REVIEW

Advances in facial fracture care in patients with zygomaticomaxillary complex fractures

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Purpose of review
Zygomaticomaxillary complex (ZMC) fractures pose both functional and aesthetic challenges, requiring careful surgical planning to optimize outcomes while minimizing morbidity. Recent advancements in surgical planning, fixation strategies, and implant technology have refined the approach to ZMC fracture repair. This review highlights these developments and discusses their implications for surgical decision-making, emphasizing strategies that balance reduction accuracy with the least invasive intervention.

Recent findings
Studies suggest that minimizing fixation points in properly selected ZMC fractures does not compromise patient satisfaction or postoperative symmetry. Intraoperative CT is increasingly utilized and has been shown to reduce unnecessary incisions and implants while improving reduction accuracy. Computer aided surgical planning has demonstrated improved surgical precision through preoperative planning, guiding plate placement, and enhancing anatomical symmetry. Additionally, patient specific implants (PSIs) have emerged as valuable tools in complex or revision cases, offering more precise reconstruction with reduced operative time. Augmented reality (AR) is a rapidly emerging technology that holds promise for surgical planning and navigation for ZMC fracture repair.

Summary
Wider adoption of intraoperative CT has improved surgical assessment, while advances in computer aided surgical planning and patient specific implants continue to refine surgical workflows and outcomes. As technology evolves, future research should focus on optimizing cost-effectiveness and further integrating digital planning tools. AR, still in its preliminary stages, may represent a significant innovation in enhancing surgical precision and visualization during ZMC fracture repair.

Keywords
craniofacial trauma, intra-operative imaging, orbital floor, zygomaticomaxillary complex

INTRODUCTION

Patients presenting with zygomaticomaxillary complex (ZMC) fractures pose both aesthetic and functional challenges. These facial fractures are known by many names, including zygomatico-orbito-maxillary complex (ZOMC), tripod, or tetrapod fractures, based on the relevant affected facial bones, suture lines, or facial buttresses. Functionally, severe, unrepaired ZMC fractures can potentially lead to facial asymmetry, double vision (diplopia), or trismus. Facial asymmetry can specifically present in the form of malar flattening with alteration of the midfacial height, width, and projection. Careful work-up, examination and radiographic review are necessary to determine when and to what extent surgical intervention may be necessary.

If surgery is required, the goal is to establish accurate reduction with stable rigid fixation techniques while minimizing morbidity and associated surgical risk. Specifically, surgical technique decisions should consider incorporating a minimum number of incisions and using the fewest number of plates and screws that are necessary.

ZMC fractures present two unique challenges for the surgeon to balance creating adequate exposure of the fractures to allow reduction and appropriate fixation.

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KEY POINTS

- Zygomaticomaxillary fracture reduction can be effectively performed with the fewest number of incisions/approaches needed access the fracture segments.
- The fracture reduction at the zygomaticomaxillary and zygomaticofrontal suture lines are common sites for hardware fixation, which is typically completed with titanium or in some cases, resorbable implants.
- Outcomes of zygomaticomaxillary complex repairs tend to be good, yet precision of fracture reduction and confirmation can be achieved by surgeon use of computer aided surgery for planning (e.g. virtual surgery), intraoperative navigation, and confirmation of reduction in intraoperative CT.
- Augmented reality offers surgeons a new realm in craniomaxillofacial trauma to leverage technology in improving fracture segment planning, visualization and orbital volume calculation.

(1) Access – no single incision or approach gives access to the entire complex. An assessment of the fracture pattern is necessary to determine how many and which access points are needed. Options include, but are not limited to transoral, transconjunctival and blepharoplasty approaches with rare inclusion of a coronal incision.

(2) Orbit – orbital floor injuries are inherently associated with ZMC fractures. Some fractures may require intervention for large concurrent orbital floor injuries, while others do not. Of note, zygoma fracture reduction can potentially enlarge a preoperatively small orbital floor injury and subsequently necessitate repair.

The purpose of this review is to discuss recent advances in surgical approaches and adjunctive technologies for ZMC repair. The role of intraoperative imaging, computer aided surgical planning, and the use of patient-specific implants will all be discussed.

