orbits. The difference between the 2 sides was 6.61 ± 3.63 cm^3 (t = 8.349, P = .000), which represented the virtual volume increment of the fractured orbits. After surgery, the mean orbital volume of the fractured sides decreased to 27.23 ± 3.29 cm^3, which was 4.24 ± 2.41 cm^3 less than the preoperative value; there was a significant difference in the pre- and postoperative values (t = 8.047, P = .000). However, the difference between these values was still 2.23 ± 2.86 cm^3 larger than that of the contralateral sides, in which case the difference was statistically significant (t = 3.801, P = .001).

The difference in the degree of enophthalmos and the orbital volume between 2 sides and the difference in the pre- and postoperative values of these parameters on the affected sides are listed in Table 1. Correlation analysis revealed that the preoperative degree of enophthalmos and the orbital volume increment correlated significantly (γ = 0.446, P = .042), with the regression formula being enophthalmos = 0.446 × orbital volume increment ± 2.406 (Fig 3). After orbital reconstruction, the resolved degree of enophthalmos and the decrease in orbital volume also correlated significantly (γ = 0.586, P = .005), with the

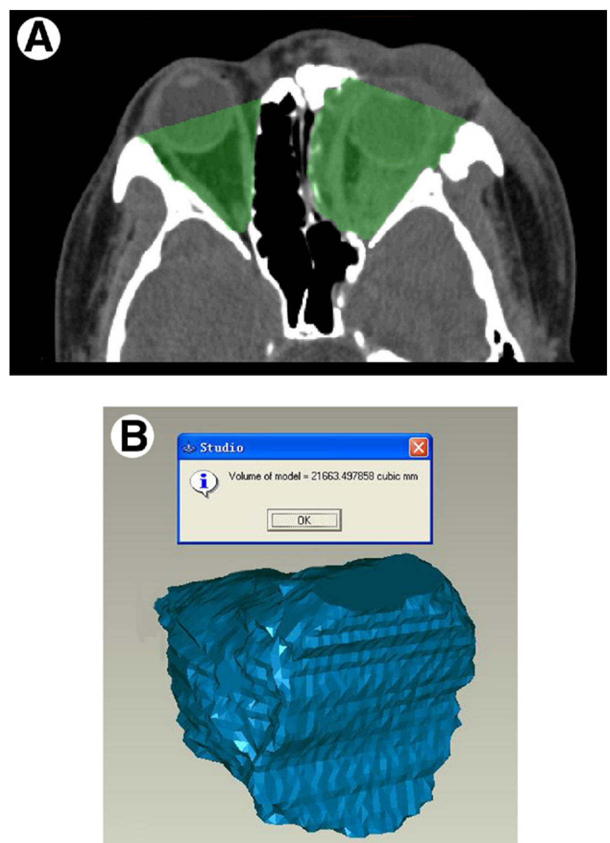

FIGURE 2. Illustration of orbital volume calculation. *A*, Serial axial computed tomographic slices 0.625-mm thick were used to outline the bony orbital border between the optical nerve foramen and the connecting line of the zygomaticofrontal suture to the nasomaxillary suture. *B*, Calculations were made by the computer, and the value of the orbital volume was determined.

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Table 1. DIFFERENCES IN En AND OV BETWEEN 2 SIDES AND BETWEEN BEFORE AND AFTER OPERATION

	Difference in En (mm)	Difference in OV (cm^3)
Between 2 sides before operation	4.05 ± 2.02	6.61 ± 3.63
Between 2 sides after operation	2.03 ± 1.52	2.23 ± 2.86
Affected orbit before to after operation	2.01 ± 1.46	4.24 ± 2.41

Abbreviations: En, enophthalmos; OV, orbital volume.

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regression formula of enophthalmos $= 0.586 \times$ decrease in orbital volume $\pm$ 0.508 (Fig 4). A significant correlation was also observed between the unresolved degree of enophthalmos after surgery and the retained orbital volume expansion ($\gamma = 0.494$, $P = .023$), its regression formula being enophthalmos $= 0.494 \times$ orbital volume expansion $\pm$ 1.415 (Fig 5).

