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OPTIMIZATION OF SURGICAL TREATMENT OF ISOLATED ORBITAL FLOOR FRACTURES IN CHILDREN USING THREE-DIMENSIONAL MODELING AND PATIENT-SPECIFIC TITANIUM IMPLANTS

Bekmuradova Charos Yusufovna
Master's` degree of the Department of Pediatric Maxillofacial Surgery,
Tashkent State Medical University, Uzbekistan.
e-mail: charos.bekmuradova@mail.ru
Yuldashev Abduazim Abduvaliyevich
Doctor of Medical Sciences, Professor of the Department of Pediatric Maxillofacial Surgery,
Tashkent State Medical University, Uzbekistan
E-mail: tdsi2016@mail.ru

Annotatsiya. Ushbu maqola bolalarda ko'z kosasi pastki devorining chegaralangan sinishlarini jarrohlik davolash bo'yicha zamonaviy adabiyotlarning tahliliy sharhi hisoblanadi. Sinishlarning epidemiologiyasi, klinik ko'rinishi, diagnostika usullari, jarrohlik kirish yo'llari va implantatsion materiallar, shuningdek 3D-modellashtirish va 3D-chop etish texnologiyalarini qo'llash masalalari ko'rib chiqilgan. Muallif tomonidan 18 nafar bemorlarda olib borilgan klinik tadqiqot natijalari tahlil qilingan.

Kalit so'zlar: ko'z kosasi sinishi, bolalar, jarrohlik davolash, 3D-modellashtirish, 3D-chop etish, titan setka, individual implant, jarrohlik yondashuvi, RealGuide, Creality.

Аннотация. Данная статья представляет собой аналитический обзор современной литературы по проблеме хирургического лечения изолированных переломов нижней стенки орбиты у детей. Рассмотрены вопросы эпидемиологии, клинической картины, методов диагностики, хирургических доступов и имплантационных материалов, а также применения технологий 3D-моделирования и 3D-печати. Проанализированы результаты собственного клинического исследования 18 пациентов.

Ключевые слова: перелом орбиты, дети, хирургическое лечение, 3D-моделирование, 3D-печать, титановая сетка, индивидуальный имплант, хирургический доступ, RealGuide, Creality.

Abstract. This article presents an analytical review of current literature on the surgical treatment of isolated orbital floor fractures in children. The epidemiology, clinical presentation, diagnostic methods, surgical approaches, implantation materials, and the application of 3D modeling and 3D printing technologies are examined. The results of the authors' own clinical study of 18 patients are analyzed.

Keywords: orbital fracture, children, surgical treatment, 3D modeling, 3D printing, titanium mesh, individual implant, surgical approach, RealGuide, Creality.

1. INTRODUCTION

Isolated fractures of the orbital floor represent one of the most clinically significant injuries of the middle facial zone. According to Koenen L. and Waseem M. (2023), orbital floor fractures account for 4 to 16% of all facial skeleton fractures in isolation, and up to 30–55% when combined with zygomatic complex and nasoorbitoethmoidal injuries [12]. In the structure of middle facial zone injuries, orbital floor fractures rank second only to nasal bone fractures, constituting 21 to 37%

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of cases [12].

In children, this pathology has a number of fundamental differences from adult trauma. Wei L.A. and Durairaj V.D. (2011) emphasized that children are not simply small adults: the craniofacial skeleton of a child undergoes significant changes in size, shape, and proportion during growth, which requires selecting a treatment strategy that accounts for both the nature of the trauma and the stage of development [20]. The same authors demonstrated that in children under 7 years of age, orbital fractures more commonly involve the roof rather than the floor; however, as the maxillary sinuses pneumatize with age, the vulnerability of the orbital floor increases significantly after the age of 7 [20].

