Navigation-Guided Management of Comminuted Zygomaticomaxillary Complex Fracture Concurrent With Orbital Reconstruction

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Background: Comminuted zygomaticomaxillary complex (ZMC-C) fracture with orbital reconstruction poses challenges for surgeons. Navigation-guided technique may be valuable for surgical reduction.

Purpose: This study aimed to measure the difference error between planned and actual reduction of ZMC-C fracture with orbital reconstruction using navigation-guided technique.

Study Design, Setting, Sample: This retrospective single-arm cohort study involved subjects with ZMC-C and orbital fractures from Jan 2017 to Jun 2019 at the Department of Ophthalmology, Ninth People's Hospital, Shanghai Jiao Tong University School of Medicine, China. Subjects with brain damage, unstable vital signs, allergy to titanium alloy implants, trauma to other facial bones or postoperative facial trauma were excluded.

Main Outcome Variables: The primary outcome variable was the mean 3-dimensional (3D) (Euclidean) distance error between surgical plan and actual outcome. Secondary outcomes included mean absolute distance error in transverse, vertical and anterior–posterior planes, visual analog scale score of subjects' self-satisfaction with facial aesthetics and function, orbital volume, exophthalmometry, position of bilateral zygomatic bones and surgical complications.

Covariates: Covariates included age and sex.

Analyses: Outcomes were tested using t-tests with significance at $P < .05$ to determine differences between preoperative and postoperative measurements and symmetry.

Results: The sample included 20 subjects with a median age of 39 years (interquartile range = 24.5) and 19 (95%) were male. The mean 3D distance errors were 0.5 ± 0.3 mm at the midpoint of the fracture line at the zygomatic frontal suture, 0.7 ± 0.3 mm at the most prominent point on the surface of zygoma and 0.6 ± 0.4 mm at the intersection point of the zygomatic alveolar buttress and fracture line. The maximum mean absolute distance error was 0.8 ± 0.2 mm. Postoperative visual analog scale score improved in all subjects. Mean orbital volume was reduced by 2.2 ± 0.6 cm^3, and enophthalmos improved to

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0.4 ± 0.3 mm (all $P < .01$). There were no significant differences in exophthalmometry, orbital volume and position of bilateral zygomatic bones between the affected and unaffected sides ($P > .05$).

Conclusion and Relevance: Deficient movement in the anterior–posterior plane mainly contributes to 3D distance error. The mean distance error was clinically acceptable with the aid of navigation-guided technique in managing ZMC-C fracture with orbital reconstruction.

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The zygomaticomaxillary complex (ZMC) fracture, resulting from various trauma, is one of the most common types of facial fractures.[1-3] It can cause esthetic deformities, such as malar flattening and enophthalmos, as well as functional impairment including diplopia, restriction of mouth opening and paresthesia, etc.[4,5] According to the multiple fracture classification schemes described by Zingg,[6] ZMC fractures are categorized into 3 types based on the energy of the injury, the pattern of comminution, the degree of dislocation, and the number of fractured zygomatic pillars. Comminuted ZMC fracture, classified as Type C, or ZMC-C, represent the most severe subtype (Fig 1).

ZMC-C fractures lead to severe losses of aesthetically pleasing appearance and functional impairment. However, the management of ZMC-C fractures, especially when concurrent with orbital floor and/or medial orbital wall repair, remains a significant challenge for maxillofacial surgeons and ophthalmologists due to its critical role in facial aesthetics and the complexity of reconstructing the facial and orbital contours, which are fragmented in high-energy fractures.[7] The complexity of the surgery is further compounded by the intricate regional anatomy, the innate relationship with vital structures including the globe, optic nerve and ophthalmic artery, the direct impact on the critical senses of vision, the irregularity of wounds, severe bone displacements and the potential for iatrogenic injury.[8] ZMC-C fractures have been demonstrated to necessitate secondary surgery significantly more often than milder cases.[9]

Because of these challenges, it is tempting to use intraoperative guidance in the reduction of ZMC fractures, especially with concurrent orbital reconstruction. Over the previous decades, navigation-guided surgeries have been widely applied, offering the advantage of synchronizing the intraoperative position of the instruments with computed tomography (CT) images that were previously obtained.[10] Satisfactory therapeutic outcomes can be achieved in the restoration of facial fractures with the aid of intraoperative navigation.[11,12] However, there is limited published literature describing the navigation-guided reduction of ZMC-C fractures

