Advances in Personalized Orbital Implants for Surgical Repair and Reconstruction

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KEYWORDS

• Orbital fractures • Orbital implants • Image-guided surgery • Computer-assisted surgery • 3D printing • Patient-specific implants • Custom implants • Personalized implants

KEY POINTS

- Traditional orbital reconstruction faces challenges with precision, implant fit, customization, and positional accuracy.
- Digital workflows, including computer-aided design and 3-dimensional (3D) printing, enable the creation of patient-specific implants, thereby improving anatomic fit and functional restoration.
- Technologies such as intraoperative imaging and navigation contribute to enhanced surgical precision.
- Artificial intelligence-driven automation, advancements in biomaterials, and resource optimization of 3D printing technology are key factors shaping the future of patient-specific solutions for orbital reconstruction.

INTRODUCTION

The orbit is crucial to the face's esthetic and functional aspects, as it houses essential structures like the eye, extraocular muscles, and optic nerve. The loss of structural integrity in orbital fractures poses significant challenges in reconstructive surgery as well as rehabilitation. Traditional approaches to orbital reconstruction have relied on autografts, allografts, and preformed implants, which, while effective in many cases, often fail to address patients' complex and individualized anatomic needs. Autografts, such as bone harvested from the calvarium or iliac crest, were previously favored due to their biocompatibility and ability to integrate with host tissues. However, they are associated with challenges in achieving precise contouring, donor site morbidity, and limited availability in certain situations. Similarly, commercially available preformed implants, made of titanium or porous polyethylene, are suitable for noncomplex orbital reconstructions but may not be ideal for complex or large defects, resulting in suboptimal functional and esthetic outcomes.

In contrast, patient-specific implants (PSIs) have emerged as a novel approach, leveraging advancements in medical imaging, computer-aided

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Abbreviations

AI	artificial intelligence
AR	augmented reality
CAD	computer-aided design
CAS	computer-assisted surgery
CBCT	cone-beam computed tomography
CT	computed tomography
ML	machine learning
MR	mixed reality
PEEK	polyetheretherketone
POI	patient-specific orbital implants
POI	personalized orbital implant
PSI	patient-specific implant
RAOS	robot-assisted orbital surgery
SOR	supraorbital rim
VSP	virtual surgical planning
VR	virtual reality
3D	3-dimensional

design (CAD), biomaterials, and 3-dimensional (3D) printing technologies. PSIs are custom-designed to match the patient's unique anatomy, offering precise reconstruction with the added advantages of reduced surgical time and the risk of complications such as implant malposition or extrusion. Nonetheless, conventional reconstruction methods still hold promise for most reconstructions as the indications for using PSIs are still limited and anatomic defect-specific.[1,2]

Evidence from recent literature suggests that personalized orbital implants (POIs) are superior to traditional implants in complex orbital reconstructions. Maher and colleagues[2] found that POIs resulted in better anatomic restoration and reduced revision rates compared with traditional methods. Similarly, Schreurs and colleagues[3] reported improved functional and esthetic outcomes with POIs, particularly in cases involving multiwall defects or secondary reconstructions. However, the high cost involved and the logistical challenges associated, such as the need for specialized equipment and trained personnel, remain significant barriers to the popularity of POIs.[2]

This article aims to provide a comprehensive overview of advancements in POIs for orbital reconstruction, highlighting the limitations of traditional approaches and the benefits of patient-specific solutions. The article also discusses potential challenges in the use of and future directions.

Indications for Personalized Implants in Orbital Surgery

A literature review suggests that POIs may be beneficial in various clinical indications, ranging from trauma to congenital anomalies and oncological reconstructions. The following clinical situations may benefit from better surgical outcomes with the use of POIs.[3–8]

Post-trauma Indications

- *Complex orbital fractures involving the posterior third compromise the integrity of the posteromedial bulge (Hammer's key area).*[9]

In such cases, the posterior ledge for support is often absent or poorly defined, making it challenging to achieve a stable 2-point anchorage with preformed implants. POIs allow for precise contouring and support in the posterior third, utilizing a cantilever design that ensures superior clinical outcomes (Fig. 1).

- *Two-wall defects of the floor and the medial wall where the inferomedial strut is compromised.*

The inferomedial strut is a key internal buttress that provides structural support for the orbital floor and medial walls, serving as an important anatomic landmark for achieving optimal mesh positioning during medial wall reconstruction. When compromised, it may pose difficulty in reconstructing the "zone of transition" from the floor to the medial wall and maintaining the reconstruction within the confines of the orbit. This may cause the reconstruction material to encroach into the ethmoidal cavities, failing to restore the complex geometry of the defect. POIs can be designed to bridge the defect precisely, providing structural integrity to the buttress (Fig. 2A).

- *Extensive or multiwall intraorbital defects that are not amenable to bridging using preformed implants.*

Multiwall defects often involve irregular and extensive bone loss, making it difficult to achieve adequate reconstruction with commercially available stock implants. POIs can be tailored to the exact dimensions and contours of the defect, ensuring optimal restoration of orbital anatomy and function (Fig. 2B).

- *Rim defects that need augmentation.*

Traumatic defects involving the orbital rim require precise contouring, which forms the primary step in internal orbital reconstruction. This requires the re-establishment of contours and facial symmetry, which matches the intricate anatomy of the upper face. Though bone grafts have been used with a good measure of success for

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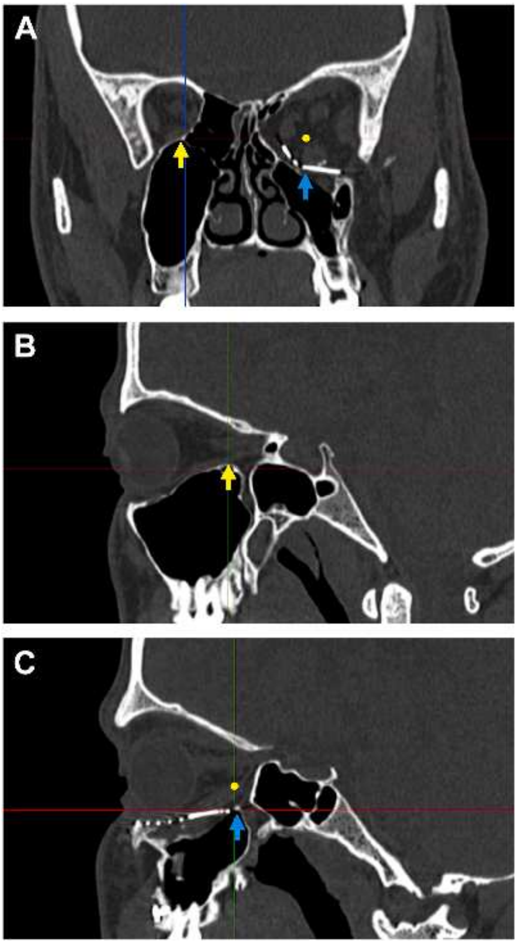


Fig. 1. CT scan of a patient with left-sided orbital fracture demonstrating the absence of posterior ledge. (*A*) Coronal CT section with intact postero-medial bulge (*yellow arrow*) of the right orbit and a large fracture of the left. Yellow dot represents the ideal level of the posterior ledge as projected from the unaffected side. Blue arrow indicates inadequate earlier reconstruction and malposition of the implant. (*B*) Sagittal section of the same patient demonstrating intact (*yellow arrow*) postero-medial bulge of the right orbit. (*C*) Sagittal section of the left orbit demonstrates lack of posterior support for the implant with resultant suboptimal reconstruction.

this indication, extended defects require intricate contouring, and may be easier to achieve with POIs (Fig. 3).

- *Complex defects involving the orbit and surrounding facial and cranial skeleton.*

These defects may require significantly large implants, which must balance size, contour, and stability. POIs may be better suited to address such defects, as native bone may not be amenable to forming complex contours, while preformed solutions may not be available to suit facial bone defects (see Fig. 3A–C).

- *Secondary or delayed presentation of orbital fracture presents with distorted anatomy and technically challenging scenarios due to previously used reconstruction material and the absence of standard reference points for implant anchorage.*

The anatomy is often distorted in such scenarios due to prior surgeries or malunion. Moreover, prior use of implants may compromise the available space for anchoring new stock implants. POIs can be designed to account for these distortions and modified or extended based on the existing anatomy to incorporate reliable fixation points and anchorage (see Fig. 1).

Congenital/Developmental Defects

- *Cranio-orbital dysplasias.*

Congenital cranio-orbital dysplasias like Treacher Collins syndrome have complex orbito-malar deformities often accompanied by agenesis of the zygomatic complex and arch. Reconstruction of such challenging clinical situations may not be amenable with autogenous bone due to the complexity of the deformed anatomy and the large quantities of bone needed. Stock implants with periorbital extensions (eg, Medpor extended malar implants) may not provide the required fit. In contrast, a POI can be fabricated to accommodate this reconstruction with precision.[10]

- *Silent sinus syndrome.*

Silent sinus syndrome results in severe intraorbital deformity and volume expansion[11] due to an imploded maxillary sinus, thus lacking the definition of the posterior ledge necessary for a "2-point" anchorage. The challenge of this condition may be better suited for a POI similar to indication 1 discussed earlier (Fig. 2C).

Postoncological Reconstruction

- *Substantial defects secondary to ablative surgery.*

Ablative surgery often results in large, irregular defects depending on the type and extent of pathology involved. The clinical indication may frequently require reconstruction of adjacent anatomic subunits as well. This nullifies the use of conventional stock implants, making POIs necessary for optimal restoration of form and function (Fig. 2D).

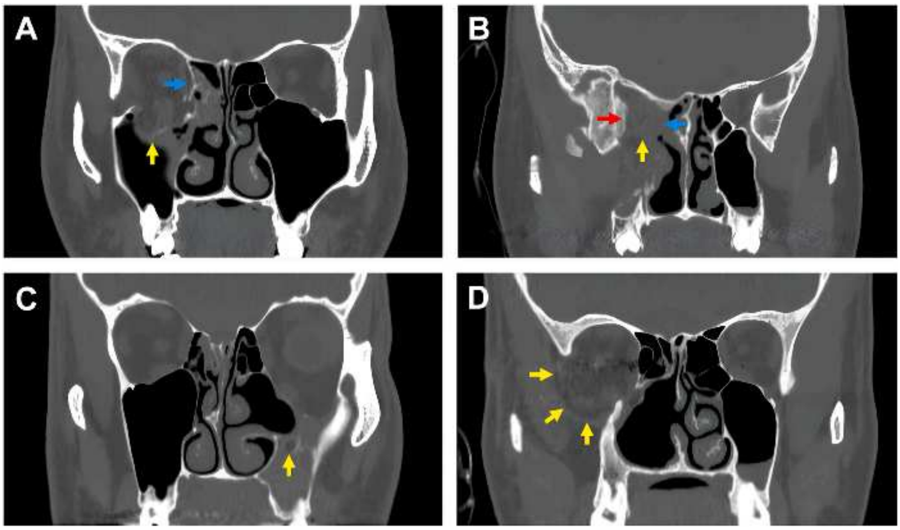


Fig. 2. (*A*) Two-wall fracture of the right orbit involving the floor (*yellow arrow*) and the medial wall (*blue arrow*). (*B*) Extensive multiwall defect involving the floor (*yellow arrow*), medial (*blue arrow*), and lateral walls (*red arrow*). (*C*) Left-sided orbital deformity secondary to "silent sinus syndrome" (*yellow arrow*) and resultant expansion in the intraorbital volume and (*D*) postablative orbital defect on the right side.