Of particular clinical significance in the pediatric population are so-called trapdoor fractures. Jordan D.R. et al. (1998) were the first to comprehensively describe this type of injury in 20 patients aged 4 to 18 years, coining the term "white-eyed blowout" to describe the characteristic absence of visible external trauma signs despite severe soft tissue entrapment [11]. Neinstein R.M. et al. (2012) demonstrated that trapdoor fractures constitute 27 to 93% of all pediatric orbital floor fractures, and that up to 33% of affected children are initially hospitalized with suspected traumatic brain injury, as nausea, vomiting, and bradycardia caused by the oculocardiac reflex mimic intracranial hypertension [15].

Despite the broad coverage of this topic in the literature, there remains no single universally accepted treatment protocol. Burnstine M.A. (2002) noted that no prospective randomized clinical trials on the treatment of isolated orbital floor fractures have been conducted to date, yet indications for surgery are sufficiently well-defined [3]. The emergence of 3D modeling and printing technologies has opened fundamentally new possibilities for individualizing surgical treatment, and a growing body of evidence supports their integration into routine clinical practice [1, 8].

The aim of this review is to analyze current approaches to the surgical treatment of isolated orbital floor fractures in children, with particular emphasis on the application of 3D modeling technologies and patient-specific implants, and to present the authors' own clinical experience.

2. LITERATURE REVIEW

2.1. Epidemiology and mechanisms of injury

The mechanisms of orbital floor fractures have been studied since the mid-twentieth century. Converse J.M. and Smith B. (1956) were the first to systematically describe the "blow-out" mechanism and proposed the corresponding term to designate fractures of the orbital floor without involvement of the infraorbital rim [5]. Smith B. and Regan W.F. (1957) subsequently proposed the "hydraulic" theory of fracture formation: a direct blow to the globe causes a sharp rise in intraorbital pressure, leading to rupture of the thinnest orbital wall [5]. An alternative "mechanical" (wave deformation) theory was proposed by Le Fort R. as early as 1901, attributing the fracture to wave deformations transmitted from the infraorbital rim [5].

Waterhouse N. et al. (1999) conducted an experimental study on 47 fresh cadaveric orbits and demonstrated for the first time that both mechanisms are capable of producing blow-out fractures, though the resulting fractures differ fundamentally in size, location, and clinical significance [19]. In children, the specific mechanical properties of immature bone — its high elasticity — determine the predominance of trapdoor fractures, a pattern that was thoroughly documented by Gerbino G. et al. (2010) in a study of 30 pediatric patients [10].

Wei L.A. and Durairaj V.D. (2011) provided a detailed analysis of age-related anatomical factors: among patients under 18 years of age, sports and recreational injuries account for approximately 67% of orbital fracture cases, while in adults, assault is the leading cause at 45% [20]. This epidemiological pattern has been confirmed in numerous subsequent studies [12, 15].

2.2. Diagnosis of orbital floor fractures

Computed tomography has become the gold standard in the diagnosis of orbital floor fractures. Burnstine M.A. (2002) recommended thin-section CT (1.0–1.5 mm) in the axial plane with coronal reconstruction as the optimal diagnostic protocol [3]. Schouman T. et al. (2008) in a study of 33 pediatric patients demonstrated that CT significantly underestimates soft tissue entrapment

compared with intraoperative findings, and that entrapment and incarceration of orbital contents are more frequently overlooked by radiologists specifically in the pediatric group [17]. This observation underscores the importance of careful clinical examination even when CT findings appear unremarkable.

Three-dimensional CT reconstruction has particular significance for preoperative planning. Gosau M. et al. (2023) showed that a protocol combining axial images, multiplanar reconstruction, and 3D models provides maximum diagnostic value compared with each method used independently [9]. The forced duction test (FDT) remains an indispensable clinical tool: Nguyen M. et al. (2025) demonstrated that a positive FDT combined with diplopia within 30° of primary gaze and CT-confirmed entrapment constitutes a firm indication for surgery [16].

2.3. Indications and timing of surgical treatment

The question of indications and optimal timing for surgery remains one of the most actively debated issues in the literature. Burnstine M.A. (2002) formulated the indications for urgent surgery — within 48 hours — as follows: a persistent oculocardiac reflex, a “white-eyed” blowout fracture, and early enophthalmos or hypophthalmos [3]. Surgery within two weeks is recommended for symptomatic diplopia with a positive FDT and CT-confirmed soft tissue entrapment, or for large orbital floor defects exceeding 50% of its area.