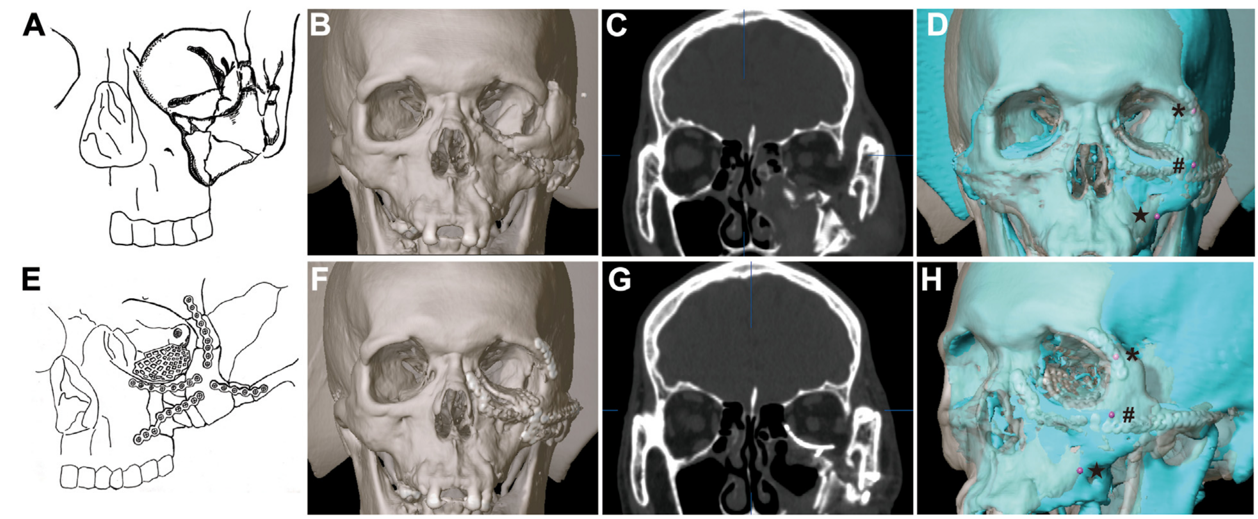

FIGURE 1. (*A*, *E*) Pictorial depiction of ZMC-C fracture and repairment of ZMC-C fracture concurrent with orbital reconstruction. Preoperative (*B*, *C*) and postoperative (*F*, *G*) computed tomography images of a patient who underwent reduction of left ZMC-C fracture concurrent with orbital reconstruction. (*D*, *H*) Anatomical landmarks of the zygoma indicated in the postoperative model. *asterisk* the midpoint of the fracture line at the zygomatic frontal suture. *hashtag* the most prominent point on the surface of zygoma. *star* the intersection point of the zygomatic alveolar buttress and fracture line. ZMC-C, comminuted zygomaticomaxillary complex.

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concurrent with orbital reconstruction. Thus, the present study characterized the utilization of a navigation system for ZMC-C fracture surgery concurrent with orbital reconstruction and evaluated the clinical effectiveness of navigation-guided surgery in this type of facial complex fractures. The purpose of this study was to measure the difference between planned and actual reduction using navigation-guided technique. The specific aim of this study was to measure the 3-dimensional (3D) (Euclidean) distance error, mean absolute distance error in the transverse (x axis), vertical (y axis), and anterior–posterior (z axis) planes between the surgical plan and actual surgical outcome, visual analog scale (VAS) score of subjects' self-satisfaction, orbital volume, exophthalmometry, position of bilateral zygomatic bones, and surgical complications.

Materials and Methods

STUDY DESIGN/SAMPLE

To address the research purpose, the investigators designed and implemented a retrospective single-arm cohort study using data collected from the electronic medical records of subjects at the Department of Ophthalmology at Ninth People's Hospital, Shanghai Jiao Tong University School of Medicine, Shanghai, China. Our research was approved by the institutional review board and adhered to the principles of the Declaration of Helsinki.

The study population was composed of all subjects with esthetic deformities and functional impairment caused by ZMC-C fractures with orbital fractures between Jan 2017 and Jun 2019. Inclusion criteria were as follows: *1)* Patients who underwent unilateral ZMC-C fracture reduction concurrent with orbital reconstruction, *2)* Indications for surgery included obvious facial deformity (with a minimum dislocation distance of 2 mm), enophthalmos (>2 mm), restriction of mouth opening and persistent diplopia unresponsive to conservative treatment, and *3)* Patients with no history of previous orbital fracture surgery or related procedures. Patients were excluded if they had *1)* brain damage or unstable vital signs, *2)* allergy to titanium alloy implants, *3)* trauma to other facial bones at the time of the ZMC-C and orbital fracture, and *4)* further facial trauma postoperatively.

