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Long-term surgical outcomes of strabismus surgery in craniosynostosis patients

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Abstract

Background

To evaluate the long-term outcomes of strabismus surgery in patients with craniosynostosis, a population known for complex ocular motility disorders.

Methods

A retrospective review (2000–2024) was conducted at a tertiary referral center. Among 49 identified patients, 31 underwent corrective surgery. Surgical success was defined as postoperative alignment within 10 prism diopters (PD) horizontally and 5 PD vertically.

Results

In the overall cohort, amblyopia prevalence was 34.7%, clinically significant astigmatism (> 1.00 D) was present in 30.6% of eyes, and astigmatic anisometropia (> 1.00 D) was found in 40.8% of patients. The primary surgical group (n = 31) was dominated by cases with inferior oblique overaction (IOOA) and V-pattern (n = 28). Among 19 patients with unilateral IOOA (Group A), short-term success was 89.5%, declining to 68.4% at long-term follow-up, with four patients requiring multiple reoperations. For nine patients with bilateral IOOA (Group B), the success rate was 77.7% short-term and 66.6% long-term, with two reoperations. Two distinct patterns of long-term instability were observed: a progressive exotropic drift and the development of new-onset contralateral IOOA.

Conclusion

Strabismus surgery in craniosynostosis is challenging and associated with lower long-term stability than routine cases. Short-term success does not guarantee a durable outcome. Patients and parents must be counseled about the significant risks of late exoshift, contralateral IOOA, and the potential need for multiple procedures, emphasizing the necessity for postoperative surveillance.

Introduction

Craniosynostosis is the premature fusion of one or more cranial sutures, resulting in an abnormal shape of the skull.[1–3] It occurs in approximately 1 in 2,500 live births, with about 15% of cases being syndromic, associated with conditions such as Crouzon, Apert, Pfeiffer, and Sathre-Chotzen syndromes.[1–6] In non-syndromic craniosynostosis, typically only one suture is involved, with sagittal craniosynostosis being more common than metopic, coronal, and lambdoid synostosis.[1–3] Common ophthalmic issues associated with craniosynostosis include refractive errors, strabismus, amblyopia, papilledema, optic atrophy, exophthalmos, and exposure keratopathy.[1–19] Early ophthalmic evaluations and regular follow-ups are crucial for the timely detection and management of these complications.[1–3,11–13]

Strabismus is a common eye condition associated with craniosynostosis, with a prevalence ranging from 20% to 90%, notably higher in cases of unicoronal synostosis and syndromic conditions.[1–3,11–13] Surgical planning and timing of strabismus surgery can be quite challenging in these patients due to the complex nature of ocular alignment. V-pattern ocular deviation combined with true or pseudo- inferior oblique muscle overaction (IOOA) is a common type of ocular motility problem in these patients.[5–10] The current study aims to investigate the long-term surgical outcomes of strabismus correction in craniosynostosis cases performed in our strabismus referral center.

Materials and Methods

Study Design and Participants:

A retrospective, interventional case series was conducted. The medical records of all patients with the diagnosis of craniosynostosis who were referred to our tertiary strabismus clinic between 2000 and 2024 were reviewed. The study adhered to the tenets of the Declaration of Helsinki and was approved by the Institutional Review Board and Local Ethics Committee of our medical school.

Data Collection:

Ophthalmic data from all preoperative and postoperative visits included: best-corrected visual acuity (BCVA) using Central, Steady, Maintained (CSM notation) for preverbal children and Snellen charts for cooperative patients ≥ 3 years old, cycloplegic refractive error (assessed 30 minutes after instillation of two drops of cyclopentolate 1%), and comprehensive anterior and posterior segment findings. Amblyopia was diagnosed in the presence of a BCVA difference of ≥ 2 lines between eyes on a Snellen chart, with no other ocular pathology to explain the deficit. In cases of bilateral reduced vision, bilateral amblyopia was defined as a BCVA of < 20/40 in each eye, in the absence of another cause. Clinically significant astigmatism was defined as a cylindrical refractive error of > 1.00 diopter (D) on cycloplegic refraction. Clinically significant anisometropia was defined as an interocular difference of > 1.00 D in spherical equivalent or an interocular difference of > 1.00 D in cylindrical power.