Lin K.Y. et al. (2022) in a retrospective study demonstrated that early surgical intervention — within 7 days of injury — is associated with significantly faster resolution of diplopia and restoration of extraocular muscle function compared with delayed surgery [13]. Koenen L. and Waseem M. (2023) emphasized that in children, muscle entrapment in the fracture zone constitutes a surgical emergency: if the muscle remains entrapped, ischemia develops, potentially leading to permanent diplopia [12].

Lighthall J.G. (2022) in a comprehensive review of controversies in orbital floor fracture management noted that more than two-thirds of American plastic surgeons perform the operation within the first 14 days, while half of British surgeons operate within 6–10 days of injury [14]. Zhang J. et al. (2022) confirmed in a systematic review and meta-analysis that early intervention is associated with better functional outcomes [21].

2.4. Surgical approaches

The choice of surgical approach to the orbital floor determines both the extent of intraoperative exposure and the pattern of postoperative complications. Four main approaches are described in the literature: subciliary, subtarsal, transconjunctival, and transantral. Appling W.D. et al. (1993) were among the first to systematically compare the transconjunctival and subciliary approaches, concluding that the transconjunctival approach is associated with a lower rate of lower eyelid complications [2].

Al-Moraissi E.A. et al. (2017) in a systematic review and meta-analysis confirmed that the subciliary approach is associated with a significantly higher incidence of ectropion and scleral show compared with the transconjunctival approach, while the latter more frequently results in entropion [1]. The overall rate of postoperative complications was 25.5%, with diplopia (11.4%), corneal damage (7.1%), proptosis (5.4%), and enophthalmos (4.9%) as the most common [1]. The transconjunctival approach is considered particularly advantageous in young patients and children due to the absence of a visible cutaneous scar.

The infraorbital (subcutaneous) approach, while technically simplest, carries a risk of conspicuous scarring and persistent lymphedema when the incision is displaced toward the temple. The intraoral approach provides access without any skin incisions and is indicated for fractures combined with zygomatic complex injuries. In complex cases involving extensive fractures, a combination of approaches may be required to ensure adequate exposure and fixation of all bony fragments.

2.5. Implantation materials

The choice of implant material for orbital floor reconstruction remains one of the most debated topics in reconstructive surgery. Gear A.J. et al. (2009) conducted a comprehensive review

identifying the following material categories: autologous bone grafts, allogenic materials, and alloplastic materials including titanium, porous polyethylene, silicone, and resorbable plates [8].

Ellis E. and Tan Y. (2003) in a comparative study of 71 orbits demonstrated that titanium mesh provides significantly better reconstruction accuracy compared with autologous cranial bone grafts, with a lower incidence of postoperative enophthalmos [7]. Mackenzie with colleagues found that titanium reconstruction of 51 orbits resulted in only one case of enophthalmos with no infectious complications over 9 months of follow-up [8].

Regarding resorbable materials, Burnstine M.A. (2002) noted that their application is justified exclusively for small defects up to 2×2 cm: the scar tissue formed after implant resorption is insufficient to provide adequate support for the globe in cases of extensive defects, leading to recurrence of enophthalmos [3]. Gear A.J. et al. (2009) reported the highest complication rate among all materials for silicone implants — 17.5% — compared with 2.4% for titanium and 5.4% for porous polyethylene [8].

2.6. 3D modeling and patient-specific implants

The application of 3D modeling and printing technologies in orbital surgery has undergone rapid development over the past decade. Stopa L. et al. (2024) in a case report demonstrated that a 3D-printed model based on preoperative CT data allowed thorough surgical preparation and potentially shortened operative duration [18]. The authors concluded that 3D printing is a valuable method that enables more thorough preparation for surgery.

Sigron G.R. et al. (2021) in a study of 34 patients demonstrated that reconstruction with the support of 3D-printed anatomical models provides significantly better functional and cosmetic outcomes compared with standard surgery without model assistance [18]. The mirror-imaging technique — virtual reconstruction of the unaffected orbit with subsequent overlay analysis — was shown to be highly reliable and reproducible.