VARIABLES

The primary outcome variable was the mean 3D distance error between the surgical plan and actual surgical outcome. The accuracy quantification method of orthognathic surgery used by Hsu et al[13] was adopted to quantify the reduction errors. The distance error between the surgical plan and actual surgical outcome was measured by 3 anatomical landmarks of the zygoma on the preoperative planning template and the postoperative models: *1)* the midpoint of the fracture line at the zygomatic frontal suture, *2)* the most prominent point on the surface of zygoma, and *3)* the intersection point of the zygomatic alveolar buttress and fracture line (Figs 1D,H). The mean 3D (Euclidean) distance error and mean absolute distance error in the transverse (x axis), vertical (y axis), and anterior–posterior (z axis) planes between the surgical plan and the actual surgical movement and for each landmark were measured.[14,15] The mean absolute distance error <2 mm was clinically acceptable.

The secondary outcome variables were therapeutic results defined as follows: *1)* A VAS score was used to assess subjects' self-satisfaction with facial aesthetics and function, both preoperatively and postoperatively. Subjects were asked to rate their self-satisfaction of their facial condition with a scale from 0 to 10 points, considering both esthetic and functional aspects. *2)* The preoperative and postoperative orbital volume on both sides were measured to evaluate the effect of orbital reconstruction. The orbital volume was measured based on CT images in iPlan CMF 3.0 software (Brainlab, Feldkirchen, Germany). The anterior border of the orbit was defined as a straight line connecting the medial and lateral orbital rims, while the posterior border was defined as the orbital apex on axial CT scans. At the sites of bone defects, a straight line connecting the closest bone edges was drawn. The orbital volume was calculated from sum of area measurements in each CT image.[16] *3)* The globe position was assessed with the use of a Hertel exophthalmometer. Enophthalmos was determined by the difference in exophthalmometry between the affected orbit and unaffected orbit. *4)* The position of bilateral zygomatic bones was measured and compared to assess the symmetry of bilateral ZMC. Three markers on the postoperative reconstructed 3D virtual templates were selected, and the distance between these markers were measured. The porion (po) was defined as the uppermost point of the external auditory canal. The zygomaxillare (zm) was defined as the lowest point of zygomaticomaxillary suture. The anterior nasal spine (ans) was defined as the tip of the anterior nasal spine. The linear distance between the porion and zygomaxillare (po-zm) could reflect the position of the zygomatic bone anteriorly and posteriorly, while the distance between the anterior nasal spine and zygomaxillare (ans-zm) was taken to determine the lateral and medial displacement of the zygomatic bone. Symmetry of bilateral ZMC, characterized by the difference in po-zm and ans-zm relative to the unaffected side, was thus measured. The standard for significant zygomatic arch displacement was defined as a minimum displacement of 2 mm.

DATA COLLECTION METHODS

Electronic health records for study subjects were reviewed for the demographics and operative variables. All CT images for preoperative planning were imported into the iPlan CMF 3.0 software. Firstly, the skull was outlined, and the position of the bone fragments was manually segmented and marked with different colors (Fig 2A). Secondly, an ideal 3D simulation template of the bone structure of the affected side was created by mirroring the unaffected side. Then, with the side-to-side comparison, the broken pieces were reassembled to rebuild the zygomatic structure (Fig 2B). Thirdly, the autosegmentation images of the orbital structure from the contralateral side (green, Fig 2C) were constructed and used as the mirror design reference for the affected side (red, Fig 2C). This newly constructed orbital structure template, combined with the rebuilt zygomatic structure template, was applied as the final simulation template (Fig 2D). The expected postoperative images of fracture repair could be visualized. Finally, the original and simulated virtual datasets were introduced into the surgical navigation system (Brainlab) for guidance during surgery.