Surgical Details and Outcome Definitions:

Ocular deviation was quantified preoperatively and at all postoperative visits using the alternate prism cover test for both distance (6m) and near (1/3m), measured in prism diopters (PD). All measurements were performed by the same senior strabismologist to ensure consistency. Surgical success was defined as postoperative alignment within ≤ 10 PD of orthotropia horizontally and ≤ 5 PD vertically at the short-term and long-term follow-up. Alignments exceeding these thresholds were classified as surgical failure. Reoperation rates and the stability of alignment between the short-term (1-month) and long-term (≥ 6 months) visits were discussed.

Statistical Analysis:

Demographic and clinical data are summarized using counts and percentages for categorical variables. For continuous variables (e.g., age, prism diopter deviation, spherical equivalent), the Shapiro-Wilk test was used to assess normality. Normally distributed data are presented as mean ± standard deviation, and non-normally distributed data as median and interquartile range [IQR] or full range.

Results

Patient Demographics and Clinical Overview

A total of 49 patients with craniosynostosis were referred to our clinic over the 25-year period. All patients had previously undergone cranial vault remodeling surgery prior to ophthalmic referral. The cohort comprised 26 females and 23 males. The median age at the first ophthalmic evaluation at our center was 5 years (range, 0.5 to 39 years old). At the initial visit, amblyopia was diagnosed in 17 patients (34.7%). This was unilateral in 14 patients and bilateral in three patients. Clinically significant astigmatism was present in 30 of 98 eyes (30.6%), of whom 24 had with-the-rule astigmatism, two had against-the-rule astigmatism, and four had oblique astigmatism. Significant astigmatic anisometropia was found in 20 patients (40.8%), and significant anisometropia of the spherical equivalent was found in 9 cases (18.3%). Optic nerve abnormalities were noted in several patients. Five patients exhibited temporal pallor of the optic discs. One patient presented with papilledema at the initial visit and was urgently referred back to neurosurgery for further management, which included shunt placement. One patient had a bilateral myelinated nerve fiber layer.

Prevalence and Spectrum of Strabismus

All 49 patients underwent a comprehensive strabismus evaluation. Six patients maintained orthotropia at all visits, while the remaining 43 patients (87.7%) exhibited ocular misalignment. Of these, 31 cases underwent corrective strabismus surgery and constitute the primary intervention group for outcome analysis. The patterns of misalignment within the surgical cohort were diverse, though dominated by features of craniosynostosis-related dysmorphology. Over-elevation in adduction (true or pseudo-IOOA) was a predominant finding, present in 28 individuals of the operated group (Figs. 1–7). Only three patients presented with sensory exotropia (XT) of 35, 40, and 60 PD, without significant IOOA, and were operated on through horizontal rectus surgery. Two cases achieved orthotropia and remained stable until two years after the surgery, and the other patient developed recurrence of XT (exoshift over time) through 18 months after surgical correction, but declined further surgery. Detailed analysis focused on the 28 patients exhibiting IOOA. Within this subgroup, IOOA was unilateral in 19 patients (Figs. 1–3, 6, 7) and bilateral in 9 cases (Figs. 4, 5).

Surgical Management and Outcomes

All surgeries were performed by a single senior strabismus consultant (M.F) using the following management strategy. For horizontal deviation in the primary position:

- One rectus muscle surgery for horizontal deviations up to 15 PD
- Two rectus muscle surgery for deviations of 15–50 PD
- Three rectus muscle surgery for deviations exceeding 50 PD
- Half tendon horizontal rectus muscle transposition for V-pattern (upgaze-downgaze difference) up to 30 PD
- Full tendon horizontal rectus muscle transposition for V-pattern over 30 PD

Various inferior oblique (IO) weakening procedures were performed:

- IO disinsertion or small myectomy for grade 2+
- IO myectomy for grade 3+
- IO large myectomy, anterior transposition, or two vertical muscle surgery for grade 4+

Group A: Patients with Unilateral IOOA (n = 19)