Raisian S. et al. (2017) in a randomized clinical trial compared the use of titanium mesh pre-bent on a 3D-printed model with manual intraoperative bending. The results demonstrated that the 3D model-assisted group achieved significantly better outcomes regarding enophthalmos correction and overall complication rates [16]. The authors concluded that preoperative adaptation of the implant on an individual model should be considered the method of choice when available.

Duchesne B. et al. (2025) in a systematic review conducted according to PRISMA 2020 guidelines analyzed 9 studies published between 2019 and 2024 and concluded that pre-bent patient-specific implants shaped on 3D models demonstrate superior accuracy, lower operative times, and better cost efficiency compared with intraoperative mesh shaping [6]. Custom-designed PSIs offer high precision and clinical benefit but require longer production time. The authors emphasized that virtual surgical planning, 3D printing, and intraoperative navigation significantly improve surgical planning and outcomes in orbital floor reconstruction [6].

Michelutti L. et al. (2024) in a systematic review of 3D printing applications for orbital disorders noted that 3D printing technology has several distinct applications in orbital surgery: direct printing of implants, fabrication of models for preoperative implant adaptation, creation of surgical templates, and surgical education [14]. The materials used include titanium, photopolymerized plastic, porous polyethylene, PMMA, polylactic acid filament, and polyamide.

Singh A.K. et al. (2023) in a systematic review and meta-analysis specifically addressing the question of whether pre-shaping of orbital implants on patient-specific 3D-printed models is advantageous compared with conventional free-hand shaping provided strong evidence in favor of the 3D model-assisted approach, demonstrating improved volumetric accuracy and reduced operative time [17].

For pediatric patients specifically, Kim W.S. et al. (2020) proposed a theoretical model and personalized 3D printing-assisted surgical solution for pediatric orbital trapdoor fractures, demonstrating that this approach enables accurate and efficient surgical planning while accounting for the unique anatomical characteristics of the immature facial skeleton [11].

3. RESEARCH METHODOLOGY

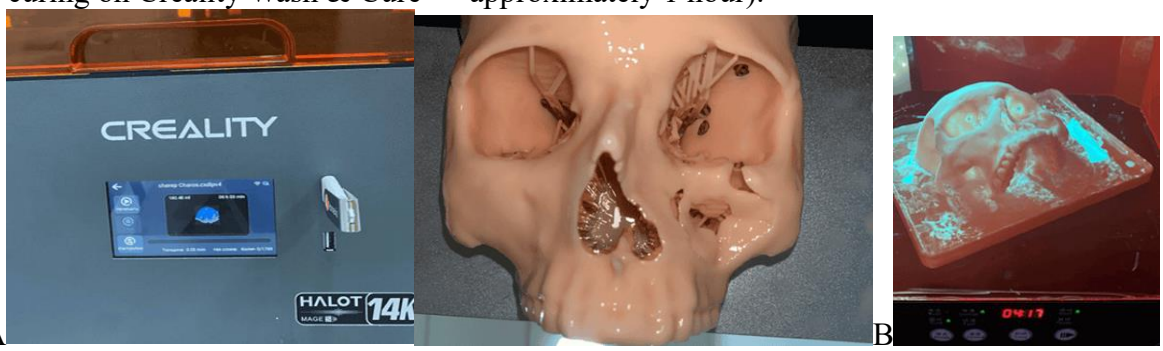
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The present study analyzed the results of surgical treatment of 18 male patients aged 6 to 17 years with isolated orbital floor fractures who received treatment at the Department of Pediatric Maxillofacial Surgery of the Dental Clinic of Tashkent State Medical University between 2024 and 2026. The study was prospective and observational in design.

Inclusion criteria: age 6–17 years; characteristic clinical presentation including enophthalmos, binocular diplopia, and hypoesthesia in the infraorbital nerve distribution zone; CT-confirmed fracture with displacement; and informed consent from legal representatives.