All surgeries were performed by the same surgeon under general anesthesia. Surgery was undertaken through the original wound or a preauricular incision to the zygomatic fractures, an extended transconjunctival approach to the orbital rim, orbital floor and/or medial orbital wall fractures, and an oral vestibule incision to the maxillary fractures. A dynamic reference frame was attached to the patient's skull. The registration was based on a combination of point registration and surface matching of the fiducial markers (stable bony markers) around the orbit. After patient-to-image registration, 2 LED emitter-sensor units controlled the probe and the dynamic reference frame. The live position was thus associated with the CT images. With the guidance of the navigation system, the dislocated bone fragments were repositioned, which started with the inferomedial orbital rim, followed by the orbitozygomatic bone and the supraorbital margin, to rebuild the buttress of the orbital floor. The malar eminence was defined as the most prominent point of the zygomatic bone on the axial plane. The probe was then placed on the malar eminence to precisely confirm or modify the position of the restored zygomatic body (Fig 3A). Once the repositioned bone fragments accurately approximated the preoperative design, the malar arch was fixed by titanium plates and screws, and the orbital wall was reconstructed by titanium plates and meshes. The newly reconstructed strut structure was also confirmed by the probe (Fig 3B). The comminuted bone fragments,

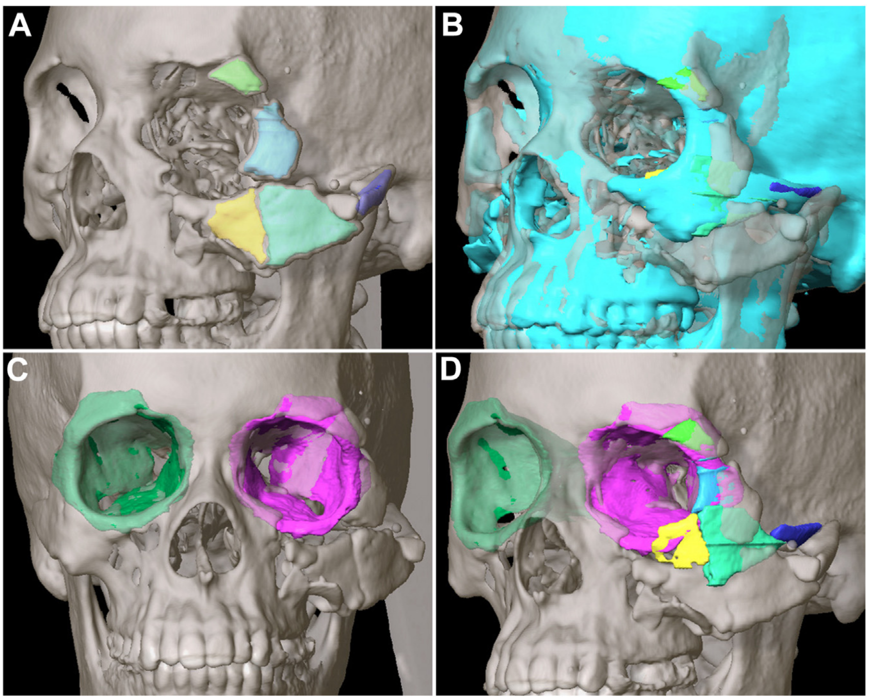

FIGURE 2. Preoperative planning. (*A*) Preoperative 3-dimensional computed tomography reconstruction showing the position of bone fragments marked with different colors. (*B*) The rebuilt zygomatic structure template by mirroring the unaffected side. (*C*) The rebuilt orbital structure template by mirroring the unaffected side. The green area and red area show the contralateral side (template) and the affected side, respectively. (*D*) The final simulation template for ZMC-C fracture surgery concurrent with orbital reconstruction. ZMC-C, comminuted zygomaticomaxillary complex.

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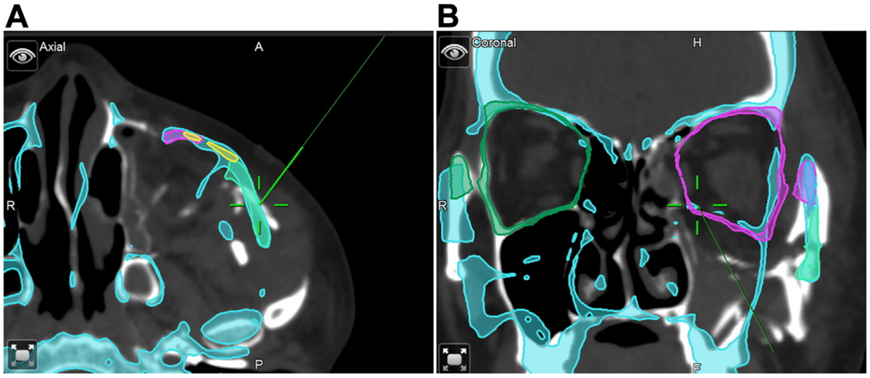

FIGURE 3. Intraoperative navigation. (*A*) The probe is placed on the malar eminence to confirm the position of the restored zygomatic body. (*B*) The probe is placed on the newly reconstructed strut structure to verify whether the reconstruction of the inferomedial orbital wall is in line with the surgical planning.