APPROACH AND POINTS OF FIXATION

Patients with ZMC fractures should be given a frank discussion on the possible outcomes if the ZMC fracture is not treated. When open reduction internal fixation (ORIF) is indicated, surgical decision making progresses to the minimum required surgical approaches to achieve proper reduction, their sequencing, and the required fixation. To investigate that question, Rahbin *et al.* [1▪] reviewed the effect of the number of fixation points on patient satisfaction and malar symmetry as measured by patient survey, photograph review, and reduction on computed tomography (CT) imaging. While postoperative CT imaging noted greater malar asymmetry for patients who underwent one point of fixation compared to >1 point of fixation, this did not correlate with postoperative surgeon analysis of the patient photos. Additionally, no difference in patient satisfaction was noted between patients who underwent either one, two or three points of fixation. The study is limited by possible selection and response bias given the retrospective and survey nature of the study yet does suggest patient satisfaction can be achieved with more minimal surgical intervention in select ZMC fractures.

There remains an undefined clinical question in treating ZMC fractures regarding the necessary hardware and placement to adequately fixate reduced fractures. To test the hypothesis that more fixation is more effective, Arjmand *et al.* applied forces with a pulley system to human anatomic specimens after placing 1.2 mm thickness titanium plates for either one-, two- or three-point fixation [2▪]. The authors created a model that suggested the fracture gap displacement remained less than 1 mm under force loading and determined that fewer points of fixation may be appropriate.

SURGICAL DECISION POINTS

In the authors' opinion, ORIF of ZMC fractures typically include at least two approaches, yet the extent of repair depends on both the degree of comminution and displacement. Overall, the midfacial skeleton is approached through a transoral, sublabial approach. Sub-periosteal dissection is completed within the maxilla and zygoma and can extend superiorly to the level of the infra-orbital rim. Via this single approach, the medial and lateral vertical midfacial buttresses, as well as the transverse buttresses (e.g. orbital rim and dentate maxillary arch) are all exposed.

At this stage of the operative repair, the utility of additional access via transconjunctival and upper eyelid blepharoplasty incisions can be evaluated. The transconjunctival approach facilitates evaluation of the inferior orbital rim and orbital floor from the infero-medial buttress to the lateral extent at the zygomatico-sphenoid (ZS) suture. Additional access can be gained with a lateral canthotomy, but is not always necessary. The blepharoplasty approach allows for exposure of the zygomatico-frontal (ZF) suture. It is rare to use a coronal approach except in complex pan-facial trauma where the root of the zygoma is accessed to assure midfacial width restoration. When considering the coronal approach, the authors' feel that the surgical sequala (e.g., alopecia, temporal hollowing, etc.) outweigh the benefits.

The surgeon can use a variety of landmarks to confirm the reduction of the ZMC fracture segments into premorbid, anatomic alignment. The reduction can be executed with a bone hook or Carroll-Girard screw placed into the stable segment of the body of the zygoma, either through the sublabial incision or an additional small percutaneous incision directly overlying the desired placement site. After the body of the zygoma is reduced, the reduction at the inferior orbital rim, ZF and ZS sutures are all assessed. The inferior orbital rim represents an important site of reduction since even subtle bony step-offs can result in palpable deformities not concealed by the thin lower eyelid skin.

The ZS suture, accessed through either the transconjunctival or blepharoplasty approaches, provides the most sensitive assessment of midfacial projection, width, and rotation due to its length and involvement of multiple planes. Therefore, prior to beginning the process of rigid fixation, the reduction of the ZMC should be assessed at the ZS suture site. The narrow bony width at the ZF suture site alone provides limited information regarding the rotation of the ZMC complex but does aid in assessment of the vertical dimension of reduction and can provide a stable site to begin placement of the hardware. Subsequent sites of rigid fixation commonly include the inferior orbital rim and zygomaticomaxillary buttress (e.g. lateral buttress).