Exclusion criteria: fracture without displacement and without reduction of orbital volume; absence of enophthalmos, binocular diplopia, and hypoesthesia; active inflammatory processes; refusal of legal representatives to participate.

Examination protocol: All patients underwent clinical examination, mandatory ophthalmologist consultation including optical coherence tomography (OCT) on the Optovue Solix platform, and multislice CT (MSCT) with 3D reconstruction. Preoperative planning was performed in RealGuide software (3DIEMME, Italy) with subsequent fabrication of anatomical orbital prototypes using the Creality photopolymer 3D printer (print time approximately 6 hours; cleaning and UV curing on Creality Wash & Cure — approximately 1 hour).



A B C

Fig. 1 A) *Importing the STL file of the anatomical orbital model into the Creality slicing software and configuring the printing parameters;* ***B)*** *A life-size anatomical 3D model of the patient's midface, fabricated via photopolymer resin printing on a Creality system;* ***C)*** *The final post-processing stage of the anatomical model in the Creality Wash & Cure station: isopropyl alcohol (IPA) rinsing followed by UV curing to ensure complete material polymerization.*

Surgical treatment: All interventions were performed under endotracheal anesthesia. The choice of surgical approach and implant type was individualized based on fracture characteristics, defect volume, and patient age. In two cases with extensive non-standard defects, individually adapted titanium mesh plates were fabricated based on 3D-printed models; in remaining cases, standard titanium mesh and linear mini-plates were used. Postoperative management included antibiotic therapy, anti-edema treatment, general supportive therapy, and analgesics. Dynamic follow-up was conducted for 2 years.

4. ANALYSIS AND RESULTS

Over the study period (January 2024 – April 2026), 18 patients with isolated orbital floor fractures were treated, constituting 31.6% of all maxillofacial fractures during this period. All patients were male. The age distribution showed predominance of the 15–17 year group (33.3%), followed by 11–14 years (16.7%) and 6–10 years (11.1%). The predominance of older adolescents is consistent with the data of Wei L.A. and Durairaj V.D. (2011), who associated the increased vulnerability of the orbital floor in puberty with progressive pneumatization of the maxillary sinuses [20].

The predominant causes of injury were domestic trauma sustained during conflicts (55.6%) and sports injuries including sparring (44.4%). This distribution is consistent with the epidemiological data reported by Koenen L. and Waseem M. (2023) for the pediatric-adolescent male population [12].

At admission, the following clinical symptoms were identified: diplopia in 9 patients (50.0%), enophthalmos in 8 (44.4%), infraorbital nerve hypoesthesia in 8 (44.4%), hyposphagma in 5 (27.8%), chemosis of the bulbar conjunctiva in 3 (16.7%), and limitation of ocular motility in 2 (11.1%). The two patients with ocular motility limitation — indicating probable inferior rectus muscle entrapment — underwent urgent surgery within 48 hours, consistent with the recommendation of Burnstine M.A. (2002) [3] and Koenen L. and Waseem M. (2023) [12].

Fifteen patients (83.3%) were admitted in the acute period (within 14 days of injury); 3 patients (16.7%) presented in the delayed period, with fibrous adhesion formation already identified in the fracture zone at the time of admission. This finding is consistent with the data reported by Lighthall J.G. (2022), who noted that delayed diagnosis of orbital fractures is a significant clinical problem associated with superficial examination at the primary care level [14].

The infraorbital approach was used most frequently (14 patients, 77.8%), followed by the subciliary approach (3 patients, 16.7%), transconjunctival approach (1 patient, 5.5%), and combined infraorbital-intraoral approach (3 patients, 16.7%). The predominance of the infraorbital approach is explained by its technical accessibility and adequate exposure of the infraorbital rim and orbital floor in the majority of cases.

A total of 40 implants were used in 18 patients. Linear titanium mini-plates were most widely used (31 implants, 77.5%). Titanium mesh plates were used in 6 cases: 4 standard and 2 individually adapted using 3D-printed models. Z-shaped and L-shaped mini-plates were used exclusively via the intraoral approach (1 and 2 cases respectively).