This subgroup consisted of 13 female and six male patients, with overaction on the right side in 13 cases and on the left side in six cases. Nine patients presented with simultaneous V-pattern horizontal deviation, which was esotropia (ET) in five cases and exotropia (XT) in four cases. Short-term surgical success was achieved in 17 of 19 patients at the 1-month visit. At the long-term follow-up, the success rate declined from 89.5% to 63.2%, and four patients underwent additional operations. We observed two patterns of late postoperative changes:

- Development of contralateral IOOA: Five patients developed new-onset, clinically significant IOOA and hypertropia in the contralateral eye. One case was diagnosed with anti-elevation syndrome (Fig. 6) and declined further surgery. Four patients developed head tilts to the opposite side, indicating that the pattern of hypertropia in the contralateral eye was likely a manifestation of masked bilateral superior oblique palsy. All of these cases underwent contralateral IO weakening and finally achieved orthotropia. Details are described in Table 1.
- Progressive exoshift: Five patients developed consecutive or increasing XT over the period of annual visits postoperatively (Fig. 7). Details of surgical correction are described in Table 1.

Table 1
Short-term and long-term outcomes of strabismus surgery in Group A patients

N	Sex	Age	IOOA grade (vertical deviation in PP)	Horizontal deviation	Surgery	Short-term ocular deviation	Long-term follow-up	Ocular deviation
1	M	2	L 2+, L HT 10 PD	no	L IO small myectomy	Orthotropia	6 months	Orthotropia
2*	F	5	L 2+, L HT 8 PD	no	L IO disinsertion	Orthotropia	2 years	Orthotropia
3	M	2	R 2+, R HT 8 PD	no	R IO disinsertion	Orthotropia	2 years	Orthotropia
4	F	2	L 4+, L HT 25 PD	no	L IO myectomy + R IR recess 4mm	Orthotropia	1 year	R HT 15 PD, R IOOA 3+
5	F	6	R 2+, R HT 8 PD	no	R IO disinsertion	Orthotropia	1 year	Orthotropia
6	F	11	R 3+, R HT 15 PD	no	R IO myectomy	Orthotropia	1 year	Orthotropia
7	M	5	R 3+, R HT 15 PD	no	R IO myectomy	R HT 3 PD	4 years	R HT 3 PD, XT 18 PD
8	F	3.5	R 3+, R HT 15 PD	no	R IO myectomy	Orthotropia	2 years	L HT 10 PD, L IOOA 2+
9	M	10	R 3+, R HT 18 PD	no	R IO myectomy	R HT 4 PD	6 months	R HT 4 PD
10	F	39	R 2+, R HT 10 PD	no	R IO small myectomy	Orthotropia	1 year	Orthotropia
11*	F	4	L 4+, L HT 30 PD	V pattern ET 15 PD	R MR recess 5.5mm + L IO anterior transposition + R IR recess 4mm	R HT 5 PD + ET 8 PD	12 years	R HT 5 PD, ET 10 PD
12	F	3	R 3+, R HT 15 PD	V pattern ET 30 PD	B MR recess 4.5mm + R IO myectomy	Orthotropia	7 years	L HT 8 PD, L IOOA 2+, XT 25 PD
13*	M	2	R 3+, R HT 18	V pattern ET 30 PD	B MR recess 4.5mm + R IO	L HT 10 PD, L IOOA	1 year	L HT 10 PD, L IOOA

N	Sex	Age	IOOA grade (vertical deviation in PP)	Horizontal deviation	Surgery	Short-term ocular deviation	Long-term follow-up	Ocular deviation
			PD		myectomy	2+, ET 8 PD		2+, ET 8 PD
14	M	5	R 4+, R HT 20 PD	V pattern ET 40 PD	B MR recess 4.5mm + R IO anterior transposition	Orthotropia	2 years	Orthotropia
15	F	18	R 3+, R HT 15 PD	V pattern XT 25 PD	B LR recess 6mm + R IO myectomy	R HT 4 PD, XT 5 PD	3 years	Orthotropia
16*	F	5	R 4+, R HT 18 PD	V pattern XT 35 PD	L LR recess 10mm + LMR resect 3mm + R IO anterior transposition	XT 6 PD	2 years	XT 12 PD
17*	F	14	L 4+, L HT 25 PD	V pattern ET 60 PD	B MR recess 7mm + L IO anterior transposition	ET 10 PD	6 months	ET 10 PD
18	F	5	R 2+, R HT 10 PD	V pattern XT 18 PD	L LR recess 10mm + R IO small myectomy	XT 6 PD	6 months	XT 6 PD
19	F	5	L 3+, L HT 15 PD	V pattern XT 20 PD	L LR recess 11mm + L IO myectomy	XT 14 PD	6 months	XT 20 PD