USE OF INTRAOPERATIVE COMPUTED TOMOGRAPHY

Surgical accuracy can be confirmed with intraoperative CT scan. Intraoperative revision of the hardware is reported to range between 12% and 60% of cases where intraoperative imaging is employed [3–9]. Therefore, CT imaging plays an important role in the intraoperative decision-making and allows for assessment of the orbital floor after optimal bony reduction. Ovaitt *et al.* reported in a 2024 retrospective review (2009–2022) that the use of intraoperative CT led to a significant reduction in the number of incisions required for ZMC fracture repair ($n = 84$) [10■■]. The use of a transconjunctival approach decreased from 73.7% to 26.1 of cases % ($n = 84$) when intraoperative CT was used. This was associated with fewer orbital rim (76.3% vs. 21.7%) and orbital floor implants (52.6% vs. 17.4%). They surmise that this reduction in transorbital approaches is likely due to a confirmation that the orbital floor did not require exploration [10■■]. Additionally, once part of an established workflow, the fracture reduction is evaluated with an intraoperative CT in a timely fashion. At the authors' institution it was found to add only approximately 15–20 min to the total operative time [11,12].

WHEN IS ORBITAL FLOOR EXPLORATION WARRANTED IN ZYGOMATICOMAXILLARY COMPLEX FRACTURES?

The typical ZMC fracture pattern includes a fracture line from the superior-lateral ZF suture line, traversing along the ZS suture and continuous with the orbital floor and infraorbital rim, with incomplete fractures being possible. Not all ZMC fractures require an orbital exploration. Yet the inadequate reduction and fixation of the orbital floor fracture component can lead to aesthetic and functional deficits. In general, the potential need for repair of the orbital floor component of the fracture represents a challenge in clinical decision making.

In some ZMC fractures, the need for orbital repair is imperative, including urgent indications such as orbital muscle entrapment, hemodynamic instability related to oculocardiac reflex, or significant enophthalmos [13]. However, more often the decision regarding orbital exploration is not as straightforward. ZMC fractures importantly can cause an initially significant decrease in orbital floor volume [14], and once swelling reduces, reveals a clinically significant orbital floor fracture that necessitates repair, which has led to debate about whether the surgeon should explore the orbital floor.

The literature suggests that as few as 23% of complex operative ZMC fractures require exploration and repair of the orbital floor [15]. Determining which fractures necessitate repair can be assisted with intraoperative CT taken after the reduction of the ZMC fracture, with special attention to the orbital floor volume. This must be paired with carefully performed forced duction testing to assure that the intraocular contents (e.g. periosteum, fat, or muscle) are not entrapped in the reduced fracture segments. Obayemi *et al.* reported that patients were more likely to need concurrent repair of the orbital floor during ZMC fracture repair when either there was >4 mm displacement of the orbital floor or the presence of severe comminution [16■].

The authors prefer to follow this protocol and use the intraoperative CT to help guide orbital exploration and orbital floor implant placement, except when obvious floor defects are noted. A transconjunctival approach gives safe access to explore the floor and repair the defect. The value of a cautious approach to orbital intervention in ZMC fractures has also been suggested by Buttar *et al.* [17■]. Their retrospective review noted that while patients undergoing concurrent ZMC and orbital floor repair had an increased size of the orbital floor fracture compared to patients who underwent ZMC fracture repair alone, the two groups had similar preoperative rates of diplopia and those undergoing concurrent repair had a higher rate of postoperative diplopia in the short term [17▪].

COMPUTER AIDED SURGICAL PLANNING

Surgeons are increasingly embracing computer aided planning to improve surgical accuracy in ZMC fracture repair. Committeri *et al.* performed a prospective randomized trial comparing patients managed with two different methods of computer aided surgery to prebend surgical plates and found both led to significant improvement in postoperative CT analysis of reduction compared to the control group [18]. A similar finding was noted by Jiang *et al.* in a retrospective study in which symmetric outcomes were improved for the patients treated with patient-specific cutting guides compared to controls [19]. In addition to allowing for prebending of titanium plates, computer aided surgery can be used to plan for intraoperative CT-guided navigation, another confirmatory tool for reduction. In the authors' practice, CT-navigation software is utilized to create a mirror image of the normal hemiface and used as a guide to reduce the fracture, allowing for optimal symmetry to be achieved. Intraoperative CT imaging provides final confirmation of the result.