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with volumes of at least moderate size, would be restored. The bone fragments with a diameter less than 5 mm would be discarded or used to fill the interosseous gap. Finally, the probe was again utilized to verify the anatomical position of the reconstructed ZMC and orbit, ensuring excellent symmetry of the bilateral orbit and malar eminence. The preoperative and postoperative CT images were reviewed by the same person for assessment of anatomic displacement.

DATA ANALYSIS

Statistical analysis was performed using SPSS Statistics 22.0 (IBM, IL, USA). A sample size calculation was performed for the mean 3D distance error to detect an error of 2 mm between the planned and actual anatomical landmarks with an α error of <0.01 and β error of 0.1. A sample size of 17 was adequate for 3 anatomical landmarks selected. Paired *t*-tests were used to compare differences in continuous variables. A *P* value of less than .05 was considered to indicate a statistically significant difference.

Table 1. PATIENT DEMOGRAPHICS

Sex, n (%)	
Male	19 (95)
Female	1 (5)
Laterality, n (%)	
Right	7 (35)
Left	13 (65)
Age, n (%)	
0 to 30 yrs	6 (30)
30 to 60 yrs	13 (65)
60 to 90 yrs	1 (5)
Injury etiology, n (%)	
Violence	4 (20)
Motor vehicle accidents	8 (40)
Daily life activities	3 (15)
Industrial injuries	5 (25)

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Results

A total of 20 subjects were included, of which 19 (95%) were male subjects and 1 (5%) was a female subject (Table 1). Their ages ranged from 19 to 65 years, with a median age of 39 years (interquartile range = 24.5). The fracture etiologies included 4 (20%) cases of violence, 8 (40%) cases of motor vehicle accidents, 3 (15%) cases of daily life activities and 5 (25%) cases of industrial injuries. The median time from injury to surgery was 70 days (ranging from 4 to 730 days). All subjects complained of varying degrees of facial asymmetry, diplopia, enophthalmos and restriction of mouth opening. Other accompanying symptoms included eyeball dislocation in 3 (15%) subjects and facial numbness in 8 (40%) subjects.

All surgeries were successfully completed with the guidance of navigation system without further need for additional surgeries. No subject experienced severe surgical complications such as visual acuity disturbances during hospitalization or follow-up.

In terms of the 3D (Euclidean) distance error between the surgical plan and actual surgical outcome, the mean 3D distance error was 0.5 ± 0.3 mm in distance of the midpoint of the fracture line at the zygomatic frontal suture, 0.7 ± 0.3 mm in distance of the most prominent point on the surface of zygoma and 0.6 ± 0.4 mm in distance of the intersection point of the zygomatic alveolar buttress and fracture line. A good match between the postoperative anatomic structure of the affected side and the preoperative planning template was obtained, with a maximal deviation of 1 mm. The maximum mean absolute distance error was 0.8 ± 0.2 mm at the most prominent point on the surface of zygoma in the anterior–posterior plane. Deficient movement in the

Table 2. MEAN DISTANCE ERROR OF ALL LANDMARKS

Landmark	Mean 3D Distance Error (mm)	Plane	Mean Absolute Distance Error (mm)
L1	0.5 ± 0.3	Transverse (x)	0.2 ± 0.1
		Vertical (y)	0.3 ± 0.1
		Anterior–posterior (z)	0.6 ± 0.4
L2	0.7 ± 0.3	Transverse (x)	0.2 ± 0.4
		Vertical (y)	0.5 ± 0.1
		Anterior–posterior (z)	0.8 ± 0.2
L3	0.6 ± 0.4	Transverse (x)	0.4 ± 0.2
		Vertical (y)	0.2 ± 0.1
		Anterior–posterior (z)	0.7 ± 0.2

Abbreviations: L1, the midpoint of the fracture line at the zygomatic frontal suture; L2, the most prominent point on the surface of zygoma; L3, the intersection point of the zygomatic alveolar buttress and fracture line.

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anterior–posterior plane mostly contributed to the mean 3D distance error (Table 2).