GENERAL WORKFLOW FOR VIRTUAL SURGICAL PLANNING AND COMPUTER-ASSISTED SURGERY

Virtual surgical planning (VSP) and computer-assisted surgery (CAS) have revolutionized the creation and implementation of PSIs in orbital reconstruction. This process enhances accuracy, reduces surgical time, and optimizes functional and esthetic outcomes.[12,13] Key steps in the VSP and CAS workflow include the following.

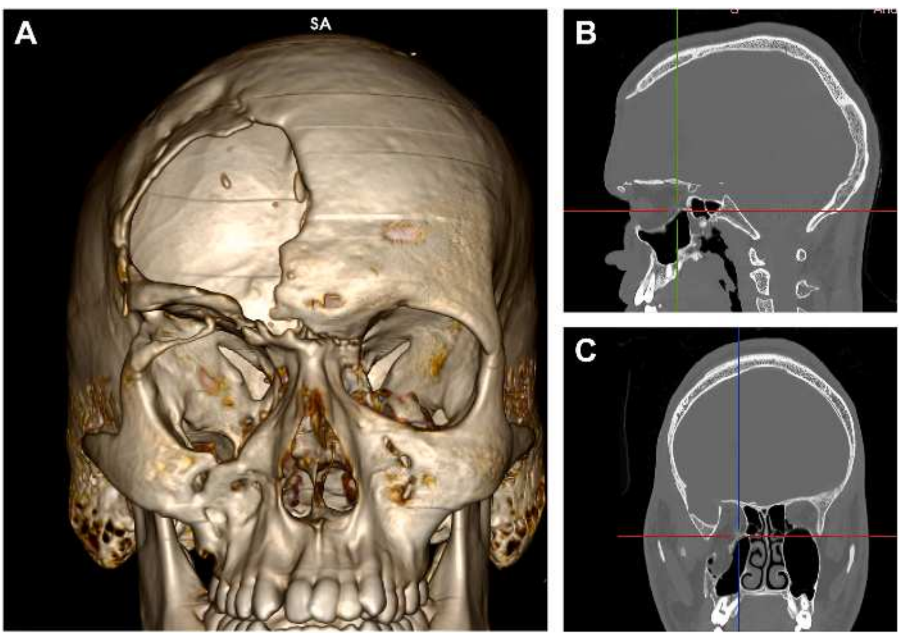


Fig. 3. The 3D image of a complex post-traumatic deformity involving the orbit, midface, and the frontal bone on the right side (*A*) with severe depression of the infraorbital rim. (*B*) Sagittal section demonstrating the frontal craniectomy defect and orbital floor fracture, and (*C*) coronal section showing intraorbital deformity.

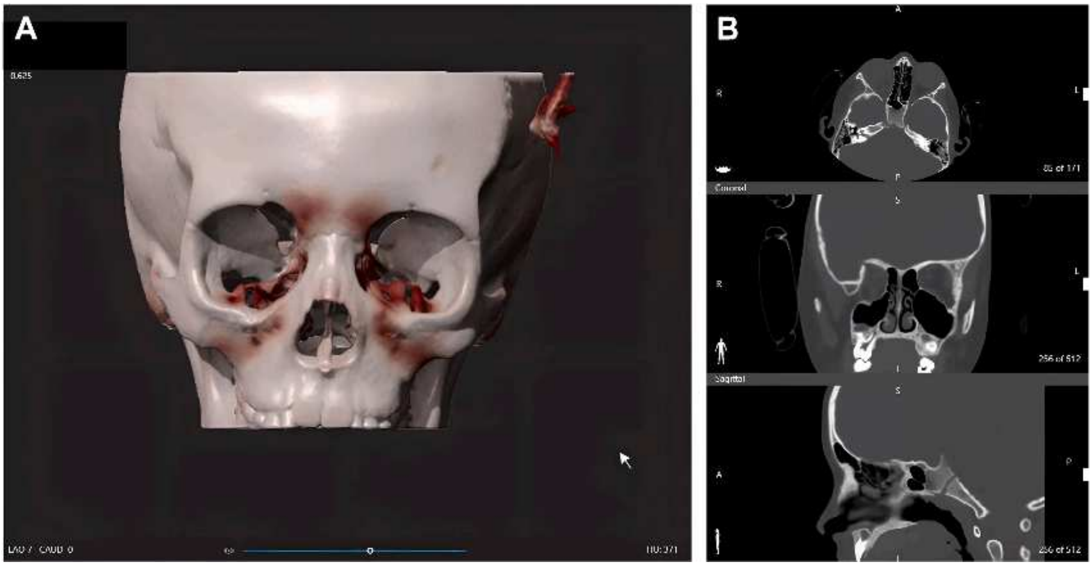


Fig. 4. Diagnostic view of CT data of a patient. (*A*) The 3D volume rendered image and (*B*) multiplanar view with axial, coronal, and sagittal windows.

Clinical Examination, Imaging, and Planning

Clinical examination

Evaluation involves both functional and cosmetic assessment of the face, along with a comprehensive ophthalmic evaluation.[14] Patient history, symptoms, and complaints should guide the examination. Key aspects of assessment include globe displacement in sagittal and vertical planes, diplopia, and periorbital symmetry and esthetics.

Imaging and data acquisition

High-resolution imaging is the basis of CAS and VSP. Helical computed tomography (CT) (Figs. 4A, B, and 5A) with a slice thickness of 0.625 to 1 mm ensures precise 3D reconstruction. Although MRI is unsuitable for bony structures, it complements CT by visualizing soft tissue, nerves, and vasculature (Fig. 5A, B). Cone-beam CT (CBCT), when used, should have a voxel resolution of 100 to 600 μm and cover the orbit, surrounding cranial and midfacial structures in its field of view.[13]

3-Dimensional modeling and defect analysis

Virtual models enable the detailed evaluation of orbital defects, including dimensions, shape, rim alignments, and intraorbital volume changes (see Fig. 4A). Mirroring the unaffected side facilitates the assessment of unilateral deformity, while anthropometric standards and anatomic models guide the evaluation of bilateral defects.[15]

Image segmentation and virtual surgical planning

Segmentation isolates critical structures, such as the orbital walls, floor, and adjacent craniofacial skeleton, allowing for the precise definition of defects and intact anatomy (Fig. 6). Advances in

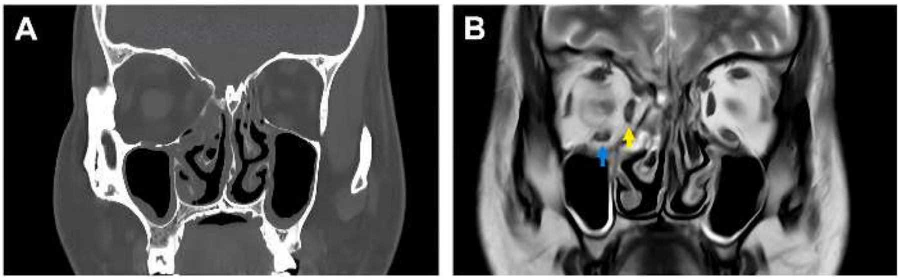


Fig. 5. (*A*) High resolution coronal CT image demonstrating a right-sided fracture of the orbital floor and medial wall. (*B*) Coronal MRI image of the same patient, revealing high definition of soft tissues, good visualization of orbital volume expansion. The image shows change in orientation of inferior rectus (*blue arrow*) and medial rectus (*yellow arrow*) and herniation of intraorbital fat into the maxillary and ethmoid sinuses.

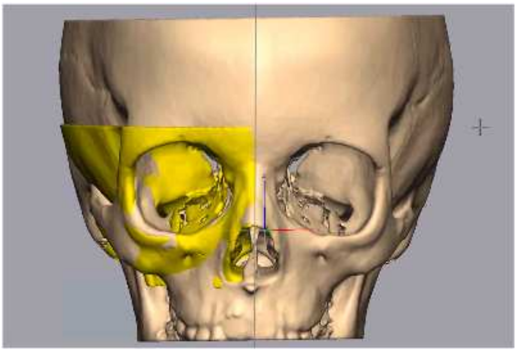


Fig. 6. Steps involved in VSP. Segmentation, mirroring, and superimposition of the unaffected left orbit and zygoma (area in *yellow*) on to the fractured right side.

image segmentation and 3D modeling have significantly improved precision in orbital reconstruction. Digital subtraction techniques are now commonly integrated to isolate critical areas in trauma and complex defects (**Fig. 7**) while also enabling the removal of implants, debris, and tissue fragments for precise POI design.[16] 3D printing further enhances diagnostics by creating patient-specific anatomic models (**Fig. 8**), which improve defect visualization and facilitate implant planning.[17] Additionally, artificial intelligence (AI) and machine learning (ML) play a growing role in automated segmentation: yet another technological innovation integrated into mainstream clinical practice, where AI enables the automatic identification of anatomic regions to streamline workflow efficiency.[18,19]

VSP enhances orbital volume restoration and implant positioning, reducing postoperative complications such as enophthalmos and diplopia.[20] González and colleagues[21] highlighted that VSP enhances preoperative visualization and customization, ensuring a more precise anatomic fit than traditional methods (**Figs. 9–11**). Studies indicate that VSP-assisted procedures reduce operative time by 25% to 40% and lower revision rates by enabling surgeons to anticipate and address intraoperative challenges. AI-driven segmentation and predictive modeling refine implant design by automating defect analysis and optimizing shape and size, improving implant positioning accuracy and minimizing intraoperative adjustments. This ultimately enhances both functional and esthetic outcomes. While experienced surgeons may achieve similar results in simpler cases, evidence strongly supports using technology-guided approaches for complex orbital defects.

VSP software has evolved significantly, offering greater functionality than earlier versions. The literature identifies Materialise Mimics as the most commonly used software for orbital reconstruction due to its advanced anatomic segmentation and 3D modeling capabilities, making it essential for preoperative planning and implant design. Geomagic Freeform is particularly useful for implant designing, while iPlan CMF (Brainlab) is closely associated with trauma-based orbital reconstruction, integrating with surgical navigation systems for improved intraoperative accuracy.[22] iPlan also features AI-driven automated segmentation, a key advancement in VSP.[23]

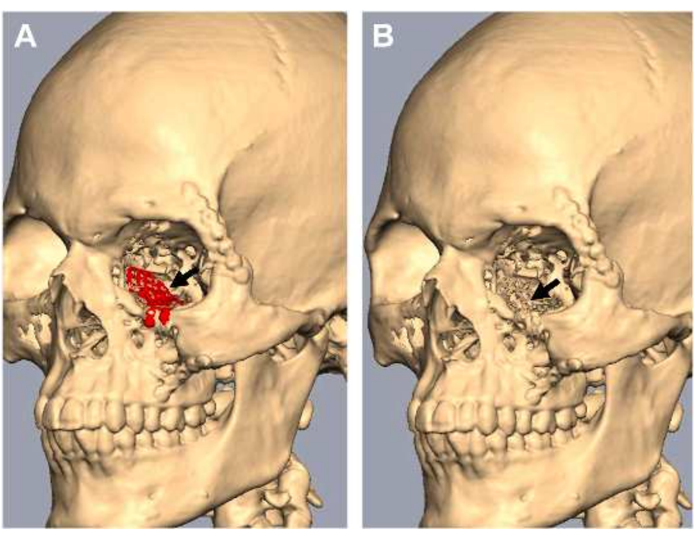


Fig. 7. Digital subtraction technique (*A*) virtual skull model demonstrating reconstruction used earlier (*black arrow*) and (*B*) virtual skull with implant removed.