IMPLANT MATERIALS FOR FRACTURE FIXATION

Titanium

Titanium has typically been utilized as it represents an inert material with good biocompatibility that generates minimal immuno-reactivity. Titanium possesses greater stability, stress resistance and is lightweight. For midface fractures, load-sharing mini-plates between 0.5 and 1.0 mm in thickness can utilized. Titanium implants require either intraoperative bending, patient specific implants, or the use of anatomic preformed plates. While usually well tolerated, they sometimes can become palpable, develop biofilm or lead to infection, like any other permanent implant.

Bioresorbable

Absorbable implants are used particularly in pediatric cases. There is mixed evidence as to when a child's face may be affected using permanent hardware, yet the authors try to balance the effects of potential additional craniofacial growth with the need for stable load-sharing fixation when choosing between titanium and absorbable polylactide polymers. Concerns about the tensile strength and inflammatory reactions around the bioresorbable implants are considered. The authors prefer absorbable plates and screws in children under approximately 10 years old and in minimally displaced fractures that will heal with minimal fixation material.

Patient-specific implants

PSI offer potentially more precise anatomic reduction, improved functional and aesthetic outcomes, and reduced operative time in ZMC fracture repair. They may also eliminate the need for intraoperative bending and reduce complications such as plate exposure or stress shielding. PSIs are particularly beneficial in complex and/or revision cases, although cost, production time and the need for collaboration with specialized manufacturers remain limiting factors.

The use of 3D printing represents a potential avenue to aid in production time while offering a reduction in cost. DeBusk *et al.* found that for 3D printed mandibular reconstruction plates, they were comparable to industry plates in regards to osseous union while representing over $6000 of cost savings per plate [20]. In the authors' experience, based on current work flow and cost, PSIs are most beneficial in complex cases, such as blast injuries and revision surgeries.

AUGMENTED REALITY

Augmented reality (AR) presents a unique platform to improve preoperative surgical planning and augment intraoperative visualization of craniofacial fractures (Fig. 1), specifically studied by Lin *et al.* in ZMC fracture segments [21]. Kim *et al.* has presented 35 cases using AR to presurgically plan and use 3D printed tracking plates [22▪▪]. Although the technology is developing rapidly and the best circumstances for utilization of AR remain to be discovered, the authors of this report believe that it has potential to improve accuracy of midfacial fracture reduction and perhaps lead to a more efficient operative work-flow. There are currently three primary means of using the AR platform as it relates to ZMC fracture management:

(1) Simulation training for medical students and residents, as well as patient education [23],
(2) Preoperative, 3D visualization of the fractured facial bones to assist with planning for where bony reduction and hardware placement will be needed, including prebending of plates (Fig. 2),