The main preoperative symptoms, such as enophthalmos, diplopia, facial asymmetry and restriction of mouth opening were all obviously improved. Most subjects with facial numbness showed improvement after surgery. Although one subject continued to experience persistent facial numbness, there was some improvement over time. Postoperative VAS score of subjects' self-satisfaction with facial aesthetics and function showed that 17 (85%) subjects were completely satisfied with their postoperative ophthalmologic and maxillofacial outcomes at 12 months postoperatively, while 3 (15%) subjects were mostly satisfied but complained about the facial scar contracture due to severe initial injuries (Table 3 and Fig 4).

The orbital floor, as a component of the ZMC, was affected in all 20 subjects, 10 (50%) of whom also had concurrent medial orbital wall fractures. The mean orbital volume was 30.7 ± 1.6 cm^3 for the affected orbit preoperatively and 28.3 ± 1.4 cm^3 for the unaffected orbit. The mean reconstructed orbital volume was 28.6 ± 1.5 cm^3 ($P > .1$ compared to the unaffected orbits). Significant orbital volume reduction of 2.2 ± 0.6 cm^3 in the reconstructed orbit was achieved with the guidance of the navigation system ($P < .01$). The mean enophthalmos was 3.8 ± 1.5 mm of the affected orbit and improved to 0.4 ± 0.3 mm postoperatively ($P < .01$, Table 4). There were no significant differences in the exophthalmometry between the affected and unaffected orbits postoperatively ($P > .1$).

The difference in the distance of po-zm of the affected side and unaffected side was 0.1 ± 0.0 cm, indicating symmetry of the zygomatic bone anteriorly and posteriorly ($P > .1$). The difference in the distance of ans-zm was 0.1 ± 0.0 cm, ensuring minimum lateral and medial displacement of the zygomatic bone ($P > .1$, Table 5).

Discussion

The aim of this study was to measure the difference error between planned and actual reduction of ZMC-C fracture concurrent with orbital reconstruction using navigation-guided technique.

ZMC-C fractures are the most severe type of facial fracture, causing facial deformities and functional impairment in patients.[8] This severe type of fracture

Table 3. VISUAL ANALOG SCALE SCORE OF SUBJECTS' SELF-SATISFACTION

VAS Score of Subjects' Self-Satisfaction (points)	Preoperative (n, %)	1 mo Postoperatively (n, %)	12 mo Postoperatively (n, %)	24 mo Postoperatively (n, %)
Completely satisfied (9 to 10)	0 (0)	0 (0)	17 (85)	18 (90)
Mostly satisfied (6 to 8)	0 (0)	0 (0)	3 (15)	2 (10)
Somewhat satisfied (3 to 5)	2 (10)	9 (45)	0 (0)	0 (0)
Dissatisfied (0 to 2)	18 (90)	11 (55)	0 (0)	0 (0)

Abbreviations: VAS, visual analog scale.

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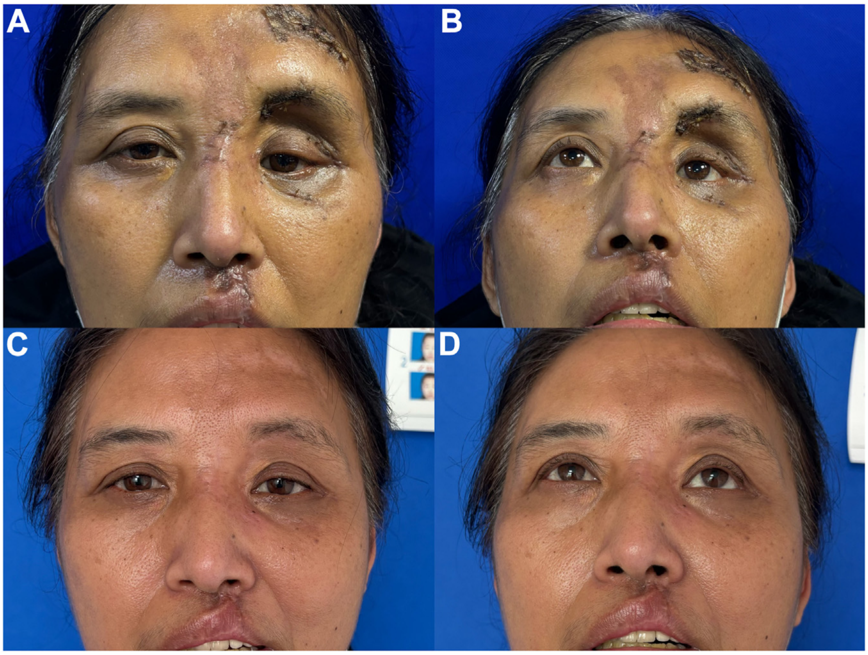

FIGURE 4. Photographs of a patient who underwent reduction of left comminuted zygomaticomaxillary complex fracture concurrent with orbital reconstruction preoperatively (*A*, *B*) and postoperatively (*C*, *D*). The patient was satisfied by the significant improvement in facial asymmetry and enophthalmos, while still bothered by the scar contracture of the lip caused by severe injury.