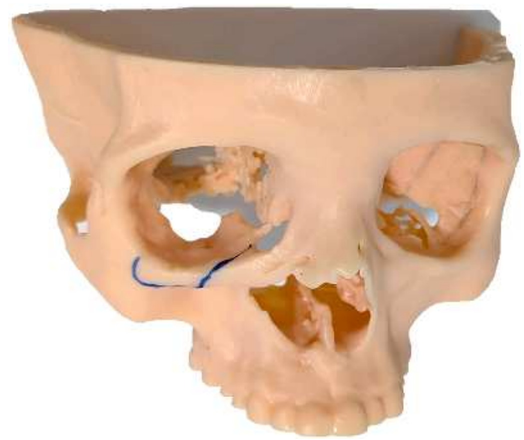


Fig. 8. Physical stereolithographic model for diagnostic use.

Implant Design, 3-Dimensional Printing and Fabrication

Implant designing

Digital implants are tailored to fit defect contours in alignment with surrounding anatomy (**Fig. 12**A, B). Virtual try-ins refine implant fit and predict outcomes, with iterative adjustments optimizing the design (**Fig. 12**C). For extensive deformities, surgical simulation may be considered to plan osteotomy, fracture reduction, and fixation (**Fig. 13**). Implant materials are selected based on their strength, biocompatibility, and the specific reconstruction needs. Defect characteristics and patient attributes are primary factors that influence implant design and selection. In contrast, materials and logistics may be categorized as secondary (**Box 1**).

Defect characteristics

Defect characteristics are one of the key determinants in the design and selection of POIs, as they dictate the complexity of reconstruction and the type of customization required. The factors critical for this assessment are:

- *Size and Extent of Defect:* Large defects (**Fig. 14**), particularly those involving multiple orbital walls, require implants that provide structural support while maintaining a thin profile (0.3–0.6 mm) to avoid excessive intraorbital bulk. Titanium is often preferred in clinical indications for its strength and ability to support cantilever designs with extensive defects.[4,5,24]
- *Location of Defect:* The anatomic location of the defect influences implant design. For example, defects involving the posterior third of the orbit, particularly the posteromedial bulge (Hammer's key area) (see **Fig. 14**), require rigid implants to restore structural integrity.[4,5,24] In contrast, rim defects may necessitate lightweight materials like polyetheretherketone (PEEK) for augmentation.[3,6]
- *Wall Involvement:* Multiwall defects pose significant challenges in contour restoration and implant insertion. Split implant designs, where multiple interlocking components are used, are often required for precise reconstruction (see **Fig. 14**).[25]
- *Rim Involvement:* Fractures extending to the orbital rim or adjacent facial bones may

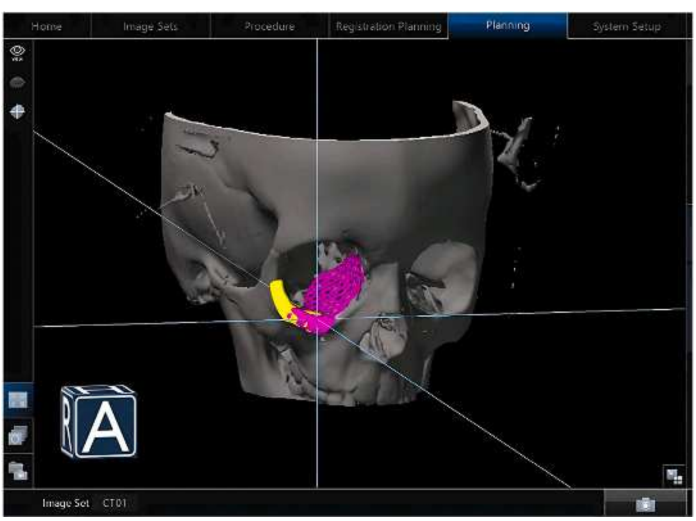


Fig. 9. VSP of the patient imported into the navigation platform for intraoperative guidance.

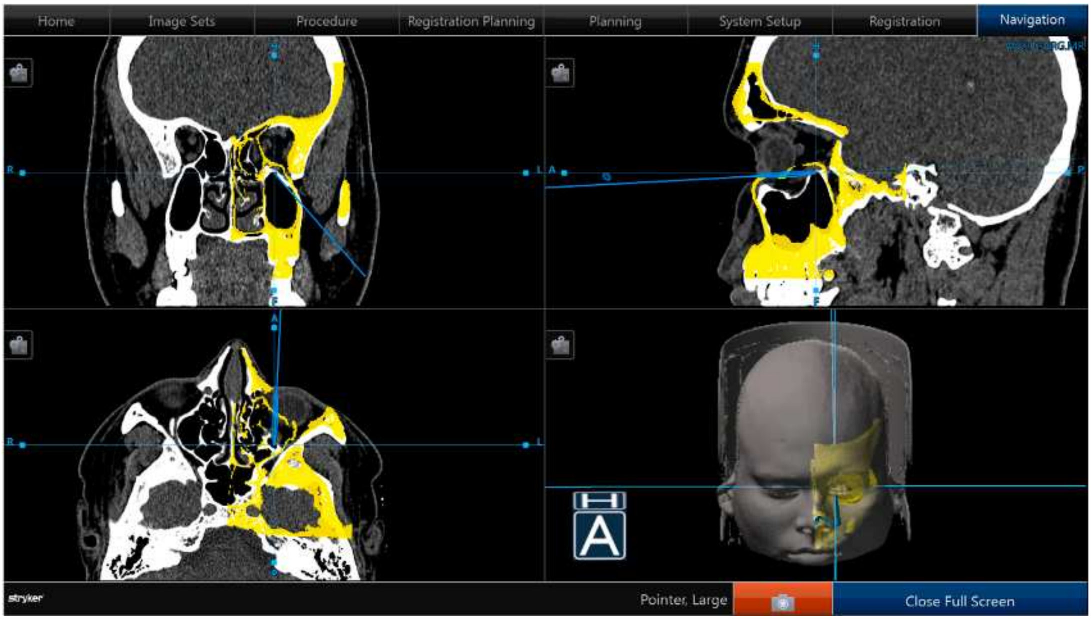


Fig. 10. Use of navigation for intraoperative guidance. Screen view demonstrating multiplanar view, with mirroring of normal side (*yellow*) to the affected side. Blue line indicates position of pointer for real time location.

require more extensive or multiple small implants for reconstruction (see Fig. 14). Figs. 15–19 demonstrate the clinical, intraoperative, and postoperative CT images of patient 1, who required rim and zygoma augmentation using a PEEK onlay, without osteotomy of malunited fragments and repositioning. Polymers like PEEK are advantageous for rim augmentation due to their lightweight yet strong properties.[8] Figs. 20–23 demonstrate the clinical and CT images of patient 2, who required rim augmentation and orbit reconstruction using titanium POI.

- *Globe Status:* In cases of anophthalmic sockets or phthisical globes, volume augmentation is often necessary to achieve symmetry. Implants with exaggerated bulges on the orbital floor may be required to address volume deficits (see Fig. 14).[3,5]

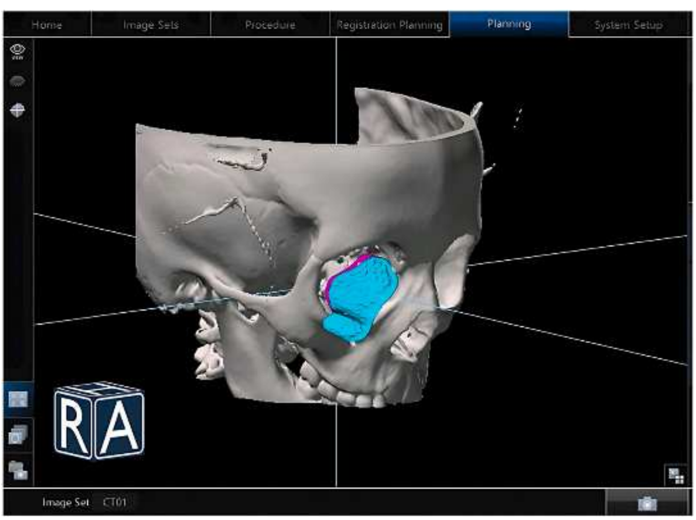


Fig. 11. Superimposition of the achieved implant position from the postoperative CT image (*blue*) onto the preoperative position (*pink*), to evaluate accuracy of implant placement.

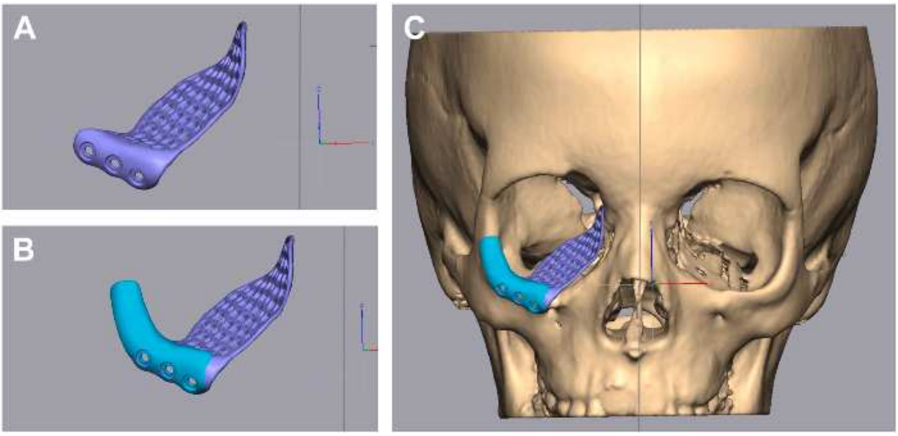


Fig. 12. Steps involved in VSP. (*A*) Virtual design of the POI, (*B*) virtual design of the positioning guide (*blue*) and orbital implant (*purple*), and (*C*) virtual try-in of the positioning guide and orbital implant on the patient's skull.