The application of the 3D modeling protocol demonstrated clear practical advantages. In cases where standard implants were used, the surgeon was required to perform multiple iterations of intraoperative mesh modification — removal, reshaping, reinsertion — each increasing operative time and soft tissue trauma. In the two cases where individually pre-adapted titanium mesh plates were used, the surgeon entered the operating room with a fully prepared implant precisely conforming to the orbital defect anatomy of the specific patient, enabling accurate placement at the first attempt. This observation is consistent with the findings of Raisian S. et al. (2017) [16] and Duchesne B. et al. (2025) [6], who demonstrated that pre-bent PSIs shaped on 3D models significantly reduce operative time and improve reconstruction accuracy.

No postoperative complications were identified in any of the 18 patients. All patients achieved full restoration of orbital anatomy and resolution of functional disorders, confirmed at follow-up over 2 years. This outcome is consistent with the results of Sigron G.R. et al. (2021), who reported excellent functional and cosmetic outcomes with 3D model-assisted reconstruction [18], and with the data of the large retrospective study by Gosau M. et al. (2016), which identified complication rates of 25.5% with traditional approaches [9]. The zero complication rate in the present series likely reflects the benefits of systematic preoperative planning, individualized approach selection, and 3D-assisted implant preparation.

5. CONCLUSION AND RECOMMENDATIONS

The analysis of current literature and the authors' own clinical experience allows the following conclusions to be drawn:

1. Isolated orbital floor fractures in children constitute a clinically significant and underdiagnosed injury. The predominance of trapdoor fracture type in the pediatric population, as demonstrated by Jordan D.R. et al. (1998) and Neinstein R.M. et al. (2012), requires heightened clinical vigilance and prompt ophthalmological assessment even in the absence of pronounced external trauma signs [11, 15].

2. Multislice CT with 3D reconstruction, as established by Burnstine M.A. (2002) and Gosau M. et al. (2023), is the diagnostic method of choice. Its integration with preoperative virtual planning software — such as RealGuide — creates a complete diagnostic-planning chain that enables individualized surgical decision-making [3, 9].

3. Early surgical intervention — within 7 days for acute fractures and within 48 hours for cases with muscle entrapment — provides significantly better functional outcomes, as confirmed

by Lin K.Y. et al. (2022) and Koenen L. and Waseem M. (2023) [12, 13].

4. The choice of surgical approach must be individualized. The transconjunctival approach is preferred in young patients due to the absence of visible scarring, as supported by Al-Moraissi E.A. et al. (2017) [1]. The intraoral approach provides access without skin incisions and is indicated for combined fractures.

5. Titanium mesh — both standard and individually adapted — represents the optimal implant material for significant orbital floor defects in children, providing mechanical stability, biocompatibility, and reliable CT visualization, as demonstrated by Ellis E. and Tan Y. (2003) and Gear A.J. et al. (2009) [7, 8].

6. The application of 3D modeling and printing technologies significantly improves the accuracy of orbital reconstruction, reduces operative time, and enables the creation of patient-specific implants. Duchesne B. et al. (2025), Raisian S. et al. (2017), and Sigron G.R. et al. (2021) have all demonstrated the superiority of 3D model-assisted approaches over conventional intraoperative implant shaping [6, 16, 18]. The authors' own clinical series of 18 patients confirms these findings: the application of 3D-printed anatomical prototypes fabricated using RealGuide software and the Creality photopolymer printer enabled precise preoperative implant adaptation and contributed to the achievement of excellent outcomes with zero complication rate.

Recommendations for clinical practice:

— Integration of MSCT with 3D reconstruction into the standard diagnostic protocol for all children with suspected orbital trauma;

— Mandatory ophthalmological consultation including OCT to document baseline visual function prior to surgery;

— Application of RealGuide-based virtual planning and 3D-printed anatomical prototypes for preoperative implant adaptation, particularly in cases of extensive or non-standard defects;

— Use of individually pre-adapted titanium mesh in complex cases to eliminate intraoperative implant modification and reduce operative time;

— Implementation of the described protocol in specialized pediatric maxillofacial surgery departments.

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