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inevitably leads to the destruction of some important anatomical landmarks, which presents great difficulties to even experienced surgeons.[17] Without stable anatomical landmarks or with comminuted displacement, it poses great difficulties in adequately narrowing the facial width at the zygoma, establishing sufficient anteroposterior projection, and handling the rotation of the body of the zygoma.[9] In addition, the displacement of the inferior orbital rim, resulting in the absence of the floor's buttress, also increases the difficulty of anatomic reduction and fixation in concurrent internal orbital reconstruction. The trend toward minimally invasive esthetic incisions further restricts the exposure of the surgical fields and intraoperative localization. Surgical complications include postoperative enophthalmos, orbital deformity, facial asymmetry, trismus due to inadequate reduction or unstable fixation, and iatrogenic injury.[18]

Table 4. MEASUREMENT OF THE ORBIT

Variables	Preoperative	Postoperative	*P* Value
Mean orbital volume (cm^3)	30.7 ± 1.6	28.6 ± 1.5	<.01
Mean enophthalmos (mm)	3.8 ± 1.5	0.4 ± 0.3	<.01

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Under these complicated surgical conditions, intraoperative visualization of the entire ZMC is not possible. Surgical reduction without a navigation system mainly depends on the surgeon's subjective judgment and may result in overcorrection or undercorrection. Therefore, the postoperative outcomes will inevitably be unsatisfactory in some cases, and about 10% patients may still have remaining midfacial deformity after conventional surgical treatment.[19] By comparison, image-guided systems have been extensively used in the reduction of various facial fractures with satisfactory outcomes.[20,21] He et al[22] reported that the proportion of good zygomatic reduction obtained using traditional surgery was only 74.3%, compared to 100% with navigation-guided surgery. Cuddy et al[9,23] advocated the use of intraoperative

Table 5. SYMMETRY MEASUREMENT OF BILATERAL ZYGOMATIC BONES POSTOPERATIVELY

Distance	Right Side	Left Side	*P* Value
po-zm (cm)	7.2 ± 0.1	7.2 ± 0.1	.6
ans-zm (cm)	5.3 ± 0.1	5.2 ± 0.1	.4

Abbreviations: ans, anterior nasal spine (the tip of the anterior nasal spine); po, porion (the uppermost point of the external auditory canal); zm, zygomaxillare (the lowest point of zygomaticomaxillary suture).

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CT for all patients undergoing orbital floor or medial wall reconstruction and pan-facial fractures, as well as ZMC, Le Fort II and III, and naso-orbital–ethmoidal fractures. When there were adjacent fractures requiring fixation and/or when 2 or 3 axes were displaced by ≥5 mm, the likelihood of CT-directed intraoperative revision ranged from 22.9 to 62.3%, reinforcing the need for guidance in the management of ZMC fractures.

The application of a navigation system can simulate the reconstruction of the ZMC-C concurrent with the orbital wall, facilitating the surgical planning preoperatively. Several factors including large bony defect, fracture at the root of the malar arch, or zygoma asymmetry in healthy individuals would increase the difficulty of the surgery. The size of bony defect can be measured preoperatively and the appropriate size and position of the fixation materials can be designed with the help of the navigation system. During surgery, the navigation system shows real-time, precise and 3D identification of positions, enabling the surgeon to accurately transfer preoperative surgical planning to the actual operation. It helps to avoid several iatrogenic injuries, such as injury to the capsule of temporomandibular joint.[14] Thus, the navigation system was expected to help to achieve satisfactory therapeutic outcomes in the restoration of facial complex fractures.

Notably, the navigation system provides no radiation to the patient with minimal additional expense associated with the additional use of these instruments, which is approximately an extra $150. Although intraoperative cone-beam CT or other techniques can produce a 3D image with reduced radiation, even reduced radiation should be avoided if an accessible technique with no radiation is applicable for the long-term benefit of the patient.