Patient-Related Challenges

The patient-related factor is another critical determinant that plays a crucial role in determining the selection of POIs. Important considerations that need to be evaluated include:

- *Soft Tissue and Bone Characteristics:* Compromised soft tissue due to radiation, scarring,[26,27] or previous trauma can complicate reconstruction.[2,3] Bone resorption or necrosis, particularly in secondary reconstructions, may necessitate lightweight implants and flaps to address soft tissue insufficiencies.[1,28]
- *Infection:* Active infections in the orbit may contraindicate immediate reconstruction with POIs. In such cases, aggressive infection control and delayed reconstruction using biocompatible implants with antimicrobial coatings are recommended.[29–32]
- *Age:* POIs are generally recommended for patients with completed orbital growth,[33] typically by age 8.[34] However, in younger patients with large defects or postablative conditions, POIs may still be indicated, though the child is still growing.[35]
- *Allergies:* Allergic reactions to POIs are uncommon but can happen, especially with polymers like PEEK and porous polyethylene, which may trigger foreign body reactions or delayed infections.[36–38] Some metal alloys containing nickel, cobalt, or chromium can also cause allergies.[39] Highly biocompatible materials, such as pure titanium or ceramics, are recommended [40,41] to reduce the risk.

3-dimensional printing and fabrication

Recent advancements in materials, fabrication technology, and postprocessing techniques have

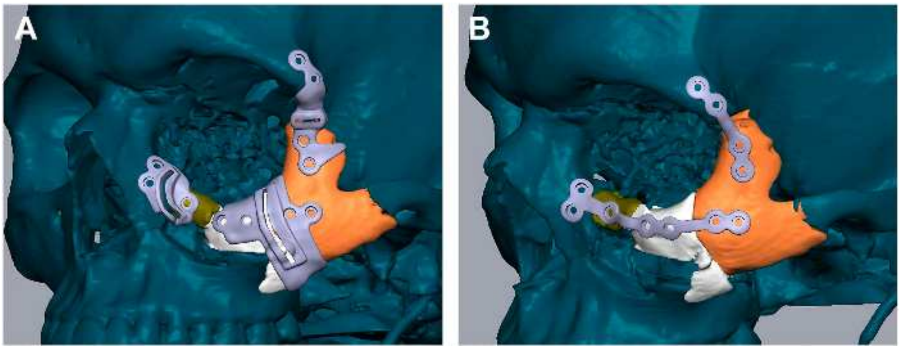
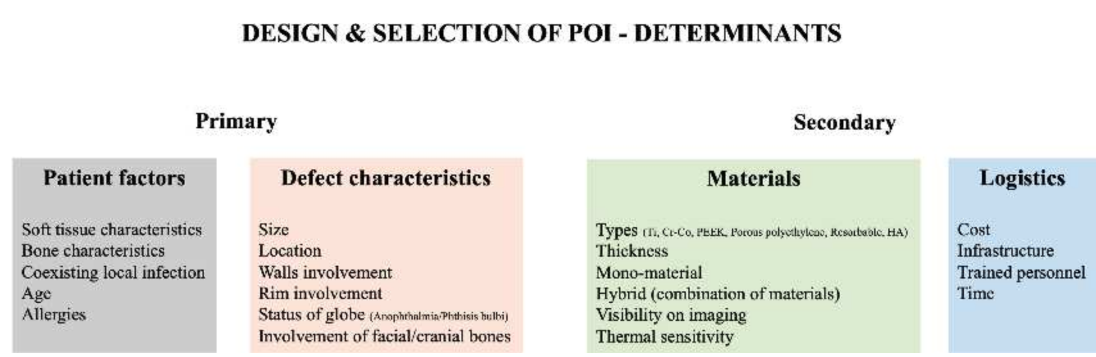


Fig. 13. VSP for secondary correction of zygomatico-orbital deformity. (*A*) Areas marked in green, white, and orange indicate malunited fractured fragments. Cutting guides (*gray*) demonstrate vertical slots to facilitate osteotomy and holes for screw fixation which guide final implant position (*B*) personalized implants (*gray*) in position after realignment of fragments.

Box 1
Determinants for implant design and selection



significantly enhanced the functionality and precision of patient-specific orbital implants (POIs).

Material selection Material selection for POIs is a critical decision that should consider the patient's specific needs, structural requirements, biocompatibility, and visibility in postoperative imaging. Among clinically viable materials, titanium remains the gold standard due to its biocompatibility, corrosion resistance, osseointegration, and ability to be customized through 3D printing and CAD/CAM technology.[42] Additionally, it possesses excellent strength, a thin profile, and versatility in form and shape.[4,43,44] In a mesh form, it also facilitates the egress of inflammatory fluid, reducing the risk of postoperative complications.[45] Titanium's visibility on postoperative imaging aids in accurate implant localization, which is crucial for assessing surgical outcomes. However, its tendency to produce MRI artifacts and the possibility of thermal sensitivity may necessitate alternative materials.[46] Such instances may indicate good use of polymers such as PEEK or porous polyethylene. Porous polyethylene (Medpor) has been proven effective due to its excellent biocompatibility, soft tissue integration, and mechanical stability.[16,44,47] While PEEK has gained popularity over the last decade for its high strength and compatibility with additive manufacturing, The lack of visibility on postoperative imaging is a minor limitation experienced during the assessment of surgical outcomes.[16,44,47] For more complex reconstructions, a hybrid approach can offer significant advantages. Combining titanium with biocompatible coatings, such as hydroxyapatite, or integrating it with PEEK can reduce metal exposure and ion release while improving osseointegration and soft tissue integration.[43] This is particularly valuable in extensive reconstructions, where different materials serve distinct roles. For example, titanium may be the ideal choice for orbital implants due to its strength, while PEEK's lightweight properties make it suitable for zygomatic augmentation in larger reconstructions.[3]

Clinical scenario A patient with extensive fronto-orbito-zygomatic reconstruction (Fig. 24) was treated with hybrid implants through an extended

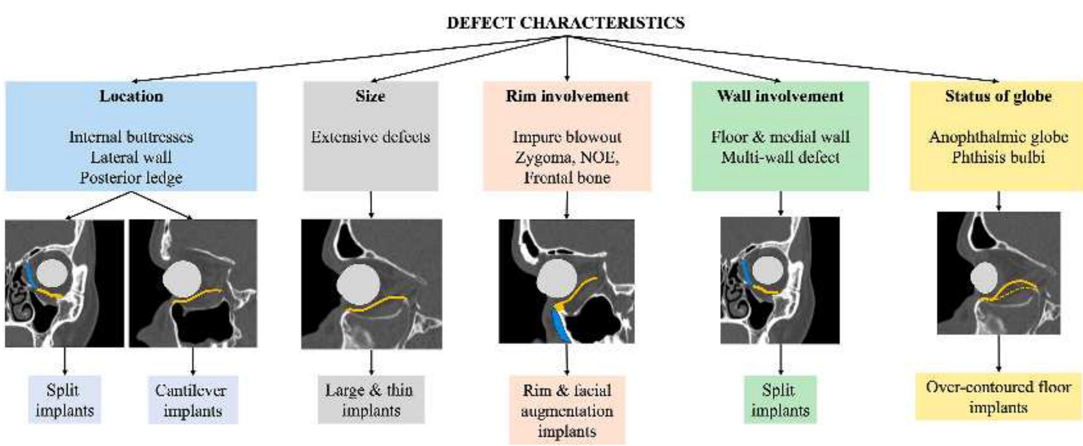


Fig. 14. Chart demonstrating defect characteristics which influence design of POIs.

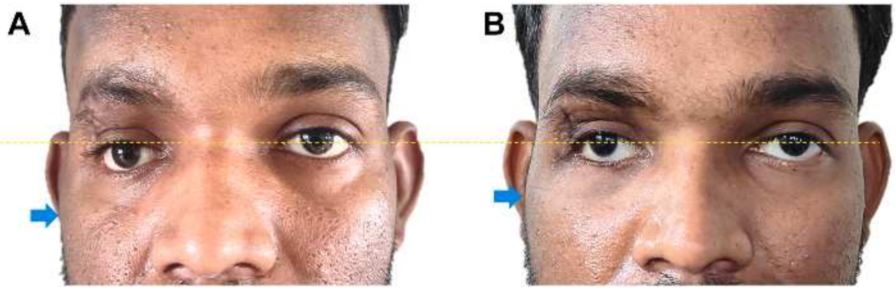


Fig. 15. Patient with zygomatico-orbital deformity. (*A*) Preoperative picture with clinical features of hypoglobus and reduced malar prominence on the right side and (*B*) postoperative picture demonstrating correction of the hypoglobus and malar asymmetry. Yellow line indicates pupillary levels and blue arrows indicate change in malar prominence.

split-design POI, where titanium provides structural support for a cantilevered intraorbital implant, while lighter PEEK implants were preferred for anatomic contouring. Careful selection of materials such as this can help surgeons optimize functional and esthetic outcomes.

Fabrication methods Additive manufacturing (3D printing) has emerged as the most commonly used technique for fully customized POIs (Fig. 25). Technologies like selective laser sintering for titanium and fused deposition modeling for PEEK are commonly used and highly effective fabrication methods.[47,48] Hybrid manufacturing, which integrates additive and subtractive techniques such as computer numerical control milling, has been developed to optimize surface smoothness and structural accuracy, further enhancing implant performance.[49,50]

Postprocessing technology plays a vital role in improving implant biocompatibility and tissue integration and commonly includes surface finishing methods, such as polishing, electropolishing, and sandblasting, to enhance implant smoothness and cellular interaction, leading to improved integration.[31,32,42] Advances such as surface coating with hydroxyapatite coatings enhance osteoconductive benefits and antimicrobial properties.[31,32,42]

Surgical Planning and Intraoperative Guidance

Surgical planning

Innovations in surgical planning have significantly improved surgical precision. A brief discussion of their influence on improving outcomes has been detailed later.

Positioning guides (Fig. 26) are widely used, providing custom templates that align with anatomic landmarks to enhance implant placement accuracy, restore orbital symmetry, guide corrective osteotomies (see Fig. 13), and protect critical structures.[13] As discussed by Sabelis and colleagues[12] and Gellrich and colleagues,[13] positioning guides offer significant advantages, including higher accuracy by reducing implant malpositioning and ensuring correct alignment with the orbital rim and walls. Additionally, they contribute to reduced operating time and lower revision rates by reducing the likelihood of corrective surgeries. Schreurs and colleagues[3] confirmed that positioning guides improve postoperative orbital symmetry, particularly in complex reconstructions involving multiple walls.

Split implant designs (Fig. 27) are a predictable solution for complex multiwall reconstructions. Their interlocking components allow for adaptability in complex trauma and oncologic defects.[25,51,52]

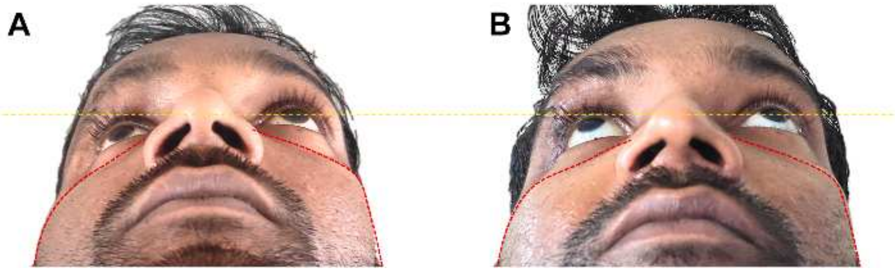


Fig. 16. Basal view of patient with zygomatico-orbital deformity. (*A*) Preoperative image with severe enophthalmos and loss of malar contour on the right side and (*B*) postoperative image improvement in the clinical status. Yellow line indicates pupillary levels, and red line indicates change in malar prominence.