N	Sex	Age	IOOA grade (vertical deviation in PP)	Horizontal deviation	Surgery	Short-term ocular deviation	Long-term follow-up	Ocular deviation

N: patient number, M: male, F: female, R: right, L: left, XT: exotropia, ET: esotropia, PD: prism diopter, LR: lateral rectus, MR: medial rectus, B: bilateral, IOOA: inferior oblique muscle over-action, PP: primary position, OU: oculus uterque, IO: inferior oblique, mm: millimeters, HT: hypertropia

***** Figs. 1 and 2 **show preoperative and postoperative photographs of patients 16 and 17, respectively.** Figure 3 **shows the preoperative photograph of patient 2.** Figures 6 and 7 **show postoperative photographs of patients 11 and 13, respectively, included in this table.**

Cases 4 & 8: Both patients developed hypertropia and IOOA in the fellow eye within 12-18 months. Each underwent a successful contralateral inferior oblique myectomy, achieving stable orthotropia that was maintained at four and eight years of follow-up, respectively.

Cases 7, 16, and 19: These patients developed an exoshift in the long-term follow-up but declined further intervention.

Case 11: This patient developed mild hypotropia after IO anterior transposition combined with contralateral IR recession. The left eye's limitation of elevation was mostly notable during abduction, consistent with the diagnosis of anti-elevation syndrome. She refused further surgery due to acceptable alignment in the primary position. (Figure 6)

Case 12: This patient developed a consecutive XT, hypertropia, and contralateral IOOA in the long-term. A second surgery of MR advancement combined with IO disinsertion in the left eye successfully restored orthotropia and corrected head tilt for 1 year after the second surgery.

Case 13: This patient developed hypertropia and IOOA in the non-operated eye, along with residual ET, in the short-term. A second surgery addressed the contralateral IOOA and residual ET. However, within one year, a consecutive XT developed, necessitating two additional medial rectus advancement procedures. An exotropic drift persisted at the final follow-up. (Figure 7)

Group B: Patients with Bilateral IOOA (n = 9)

This subgroup consisted of four female and five male patients. Preoperatively, IOOA was symmetric in six patients and asymmetric in the other three cases, producing primary position hypertropia of 5–10 PD in the eye with greater IOOA. Eight patients had simultaneous horizontal deviation: four with V-pattern XT and four with V-pattern ET. Successful alignment was achieved in seven patients (77.8%) at the 1-month postoperative visit and maintained in five (55.5%) patients through long-term visits. Two cases required further surgeries due to exoshift and persistent hypertropia. Details are described in Table 2.

Table 2
Short-term and long-term outcomes of strabismus surgery in Group B patients