Discussion

Patients with pure orbital fractures are mostly admitted to the department of ophthalmology for treatment and those with impure orbital fractures to the department of maxillofacial surgery, because the orbital involvement is considered a concomitant of zygomatic, maxillary, and naso-orbit-ethmoid fractures. Impure orbital fracture is characterized by the interruption of orbital rim continuity, large orbital wall defects with multiple-wall involvement, and deep defect extension, which can result in cosmetic disfigurement of the face and enophthalmos with or without diplopia, restricted globe movement, and visual impairment. A surgical protocol for the treatment of impure orbital fractures has been well described previously in a few reports.[8-12] The descriptions included details regarding the accurate realignment of the displaced orbital rim after restoration of the surrounding bone structures, complete reduction of the herniated orbital soft tissues, anatomic reconstruction of the demolished orbit walls, augmentation of the orbital contents, and stage II surgery after a 6-month interval to repair the ocular muscles by recession of the taut rectus inferior muscle in case of persistent diplopia. However, the delay in rectification of post-traumatic enophthalmos continues to negatively influence the treatment outcome of this condition. The treatment results obtained were often different from those ex-

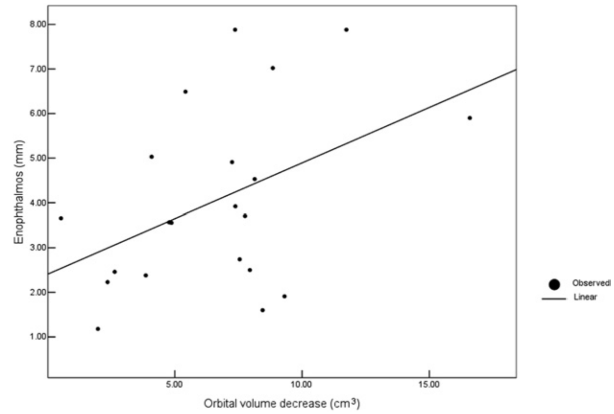

FIGURE 4. Regression line of the relation between orbital volume decrease produced by orbital reconstruction and subsequent improvement of enophthalmos.

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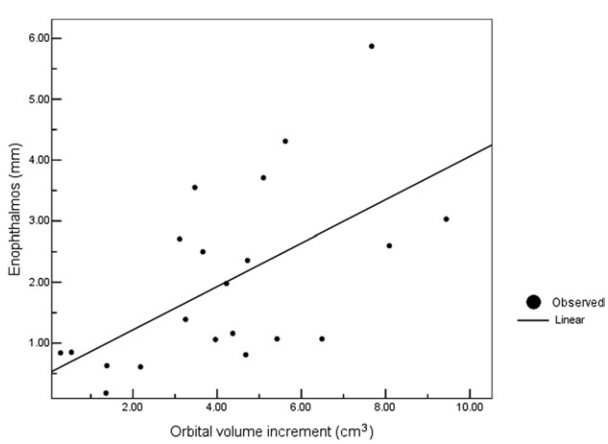

FIGURE 3. Regression line of the relation between enophthalmos and orbital volume increment before surgery.

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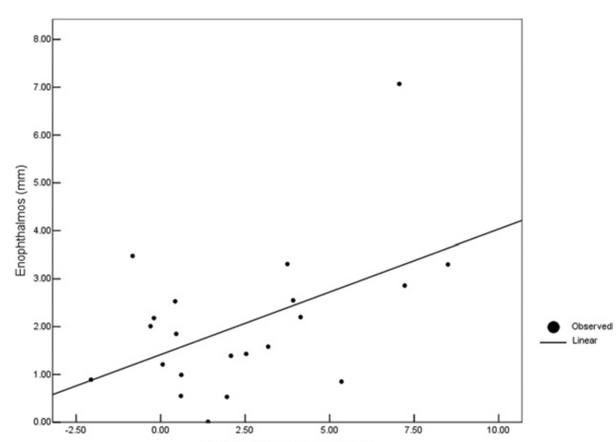

FIGURE 5. Regression line of the relation between degree of unresolved enophthalmos and retained orbital volume expansion after surgery.

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pected, despite advances in treatment methods, such as micro-fat grafting,[13] application of a tissue expander,[14] computer-aided quantified volumetric augmentation,[4,12,15] individually fabricated implants,[7,16-18] and intraoperative navigation technique.[19,20]