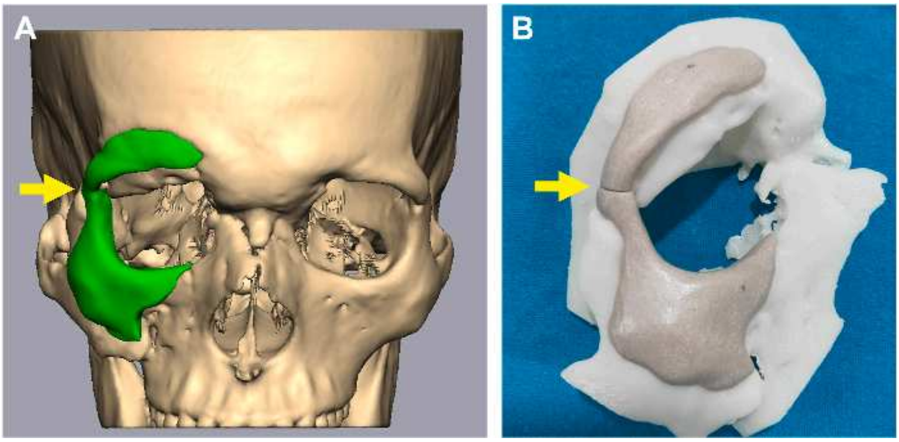


Fig. 17. Personalized PEEK implant for peri-orbital reconstruction with split design to facilitate easy insertion. (*A*) Virtual try-in and (*B*) physical try-in on STL model. Yellow arrow depicting the position of split.

These designs offer several advantages, including enhanced customization for large defects and easier placement in complex cases, as their modular reconstruction approach is particularly beneficial in situations with restricted surgical access or challenging anatomic conditions. However, Schreurs and colleagues[53 54] highlighted the challenges such as increased surgical complexity and higher costs.

Navigational implants (**Fig. 28**) are another innovation that has gained clinical acceptance. These implants incorporate customized grooves or trackers and have also been clinically accepted, enabling intraoperative navigation for more predictable and standardized placement.[13,54] Studies highlight their role in enhancing implant positioning and volume restoration. One of the primary clinical advantages is the ability to provide real-time feedback, which enables surgeons to correct implant positioning before final fixation. Additionally, intraoperative navigation using marked implants significantly reduces intersurgeon variability.[13]

Furthermore, navigation markers enhance success rates in complex cases, particularly in secondary orbital reconstructions with obscured anatomic landmarks. Ensuring precise implant orientation, they help mitigate postsurgical complications such as enophthalmos and diplopia. They are also beneficial in multiwall defects where anatomic guidance is compromised.

Self-centering implants (**Fig. 29**) and *intraorbital spacers* (**Fig. 30**) are still in the early stages of research. Self-centering implants help reduce misalignments intraorbitally, which could be beneficial for complex reconstructions with distorted anatomy.[55] While intraorbital spacers offer a VSP-assisted solution for volume augmentation in revision procedures, these implants require further validation before adoption into clinical practice.[56]

Intraoperative guidance

Intraoperative surgical guidance has significantly contributed to improvements in the accuracy of implant positioning, thereby enhancing clinical

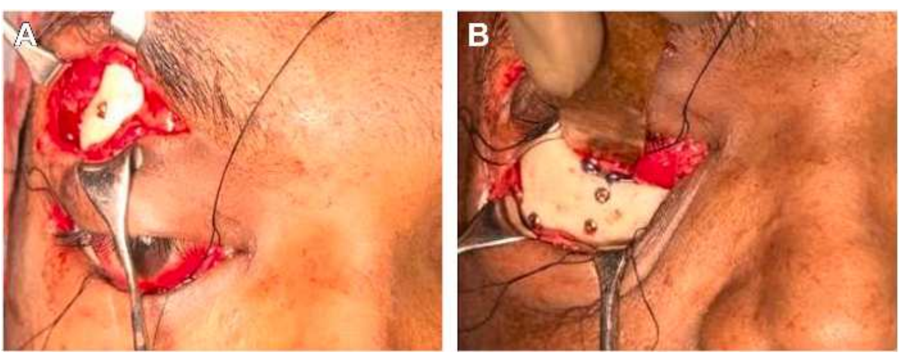


Fig. 18. Intraoperative images of implant inserted and secured with screws. (*A*) Implant for supraorbital rim (SOR) augmentation and (*B*) implant for augmentation of the zygoma and lateral orbital rim.

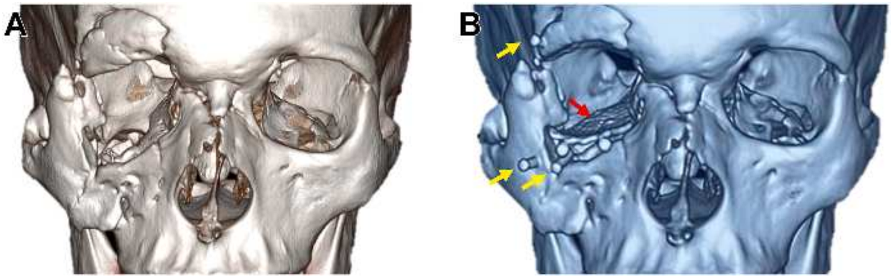


Fig. 19. The 3D CT images demonstrating (*A*) preoperative status of the deformity with gross displacement of the right zygomatic complex and SORs, (*B*) postoperative status with intraorbital reconstruction using a preformed anatomic titanium implant (*red arrow*), which was manually customized on an STL model. Onlay, PEEK implant (invisible on CT) used for SOR and zygoma has been fixed with titanium screws (*yellow arrows*).

outcomes. A review of innovations, categorized by the different levels of clinical validation and integration into surgical practice, is provided later.

Intraoperative imaging utilizes radiological equipment to assist surgeons in real-time monitoring of instrument and implant positioning relative to anatomic structures (**Fig. 31**).[57] This approach can be further enhanced by integrating virtual POI images into intraoperative imaging devices, improving visualization and accuracy. Commonly used technologies include ultrasonography, MRI, CT, and CBCT. Clinically, intraoperative imaging plays a crucial role in verifying implant placement,[53,58] avoiding critical structures,[58] and identifying soft tissue entrapments or malalignment of bony fragments.[59] The benefits of intraoperative imaging include improved precision, prevention of injury to vital structures, and a reduction in revision surgeries.[53,58–61] Additionally, it facilitates comprehensive documentation evaluation of surgical outcomes, contributing to better long-term patient care.[53,58–61] Goh and colleagues[61] highlighted that intraoperative CT enhances surgical accuracy by enabling real-time implant assessment and anatomic restoration, reducing postoperative complications and revision rates. Liu and colleagues[62] further emphasized its role in improving precision, with intraoperative imaging prompting immediate surgical corrections in 27% of cases.

Surgical navigation relies on preoperative CT or MRI data to generate a 3D template, providing real-time guidance during surgery and allowing for the precise tracking of instruments and implants (**Fig. 32**). This technology has multiple clinical applications, including implant positioning to ensure accurate volume and symmetry restoration,[63–65] improving the reduction of peri-orbital fractures in craniofacial trauma cases, and optimizing tumor margin clearance for oncologic reconstruction. Additionally, it facilitates the performance of precise osteotomies for correcting malunited fractures. Navigation can be integrated with VSP to streamline CAS by incorporating the generated plan and implant design into the navigation process. It also aids in endoscopic procedures by identifying critical anatomic structures and facilitating the sequencing and execution of surgical procedures. The key advantages of surgical navigation include improved precision through real-time tracking,[64,65] reduced need for revision surgeries, increased time efficiency, and fewer intraoperative corrections.

Furthermore, it is a valuable teaching tool for surgical trainees, enhancing their understanding and proficiency in executing complex procedures. Saptarishi and colleagues[20] highlighted that virtual

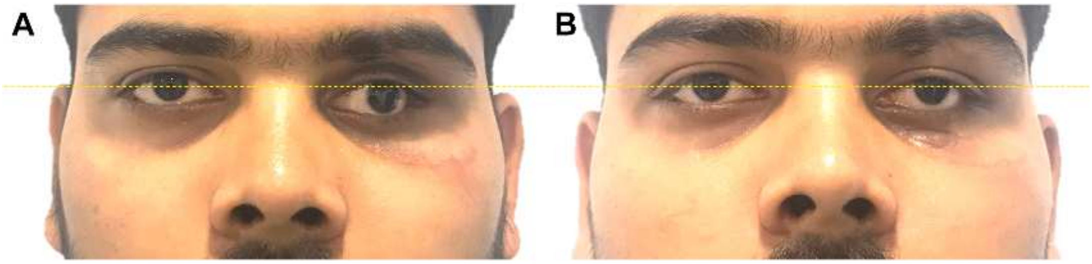


Fig. 20. Patient with persistent post-traumatic orbital deformity: (*A*) preoperative picture demonstrating enophthalmos, hypoglobus, and exotropia of the left side and (*B*) postoperative picture showing correction of the deformity following orbital reconstruction. Yellow line indicates pupillary levels.

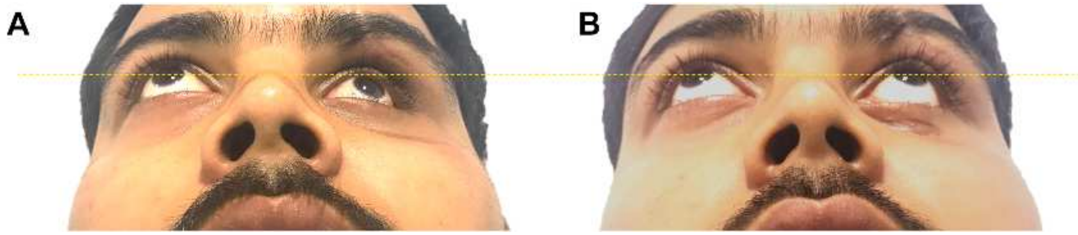


Fig. 21. Basal view of the patient (*A*) demonstrating significant enophthalmos and exotropia of the left eye, and (*B*) postoperative picture showing good clinical correction. Yellow line indicates pupillary levels.

planning with PSIs enhances anatomic accuracy and reduces complications by ensuring precise implant positioning. Gonzalez and colleagues[21] reinforced navigation's role in improving surgical precision, with 75% of studies utilizing it with virtual planning. Verbist and colleagues[65] confirmed through a meta-analysis that navigation significantly improves implant placement accuracy, resulting in better reconstructive outcomes.

ADVANCES IN DIGITAL TECHNOLOGIES FOR ORBITAL RECONSTRUCTION

The last decade has seen numerous advances in diagnostics and treatment planning for orbital reconstruction. However, most are still in experimental stages, requiring validation and widespread acceptance before they can be integrated into routine surgical workflows. The key focus has been on 3 scenarios.

- Augmented Reality and Virtual Reality (AR/VR): Enhancing surgical planning and visualization.
- AI: Role in automated segmentation and predictive modeling.
- Robotic Assistance: Precision in complex cases and emerging applications.