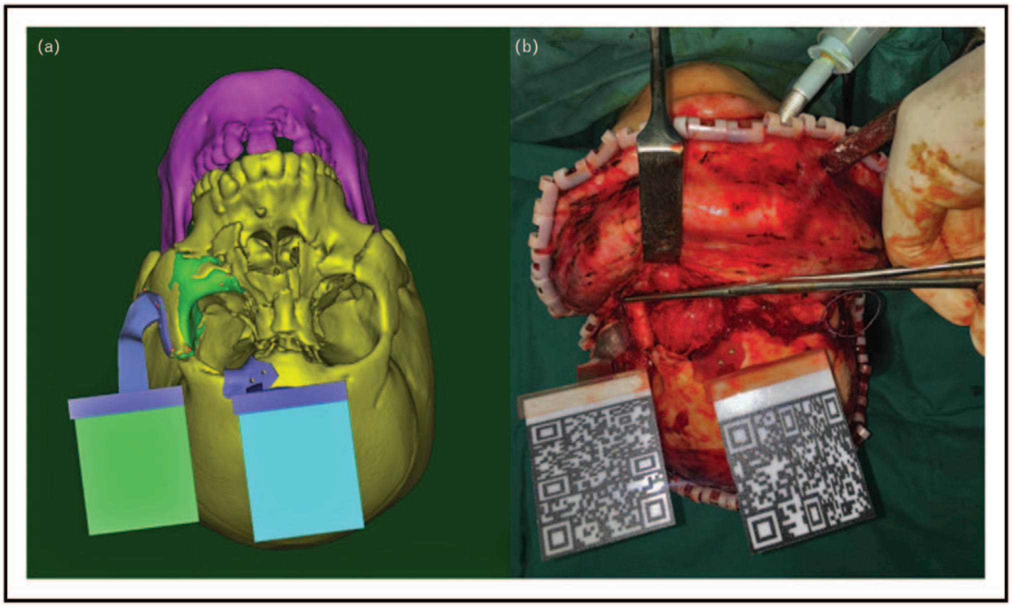

FIGURE 1. Craniofacial fractures shown on presurgical CT scan showing application of virtual reality (left) with the intraoperative photograph (right) with augmented reality tracking being demonstrated (used with permission from Lin *et al.* The application of augmented reality in craniofacial bone fracture reduction: study protocol for a randomized controlled trial. Trials. 2022 [21]) (view full-text article in PMC. 2022;23:241. doi:10.1186/s13063-022-06174-3. Copyright and License information. © The Author(s) 2022. This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third-party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit http://creativecommons.org/licenses/by/4.0/. The Creative Commons Public Domain Dedication waiver (http://creativecommons.org/publicdomain/zero/1.0/) applies to the data made available in this article, unless otherwise stated in a credit line to the data.).

(3) Dynamic intraoperative AR navigation as an alternative, or adjunct, to traditional navigation systems; for example, real-time tracking of mobile ZMC bony segments with visualization of mirrored contralateral anatomy has the potential for improved accuracy of reduction (Fig. 2).

SOFT TISSUE RESUSPENSION

A final but easily overlooked consideration in ZMC management is recognizing the importance of appropriate soft tissue resuspension during closing. Wide undermining and stripping of the periosteum can lead to soft tissue ptosis with resulting midface sagging that can become apparent after soft tissue edema has resided. This risk can be minimized through resuspending the midface periosteum by passing a suture through the orbital rim plate, if used, or drilling a hole through a stable portion of the orbital rim through which a suture can be secured.

CONCLUSION

The management of ZMC fractures requires a balance between achieving optimal reduction, maintaining stability, and minimizing surgical morbidity. Advances in intraoperative imaging, computer aided surgical planning, and patient-specific implants have enhanced surgical precision, improved outcomes, and reduced the need for extensive exposure and hardware placement. While the choice of approach and fixation strategy remains case-dependent, recent evidence suggests that a more conservative fixation strategy may yield comparable aesthetic and functional results in appropriately selected patients.

As surgical techniques continue to evolve, the emphasis remains on individualized patient care that prioritizes functional and aesthetic restoration, while incorporating beneficial technological advancements. Future research should focus on refining fixation strategies, optimizing implant materials, and integrating emerging technologies