N	Sex	Age	IOOA grade (vertical deviation in PP)	Horizontal deviation	Surgery	Short-term ocular deviation	Long-term follow-up	Ocular deviation
20	M	6	R 4+, L 4+	V pattern XT 15 PD	L LR recess 8mm + IO large myectomy OU	orthotropia	1 year	orthotropia
21	F	25	R 3+, L 3+	V pattern XT 70 PD	B LR recess 12mm + R MR resect 8mm + IO myectomy OU	XT 20 PD	1 year	XT 30 PD
22	F	4.5	R 3+, L 3+	V pattern XT 20 PD	B LR recess 5mm + IO myectomy OU	XT 5 PD	7 years	XT 30 PD
23	M	23	R 3+, L 3+	V pattern XT 60 PD	B LR recess 12mm + R MR resect 4mm + IO myectomy OU	orthotropia	1 year	orthotropia
24	M	3	R 4+, L 2+ (R HT 10 PD)	V pattern ET 35 PD	B MR recess 5.5mm + R IO large myectomy, L IO disinsertion	R HT 10 PD	1 year	R HT 10 PD
25	M	5	R 2+, L 4+ (L HT 5 PD)	no	R IO disinsertion + L IO large myectomy	orthotropia	2 years	orthotropia
26	M	3	R 2+, L 4+ (L HT 8 PD)	V pattern ET 10 PD	R IO disinsertion + L IO anterior transposition + R MR recess 5mm	orthotropia	5 years	orthotropia
27	F	7	R 3+, L 3+	V pattern ET 30 PD	B MR recess 4.5mm + IO myectomy OU	R HT 10 PD	2 years	R HT 18 PD, R IOOA 3+
28	F	5	R 4+, L 4+	V pattern ET 20 PD	B MR recess 3.5mm + IO large myectomy OU	ET 5 PD	3 years	ET 5 PD

N	Sex	Age	IOOA grade (vertical deviation in PP)	Horizontal deviation	Surgery	Short-term ocular deviation	Long-term follow-up	Ocular deviation

N: patient number, M: male, F: female, R: right, L: left, XT: exotropia, ET: esotropia, PD: prism diopter, LR: lateral rectus, MR: medial rectus, B: bilateral, IOOA: inferior oblique muscle over-action, PP: primary position, OU: oculus uterque, IO: inferior oblique, mm: millimeters, HT: hypertropia

Figures 4 and 5 show preoperative photographs of patients 21 and 27, respectively, included in this table.

Case 21: This patient developed an exoshift through 1 year follow-up and is scheduled for left medial rectus muscle resection. (Figure 4)

Case 22: This patient, initially successful, developed a progressive exoshift, necessitating reoperation 7.5 years after the initial surgery. Although a second procedure (bilateral lateral rectus re-recession and left medial rectus resection) restored orthotropia for one year, a recurrent XT of 35 PD was present at the final visit 7 years post-reoperation.

Case 24: This patient with preoperative asymmetric IOOA and a 10 PD vertical deviation maintained an identical 10 PD vertical postoperatively in the absence of horizontal deviation. The outcome was deemed acceptable to the patient, and no further surgery was planned.

Case 27: Despite symmetric IO myectomies, this patient developed a new, progressive vertical imbalance in the primary position within 2 years. A secondary IO exploration with extended myectomy was performed, but a residual 10 PD right eye hypertropia persisted and progressed. The patient declined further vertical rectus muscle surgery. (Figure 5)

Discussion

Patients with craniosynostosis are at high risk for a spectrum of ophthalmic morbidities, including significant refractive errors—notably anisometropia and astigmatism—amblyopia, and complex forms of strabismus.[1–6, 11–13] In our series, the prevalence of amblyopia (34.7%) and clinically significant astigmatism (30.6%) aligns with prior reports, underscoring the critical need for meticulous, early, and ongoing ophthalmologic surveillance in this population to facilitate timely refractive correction and amblyopia therapy.[1–3, 11–13]

Strabismus, which has a reported prevalence of 20–90% in cases of craniosynostosis, poses a significant management challenge.[1–6, 11–13] In our study, over 87% of the cases exhibited ocular malalignment. However, it is important to note that this data was collected from a tertiary strabismus referral center. Consistent with the literature, V-pattern deviation associated with true or pseudo IOOA observed in unicoronal craniosynostosis and syndromic cases [5–10] was the predominant motility disorder in our surgical cohort (over 90% of the operated cases). The pathophysiology of this vertico-torsional imbalance is multifactorial, arising from the characteristic craniofacial dysmorphology. Key contributors include retro-positioning of the trochlea secondary to superior orbital rim retro-positioning, orbital shallowing, and iatrogenic trochlear change after fronto-orbital advancement.[4–6] Orbital apex bony changes and excyclorotation of the rectus muscle paths (lateral rectus inferior displacement and superior rectus lateral

displacement) may cause gaze-dependent alterations in active and passive pulling forces and result in see-saw V-pattern deviation. In syndromic cases, midfacial retrusion can impact muscle-globe contact, and abnormalities in extraocular muscles, such as fibrosis, dysgenesis, abnormal insertion, atrophy, or hypertrophy, may lead to various forms of ocular motility dysfunction.[1–6]