Relative to simple orbital wall fractures, type A ZMC fractures (incomplete fractures) and type B ZMC fractures (tetrapod fractures),[6] the reduction of ZMC-C exceedingly requires the guidance of the navigation system, where the ZMC is divided into 2 or more fragments by additional fractures through the zygomatic body, lateral orbit or infraorbital rim in high-energy fractures. ZMC-C fractures were reported to be associated with more secondary corrections for ZMC malreduction (12%), more secondary reconstructions of the orbital floor (10%), and more functional corrections of diplopia by extraocular muscle correction (5%).[19] In contrast to type B ZMC fractures where clear anatomical landmarks and basically a complete structure could be obtained, the navigation system brought a higher improvement in reduction accuracy in type C ZMC fractures. It was also more conducive to delayed fractures compared with fresh fractures.[14,24] Orbital reconstruction with the aid of a navigation system provides visualization of the surgical procedure especially in the deep orbit and the orbital apex, where the surgical field is limited but crucial for the successful reduction of the orbital fracture. This saves time spent checking bone position during surgery, reduces the risk for iatrogenic injury such as optic nerve injury and extraocular muscle injury, and therefore ensures a safer surgery.[25] It enables the surgeon to react immediately in the operating room when real-time images show inadequate fracture reduction or improper placement of implant material, enhancing the overall quality of surgery. Another advantage of the navigation system is its ability to complete every procedure as minimally invasively as possible, thus minimizing visible scarring.[26]

Few published studies have described the outcomes of the application of navigation system in the management of ZMC-C, especially concurrent with orbital reconstruction. In our study, with the assistance of intraoperative navigation, subjects' main symptoms including facial deformities, restricted mouth opening, enophthalmos and diplopia were greatly improved. Postoperative VAS scores also gradually increased, correlating with improved edema from the injuries and/or surgery and wound healing at 1, 12 and 24 months postoperatively. Ideal remediation of orbital volume was also achieved with the aid of the navigation system. The relatively small distance error between the surgical plan and actual surgical outcome indicated the benefit and reliability of the navigation system. During the follow-up, only 1 subject was bothered by persistent facial numbness despite with some relief over time, which might result from an intrinsic infraorbital nerve injury during the trauma.

The need for concurrent orbital floor reconstruction along with the reduction of ZMC is still controversial in clinical practice. Proponents of selective orbital floor exploration advocate that precise ZMC reduction corrects orbital volume without the need for orbital floor exploration.[27] In ZMC fractures, the periorbita and tendinous attachments of the orbital contents are sometimes preserved compared with orbital blow out fracture. Loss of support from the orbital floor alone without disruption of the periosteum or supporting ligaments may have no effect on globe position.[28] However, the severity and magnitude of different injuries can vary from a linear crack to comminution of the entire orbital floor. Other confounding variables include the mechanism of injury (high vs low velocity), patient's age, size of fractures, concomitant facial injuries, and other preoperative symptoms (degree of diplopia, enophthalmos, etc).[29,30] The development of ophthalmologic complications, such as diplopia, enophthalmos, and the entrapment of extraocular muscles, is advocated as the most important determinants for orbital repair.[18]

Besides, enophthalmos may not immediately appear after the injury because post-traumatic edema following the fracture can last weeks or months, causing underestimation of late enophthalmos.[31] Exploration of the orbital floor is strongly recommended when the fracture line passes medial to the infraorbital foramen.[29] Taken together, the need for orbital floor repair should be discussed on a case-by-case basis, with the goal of performing as little surgery as is necessary to attain a satisfactory surgical outcome with minimal postoperative complications. A multidisciplinary team including ophthalmologists, maxillofacial surgeons and plastic surgeons is recommended to optimize patient outcomes in this situation.

Despite long-term follow-up, the retrospective nature and relatively small sample size of our study are major limitations to our conclusion. A prospective, randomized study of the application of the navigation system in ZMC-C fracture repair together with orbital reconstruction is necessary to further discuss this question and explore its generalizability.

In conclusion, navigation-guided technique has proven effective for managing ZMC-C fracture, especially concurrent with orbital reconstruction. Deficient movement in the anterior–posterior plane mostly contributes to mean 3D distance error. Navigation enables surgeons to identify pertinent anatomical landmarks and assess fracture reduction in real time, allowing for intraoperative corrections for bony malreduction or implant malpositioning, thereby enhancing the accuracy of reduction. Further studies are required to validate the efficacy of this technique in the treatment of ZMC fractures and orbital fractures.

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