The normal position of the eye globe within the orbit is maintained by a balance between the orbital volume and intraorbital soft tissue. A disturbance of this balance by a relative reduction of the orbital content due to orbital volume expansion and/or an absolute reduction of the tissue content due to scarring and atrophy of the orbital soft tissue will lead to enophthalmos. Late correction of post-traumatic enophthalmos by rectifying the discrepancy between the orbital volume and orbital content, achieved by implantation of materials into the orbit as per the preoperatively estimated or measured volume alone, has been proved unreliable. Reasons for the lack of reliability of this treatment approach have been described by Fan et al.[12] Repositioning of the surrounding segments can cause an absolute decrease in the orbital volume and reduction of the herniated orbital contents can produce a relative decrease, but the decrease in the orbital volume affected by these approaches is hardly predictable and occurs before the insertion of implants. Thus, the preoperatively set volume of the implant materials becomes inaccurate. Moreover, most implants are solid and it is impossible to adapt their shape to the anatomy of orbital walls. After the insertion of implants, there are, inevitably, minute empty spaces below the implants or between the implant sheets. It made the well-prepared implant volume become dimmer.

In comparison, anatomic reconstruction of the internal orbit seems to be a more definitive solution. It is believed that post-traumatic enophthalmos is caused by orbital volume expansion rather than changes in the fat content.[21] Internal orbit reconstruction is aimed at restoring the orbit anatomy to the preinjury level by achieving the virtually determined preinjury orbital volume, and reducing the herniated tissues can correct the enophthalmos efficiently. Considering these points, mirroring-reconstruction of the orbital walls using computer-aided individually fabricated shape-adapted titanium mesh was developed and has been used to correct late enophthalmos secondary to impure orbital fractures since 2004 in the Department of Oral and Maxillofacial Surgery, Beijing University. Unfortunately, the follow-up results were not as satisfactory as expected. Stage II orbital surgery to augment the extra orbital content was required in some cases.

In the present series, the average decrease in orbital volume was 4.24 cm^3, approximately equal to 65% (4.24/6.61 cm^3) of the expanded part. The average increase in the degree of proptosis was 2.01 mm, approximately equal to 50% (2.01/4.05 mm) of enophthalmos. Although the decrease in the extent of orbital volume and the degree of enophthalmos by surgery were similar to those reported by Ye et al[15] (4.08 cm^3 and 1.19 mm, respectively), the clinical results of the present study seemed to be worse than theirs. With an increase in preoperative intervals, the degree of enophthalmos in the present patients was worse and the orbital volume was larger than the respective preoperative values. Therefore, we deduced that the unfavorable outcomes were closely related to the severity of the injury and the delay in administration of definite treatment. Further, we concluded that anatomic orbital reconstruction was a deficient method for late rectification of severe enophthalmos with an orbital volume expansion greater than 4 cm^3. The reduction in orbital volume by reconstruction of the internal orbital anatomy was insufficient to restore the displaced eye globe to the normal position. An additional procedure was required to correct approximately 35% of the pathologic increase in orbital volume and 50% of the degree of enophthalmos after orbital reconstruction. The currently available method is applicable for augmentation of the orbital content and should be performed immediately or 3 to 6 months after orbital reconstruction.

In this report, 3 regression formulas have been presented. According to the formula indicating the correlation between post-traumatic enophthalmos and orbital volume increment caused by injury, 1 mm of enophthalmos was associated with an orbital volume expansion of 2.24 cm^3, which was much larger than those reported by Jin et al,[2] Ploder et al,[3] and Whitehouse et al.[5] The formula representing the correlation between the degree of unresolved enophthalmos and extent of the retained orbital volume expansion suggested that 2.02 cm^3 of the orbital volume should be augmented to resolve each millimeter of retained degree of enophthalmos; this value is also significantly larger than the recommended amounts of 1.38 and 1.12 cm^3 reported by Ye et al[15] and Fan et al,[4] respectively. Apparently, severe post-traumatic enophthalmos is associated with a higher degree of volume expansion for each millimeter of degree of enophthalmos and a sharper volume decrease relative to each millimeter of enophthalmos correction. The formula representing the correlation between resolved enophthalmos and orbital volume decrease by orbit reconstruction demonstrated that, within the extension of orbital reconstruction, the orbital volume decrease associated with 1 mm of the degree of enophthalmos correction was 1.71 cm^3. The observed points around the regress line, as shown in Figure 2, were distributed widely, indicating considerable individual differences. This discussion can enhance the surgeon's understanding of the occurrence of enophthalmos secondary to impure orbital fracture and facilitate the development of improved treatment strategies for the same.

In conclusion, the application of a computer-aided individually fabricated shape-adapted titanium mesh technique to reconstruct orbital anatomy can reduce approximately 65% of the expanded orbital volume and, correspondingly, correct 50% of post-traumatic enophthalmos.

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