Augmented Reality, Virtual Reality, and Mixed Reality

These technologies provide advanced 3D visualization of complex deformities[66–68] and assist in real-time implant positioning and adjustments during surgery (Fig. 33). They are still in the early stages of clinical implementation. VR is increasingly used for surgical training and planning, but its direct intraoperative application remains unvalidated.[66] AR and mixed reality (MR), which integrate virtual 3D anatomic models into real-time surgical environments, hold significant potential but face challenges such as lapses in accuracy, complex user interfaces, and difficulties in integrating with current imaging systems.[69–71] While preliminary studies suggest these technologies improve surgical precision and training,[67,72] further clinical trials are required for validation.

Artificial Intelligence

AI-driven technology integrated into VSP software helps in automatic segmentation, which enables isolation of the area of interest, identify intraorbital defects and associated native anatomy from procured scans.[18,19] These automated algorithms support real-time surgical adjustments and assist with calculating the precise measurements required for PSIs.[19,73] Predictive modeling is another useful innovation which produces algorithms from ML which analyze existing data for orbital reconstructions and "best fits" for implant sizes, shapes, and locations.[74,75] These models can be particularly helpful in enhancing the design process, especially in areas with complex contour defects and intricate anatomy.

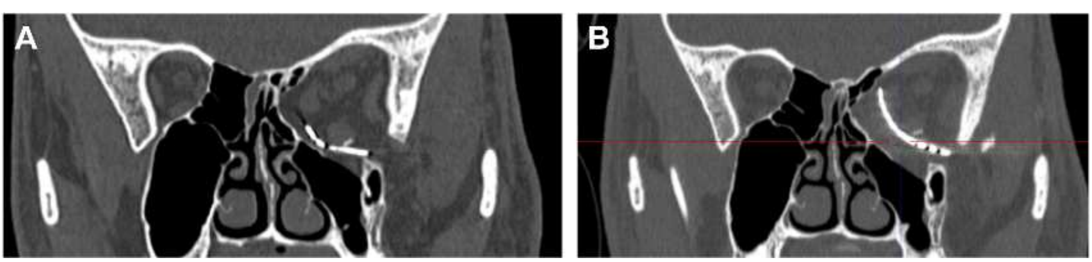


Fig. 22. (*A*) Preoperative coronal CT image demonstrating increase in intraorbital volume and suboptimal correction of floor and medial wall fractures of the left eye. Image also shows implant placed improperly. (*B*) Revised reconstruction of the left orbit using personalized titanium implant demonstrating improved radiological outcomes.

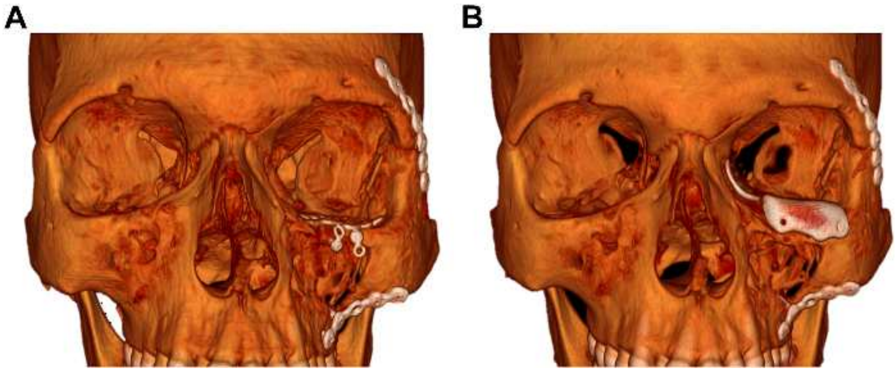


Fig. 23. The 3D CT images of the same patient showing (*A*) orbital reconstruction using preformed titanium mesh and (*B*) revision of orbital reconstruction using personalized titanium implants with augmentation of the infraorbital rim.

Robot-Assisted Orbital Surgery

While robotics is well established in fields like general surgery, its use in craniofacial and orbital procedures is limited due to anatomic complexity and high costs.[76] RAOS claims significant advantages, including tremor reduction, high-definition 3D optics, and enhanced precision in bony resection and implant placement.[16] However, accessibility issues, financial constraints, and the lack of clinical data are significant limitations to its routine clinical use.[76]

CHALLENGES, LIMITATIONS, AND ALTERNATIVE STRATEGIES

Logistical and technological barriers impact the feasibility of patient-specific orbital implants

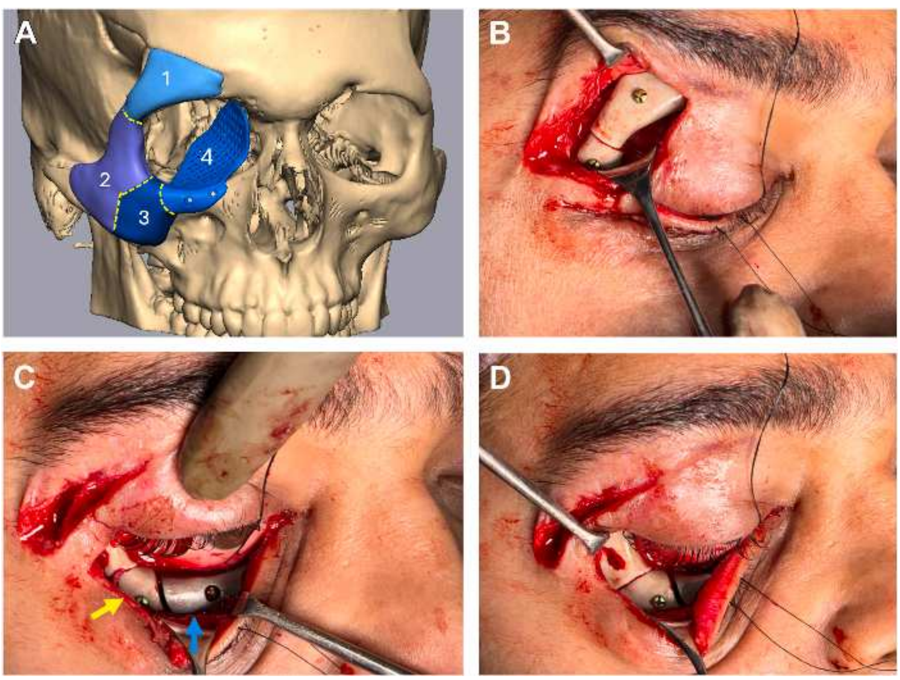


Fig. 24. Reconstruction of a right-sided fronto-orbito-zygomatic deformity using extended split design personalized solution. (*A*) Virtual try-in of implant with 4 parts (SOR and lateral orbital rim with PEEK, infra-orbtial rim and floor with titanium) and 3 junctions, marked in dotted lines, (*B*) intraoperative pictures demonstrating supraorbital implant, (*C*) lateral orbital implants (*yellow arrow*) and infraorbital rim and orbital implant (*blue arrow*), and (*D*) lateral orbital reconstruction. Approaches used were preexisting scar at the SOR, transconjunctival with cantholysis and vestibular.

Fig. 25. Fully customized personalized implant for orbital reconstruction, fabricated using VSP and additive manufacturing.

(POIs) in routine practice, especially in resource-limited settings. This section outlines key challenges in orbital reconstruction and alternative strategies to address them.

High Cost and Limited Access

A major limitation of VSP and 3D printing is cost, including high-resolution imaging, 3D modeling, and implant fabrication. Fully customized implants range from \$2600 to \$3000, making them unfeasible in resource-limited settings.[2,77] Additionally, only 34% of centers have in-house 3D printing, forcing others to rely on outsourcing.[78] *Clinical scenario:* A patient with a complex orbital fracture in a resource-limited hospital may lack access to VSP due to financial constraints or the unavailability of high-resolution imaging. In such cases, preformed implants and traditional planning methods may be used.

Operator Expertise and Training Gaps

The precision of VSP-assisted implants depends on trained technology-trained surgeons and technicians. However, training in CAS, VSP software, and 3D modeling is underutilized.[77,79,80] Inadequate training can lead to implant design, fabrication, or placement errors, increasing complications like implant malposition.[79,80] *Clinical scenario:* A surgeon unfamiliar with VSP and CAS software may design or position an implant that does not fulfill the reconstruction needs, potentially resulting in postoperative complications such as implant malposition or inadequate orbital volume restoration.

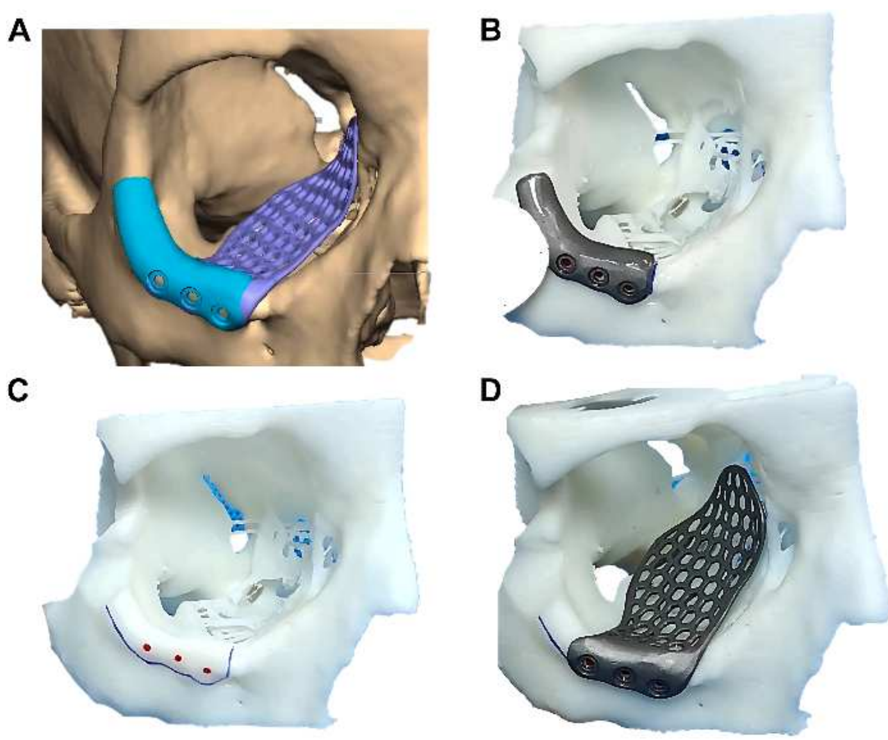


Fig. 26. Positioning guides for orbital reconstruction. (*A*) Virtual try-in of implants (positioning guide in *blue* and orbital implant in *purple*), (*B*) physical try-in of positioning guide, (*C*) guide enabled markings for fixation screws, and (*D*) physical try-in of POI.