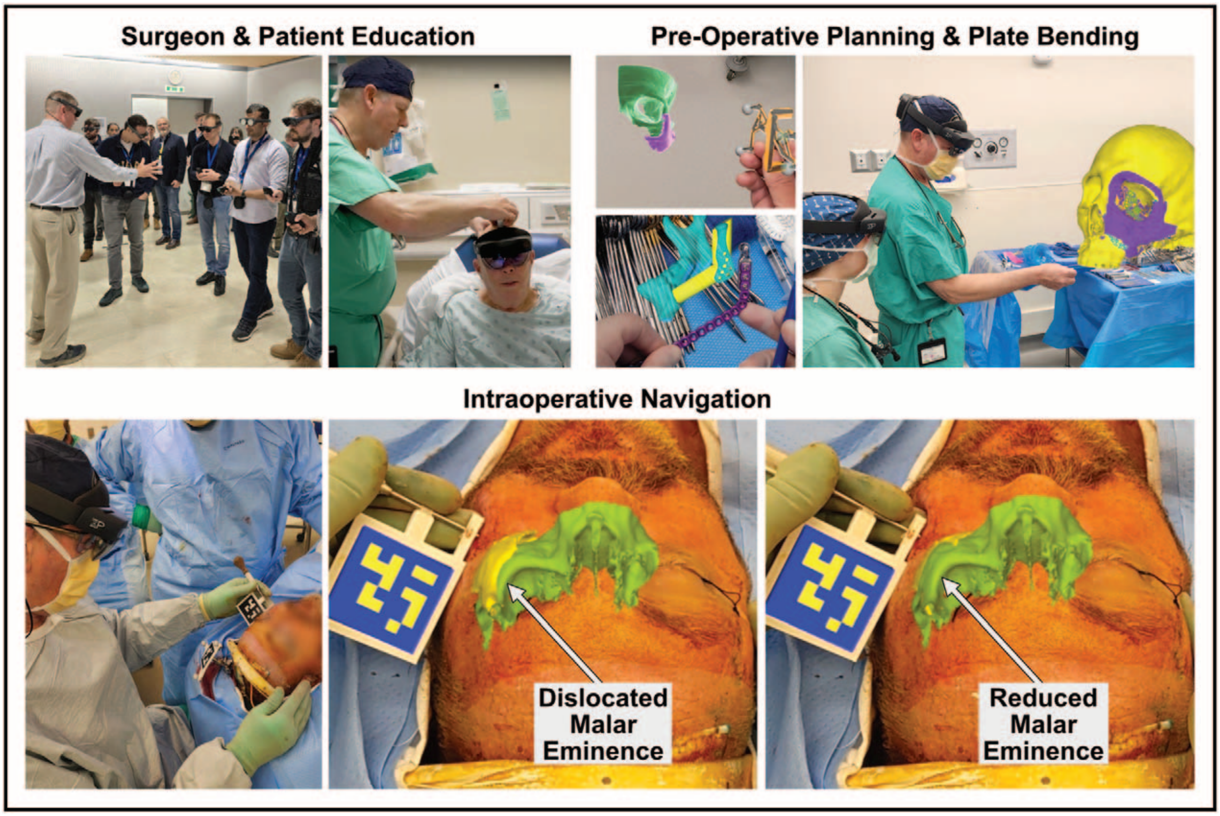

FIGURE 2. Surgeon and patient education – augmented reality simulation of facial fracture (ZMC fracture) surgical intervention with trainees, in addition to preoperative patient teaching to help explain the anticipated surgical technique. Preoperative planning & plate bending – augmented reality projections of the facial and fracture anatomy to allow for preoperative plate bending for optimized intraoperative efficiency. Intraoperative navigation – real-time tracking of a fractured, mobile zygoma body segment with visualization of mirrored contralateral anatomy.

to enhance long-term patient outcomes in ZMC fracture repair.

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Conflicts of interest

The authors have no conflicts of interest or financial disclosures.

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Papers of particular interest, published within the annual period of review, have been highlighted as:
▪ of special interest
▪▪ of outstanding interest

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Retrospective review of 84 patients comparing outcomes before and after the adoption of intraoperative CT. The study noted a significant reduction in the number of surgical incisions following intraoperative CT adoption (mean incisions: 2.45 pre vs. 1.67 post, $P < 0.001$), particularly in periorbital approaches, including transconjunctival incisions (73.7% pre vs. 26.1% post, $P < 0.001$) and lateral canthotomy incisions (23.7% pre vs. 4.3% post, $P = 0.02$). Findings suggest intraoperative imaging led to fewer unnecessary orbital floor explorations and orbital floor plating decreased from 52.6% pre to 17.4% post ($P = 0.001$).

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Retrospective cohort study of 1,914 patients analyzing clinical and radiographic predictors of surgical management in 196 ZMC fractures. Among ZMC fractures, younger patients (38.9 ± 18 vs. 56.1 ± 23.5 years, $P < 0.0001$), those with $\geq$4 mm orbital floor displacement (82% vs. 56%, $P = 0.045$), and those with comminuted orbital floor fractures (52% vs. 26%, $P = 0.011$) were more likely to undergo concurrent orbital floor repair.

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Retrospective study comparing ophthalmologic outcomes in 61 patients undergoing ZMC repair, with 32 receiving concurrent orbital floor repair and 29 undergoing ZMC repair alone. At a median postoperative follow-up of 6 weeks, no patients in either group developed enophthalmos, but diplopia occurred in 8 patients (25.0%) in the orbital floor repair group compared to none in the nonorbital floor repair group ($P < 0.05$).Furthermore, lid malposition was observed in 5 patients (15.6%) with orbital floor repair versus none without ($P < 0.05$).

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