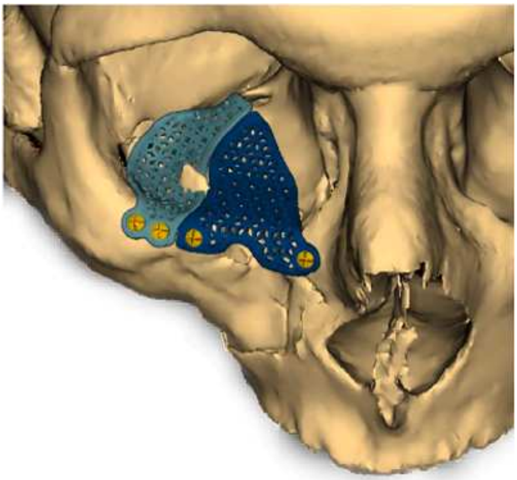


Fig. 27. The 2-piece interlocking patient-specific implant construct. (*Source* Figure 2D - Hajibandeh J, Be A, Lee C. Custom interlocking implants for primary and secondary reconstruction of large orbital floor defects: case series and description of workflow. J Oral Maxillofac Surg 2021;79(12):2539.e1–2539.e10.)

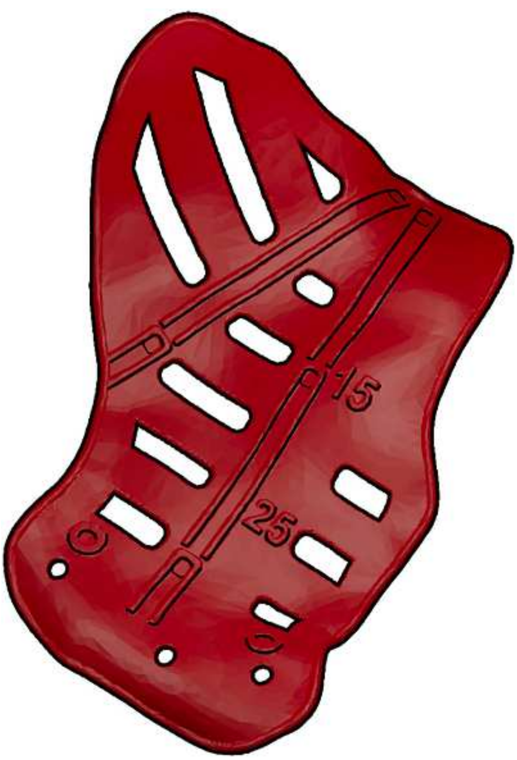


Fig. 28. PSI with navigation markers and rulers. (*Source* Figure 4 - Schreurs R, Wilde F, Schramm A, et al. Intraoperative feedback and quality control in orbital reconstruction: the past, the present, and the future. Atlas Oral Maxillofac Surg Clin North Am 2021;29(1):97–108.)

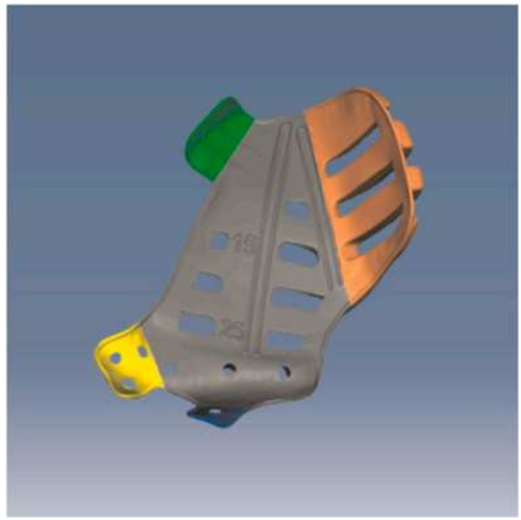


Fig. 29. Self-centering implant design with stabilizers—virtual plan and STL file of a patient-specific titanium implant with possible positions for stabilizers toward the posterior lateral (*green*) or medial (*orange*) wall, and over the infraorbital rim (*yellow* and *blue*). (*Source* Figure 2A - Zeller AN, Neuhaus MT, Gessler N, et al. Self-centering second-generation patient-specific functionalized implants for deep orbital reconstruction. J Stomatol Oral Maxillofac Surg 2021;122(4):372–80.)

Time Constraints in Urgent Cases

While VSP reduces intraoperative time, preoperative planning is time-intensive. Fully customized implants take 4 to 7 days for fabrication, which may not be feasible in emergencies.[2,77] *Clinical scenario:* A patient with inferior rectus muscle entrapment requires early surgery to restore function. Limited time may necessitate the manual customization of stock implants instead (Fig. 34).

Hybrid Workflow with Manual Customization

In resource-limited settings, a hybrid approach—VSP-guided planning with intraoperative manual adjustments—offers a cost-effective alternative. The 3D-printed anatomic models aid in shaping implants prior to surgery, thereby reducing reliance on fully customized implants.[10] These models can be produced within 8 to 10 hours, making them suitable for urgent cases.[49,77] *Clinical scenario:* A patient with a grossly displaced zygomatic complex fracture with a large orbital blow-out required delayed management of his deformity 4 months after the primary injury. This is a good clinical indication that would have benefitted from a VSP-guided surgery and PSIs. However, the patient's limited resources did not allow for POIs. The patient was managed with a

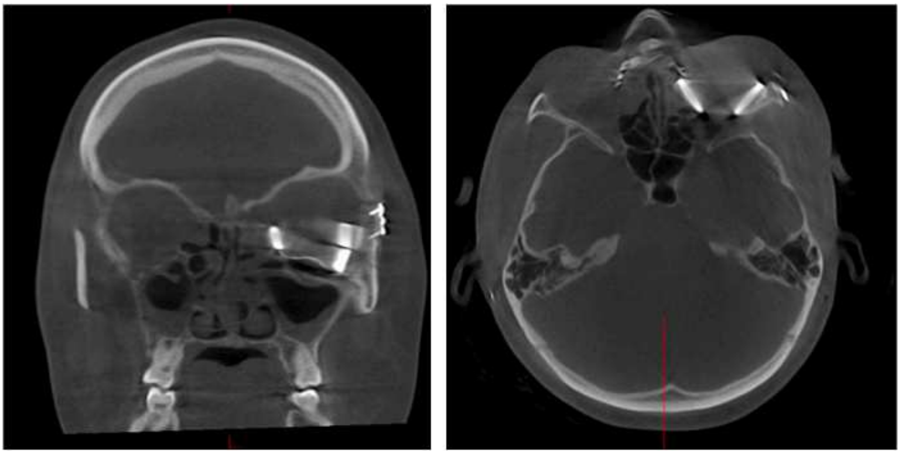


Fig. 30. The CT image (coronal view) reveals the PSI and 3 spacers in the left orbit. The CT image (axial view) shows the exact position of the spacers on the medial and lateral orbital walls. (*Source* Figure 3C&D - Spalthoff S, Dittmann J, Zimmerer R, et al. Intraorbital volume augmentation with patient-specific titanium spacers. J Stomatol Oral Maxillofac Surg 2020;121(2):133–9.)

hybrid workflow, where VSP was utilized to mirror the uninvolved side and generate a physical model for the manual adaptation of fixation plates and orbital mesh, resulting in good surgical outcomes (**Figs. 35** and **36**).

In-House 3-Dimensional Printing

Developing in-house 3D planning and printing improves access to customized implants while reducing costs. It is further discussed in section “Future Directions”.

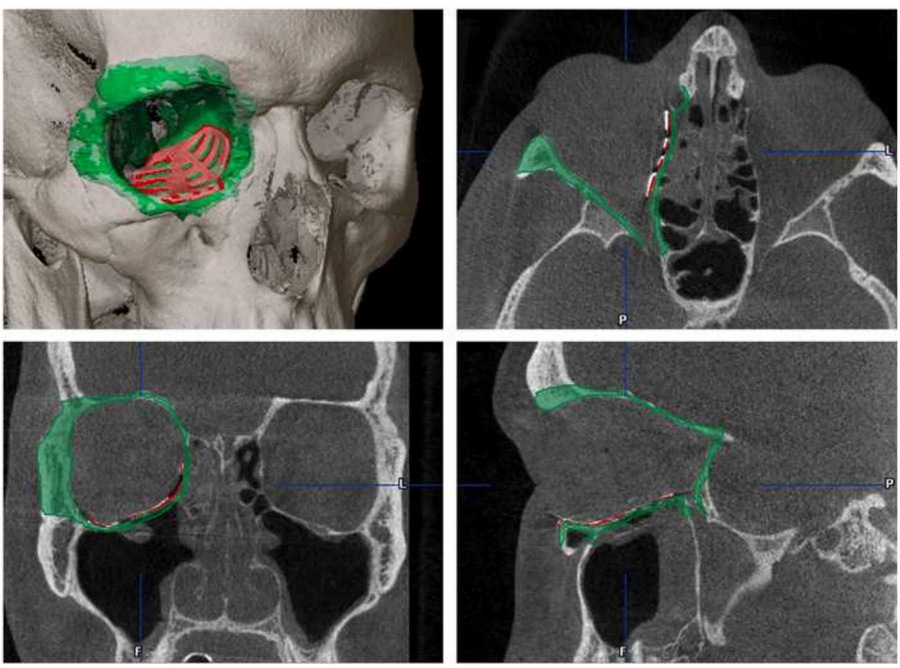


Fig. 31. Multiplanar view of intraoperative 3D imaging with superimposition of virtual planning. The green contour line shows the virtual reconstruction of the orbit and the red contour the planned implant. The image shows good fit of the radio-opaque implant in accordance with virtual planning. (*Source* **Figure 10** - Schreurs R, Wilde F, Schramm A, et al. Intraoperative feedback and quality control in orbital reconstruction: the past, the present, and the future. Atlas Oral Maxillofac Surg Clin North Am 2021;29(1):97–108.)

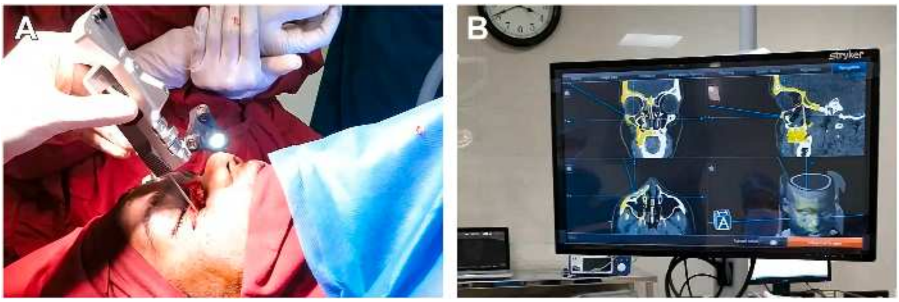


Fig. 32. Real-time surgical navigation for intraoperative guidance. (*A*) Navigation pointer being used on patient and (*B*) corresponding feedback on the screen.

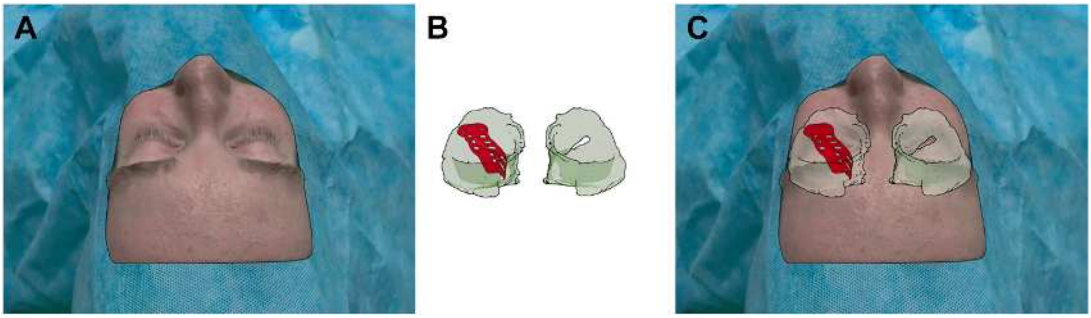


Fig. 33. Principle of augmented reality. The real world, as seen by the surgeon, is seen in (*A*). In (*B*), the virtual layer to be augmented on the real-world view is shown, which corresponds to the planned objects in the VSP. In (*C*), the augmented reality view is shown: the virtual layer is added to the real world for a combined view. (*Source* Figure 16 - Schreurs R, Wilde F, Schramm A, et al. Intraoperative feedback and quality control in orbital reconstruction: the past, the present, and the future. Atlas Oral Maxillofac Surg Clin North Am 2021;29(1):97–108.)

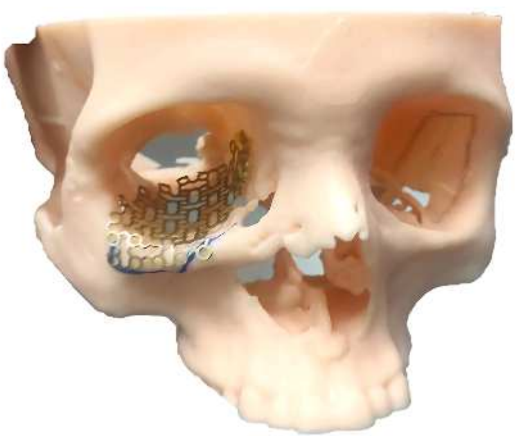


Fig. 34. Manually customized mesh for orbital reconstruction.

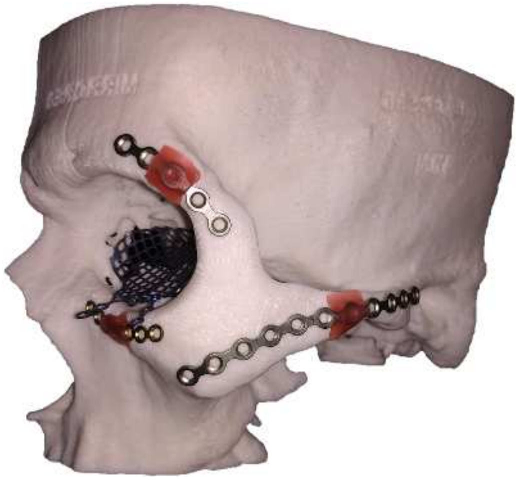


Fig. 35. Utilization of hybrid workflow, where VSP was utilized to mirror the uninvolved side and generate a physical model for the manual adaptation of fixation plates in the fronto-zygomatic, infraorbital and zygomatic arch regions, and an orbital mesh cut and contoured to fit the intraorbital defect.

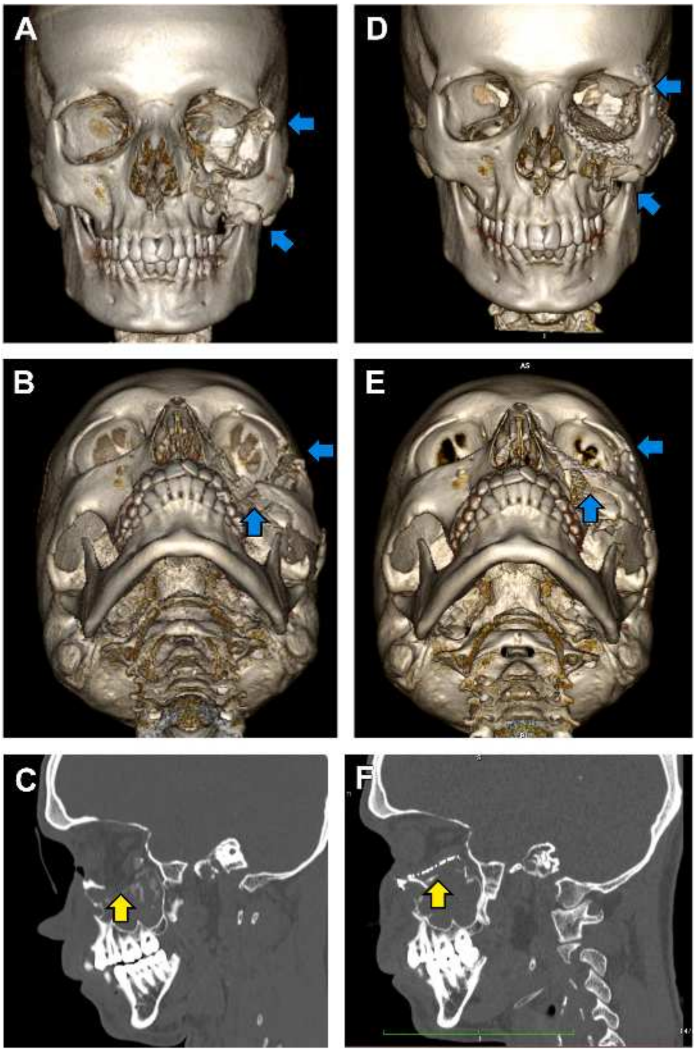


Fig. 36. (*A–C*) Patient with a grossly displaced zygomatic complex fracture (*blue arrows*) with a large orbital blow-out (*yellow arrow*) required delayed management of his deformity, 4 months after injury. (*D–F*) The patient managed successfully using with hybrid workflow demonstrating good postsurgical reduction of the fractures (*blue arrows*) and orbital reconstruction (*yellow arrow*).

Regulatory Concerns

The evolution of POIs has been propelled by advances in 4 critical areas: diagnostics and planning, implant design, biomaterials, and intraoperative guidance techniques. However, these innovations must be segregated into implementable and experimental technology based on their clinical readiness, regulatory approval, widespread adoption into routine practice and evidence base (Table 1). A critical factor in making experimental technology clinically viable is clinical validation, which requires clinical trials to ensure safety and effectiveness before it is widely used. Additionally, standardization and quality control must be established to maintain consistency and compliance with surgical standards.

Another concern is the ethics of AI-driven workflows, where transparency and accountability in automated decision-making are crucial. Regulatory policies must ensure that AI integration enhances clinical decision-making without replacing surgical expertise. Lastly, cost-effectiveness and accessibility are key considerations. For new technologies to be successfully integrated into health care systems, they must demonstrate improved patient outcomes while remaining affordable and scalable.

FUTURE DIRECTIONS

The evolution of materials and technology plays a crucial role in advancing in orbital reconstruction. Innovations in biomaterials, AI-driven processes,

Table 1
An overview of different advances in the field of personalized orbital implants, focusing on their validation and acceptance

Advances	Implemented in Clinical Practice	Experimental Technology
Diagnostics and planning	3D printing Digital subtraction Automated segmentation (AI)	Augmented reality Virtual reality Predictive modeling
Implant design	Positioning guides Split implant designs Navigational implants	Self-centering implants Intraorbital spacers
Materials and fabrication	Additive manufacturing Hybrid manufacturing Surface polishing Surface coating	Bioactive coated implants Biofabrication
Intraoperative guidance	Intraoperative imaging Real-time surgical navigation	Virtual reality, augmented reality, and mixed reality Robotics

and point-of-care 3D printing offer promising solutions for improved clinical outcomes.

Advances in Bioengineered Implants and Resorbable Materials

In addition to mainstream biomaterials, experimental materials are gaining traction. Bioactive materials, such as bioactive glass, promote bone integration and healing by releasing calcium ions, though their long-term clinical efficacy requires further study.[16,81,82] Biodegradable polymers, such as poly-lactic acid (PLA) and poly-glycolic acid (PGA), provide short-term structural support in pediatric cases, eliminating the need for implant removal. However, their resorption rates and mechanical stability require validation before widespread adoption.[16,81,82] Similarly, resorbable 3D-printable polymers, such as poly-D,L-lactic acid with β-Tricalcium-phosphate (PLDLLA/β-TCP) and poly-trimethylene carbonate loaded with 40 wt % of hydroxyapatite (Osteo PTMC), have shown promise in bone regeneration but remain in the research phase.[16,81,82] Advancements in porous hydroxyapatite infused with magnesium, fabricated using tri-ply periodic surface technology, demonstrate superior tissue integration and antimicrobial properties, though long-term outcomes are yet to be documented.[31]

Nanotechnology-enhanced materials may improve bone bonding and reduce infection risks, such as bioactive hydroxyapatite-coated titanium and plasma-sprayed silver-coated titanium implants. However, further clinical evidence is necessary before they can be widely integrated into clinical practice.[16,81,82] Other experimental innovations, such as aptamer coatings (eg, Apt19s), are being explored to enhance osteogenesis and vascularization by binding to mesenchymal stem cells.[43,83,84] The emergence of biofabrication represents a shift toward regenerative approaches in defect reconstruction, utilizing bioactive materials and tissue scaffolds.[16]

Integration of Artificial Intelligence-Driven Automated Workflows

Alongside material advancements, AI-driven automated workflows are gaining importance. AI can analyze thousands of cases to generate predictive models for optimizing implant design.[74,75] Beyond implant customization, AI plays a role in workflow optimization, assisting in diagnosis, surgical planning, intraoperative guidance, and postsurgical outcome assessment through ML.

Point-of-Care 3-Dimensional Printing for Resource-Limited Environments

Another development is the establishment of point-of-care 3D printing in health care environments. Onsite printing enables faster implant fabrication within hospitals, improving time efficiency and reducing costs. However, its implementation requires strategic cost reduction in equipment and training to ensure sustainability.[78,85] The ability to produce PSIs on demand may significantly improve accessibility to advanced surgical solutions in lower-resource settings.

SUMMARY

Personalized implants have demonstrated superior outcomes in terms of esthetics and function. However, long-term studies are needed to thoroughly evaluate their durability and the potential for long-term complications. Factors determining the indications for using POIs in clinical practice[1,2] should be carefully considered, as the current literature shows that POIs yield clinical outcomes similar to those of conventional methods for primary orbital reconstruction. The future of POIs lies in the continued integration of biomaterials, nanotechnology, and tissue engineering to further enhance the functionality of these implants. It is imperative that advances in technology be balanced with cost-effectiveness, the availability of trained personnel and facilities, and clinical validation.

CLINICS CARE POINTS

- Personalized implants are not universally applicable to all orbital reconstructions, but they offer superior functional and esthetic results when used appropriately, based on specific indications.
- The integration of virtual surgical planning workflows, which include automated segmentation, implant design, virtual try-ins, and advanced 3-dimensional printing, significantly improves reconstruction outcomes.
- Real-time image guidance during surgery enhances accuracy, reduces operating time, and minimizes the need for corrective procedures.
- Technological advancements must be balanced with real-world needs to ensure that innovations are both accessible and affordable for widespread use.

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DISCLOSURE

The authors wish to declare no conflicts of interest or financial interests. All patient photographs used in the article have been obtained with the patients' consent. The authors declare the use of artificial intelligence-assisted tools for language editing and grammar.

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