Our long-term outcomes in 31 operated patients reveal that while initial surgical success is often achievable, the alignment demonstrates a concerning propensity for late instability since the success rate declined from 87% to 61%. Two distinct, delayed postoperative patterns emerged as significant challenges. First, the phenomenon of contralateral IOOA, hypertropia, and opposite head tilt observed in our series (five patients in Group A) is particularly instructive. Postoperative hypotropia in the eye that had undergone IO weakening surgery has multiple differential diagnoses, including overcorrection of surgery, masked bilateral superior oblique palsy, and anti-elevation syndrome.[20,21] Four cases in our series showed a reversal of head tilt and had no significant limitation of elevation on abduction as seen in anti-elevation syndrome. Therefore, the most likely scenario was masked bilateral superior oblique palsy that responded well to contralateral IO myectomy in all cases. It implies that what appears preoperatively as a unilateral process may, in fact, represent an asymmetric bilateral condition. The initial surgery, by correcting the more overt overaction, may unmask a pre-existing subclinical deficit in the contralateral superior oblique muscle.[20] This highlights the necessity of informing patients and families about the potential for subsequent surgeries and supports a more guarded long-term prognosis even after an initially perfect result. Secondly, the progressive exoshift was noted in several of our patients requiring reoperation years after the initial procedure. We posit that this exoshift is attributable to two concurrent factors: a lack of robust binocular fusion due to the high prevalence of amblyopia and anisometropia in this cohort, and the altered vector forces of the horizontal rectus muscles resulting from the characteristic orbital dysmorphology of craniosynostosis, including globe extorsion and midface retrusion. The sensory deficit may fail to provide the necessary feedback to maintain alignment, while the persistent anatomical factors create a biomechanical environment predisposing to lateral deviation. Interestingly, a similar pattern of late exoshift in other complex syndromic strabismus cases, such as Moebius syndrome were previously reported, suggesting this may be a broader challenge in managing strabismus associated with craniofacial and neurological anomalies. [22]

Our findings support earlier reports that surgical success rates in craniosynostosis-related strabismus are lower than those in routine cases.[5,7,14,16–19] Critically, our long-term data demonstrate that short-term surgical success does not guarantee long-term stability, underscoring the necessity of annual follow-up for these patients. Regarding surgical technique, we recommend standard rectus muscle surgery to address the horizontal deviation in the primary position, keeping in mind the potential risk of postoperative exotropic drift. For the characteristic V-pattern and overelevation in adduction, optimal management remains debated. Parks reported short-term success of 83% with IO myectomy in six craniosynostosis cases[19], similar to our initial outcomes. However, IO weakening alone may be insufficient in complex cases. Elhusseiny and colleagues noted that SO tuck yields only a modest effect when the SO tendon is extremely lax or anatomically aberrant.[5] Some authors advocate for rectus muscle transposition over IO weakening in cases with severely extorted recti; Velez and colleagues achieved successful alignment in a

craniosynostosis child who had failed IO weakening surgery by superiorly transposing the lateral recti and nasally transposing the superior recti.[17] In our series, we performed horizontal rectus muscle transposition and aggressive IO weakening simultaneously in selected cases, achieving better alignment when IO surgery alone might not suffice. We advocate for aggressive IO weakening procedures, specifically large myectomy, which aligns with the recommendation by Coats et al. that favorable results are obtained only with IO myectomy or denervation-extirpation.[7] However, it must be emphasized that IO surgery is less predictable in this population than in routine IOOA cases.[7] Consequently, patients and families must be informed about the distinct risks, including the development of contralateral IOOA and the high likelihood of requiring additional procedures.

To the best of our knowledge, the current study provides long-term outcomes of strabismus surgery in the largest cohort of craniosynostosis cases to date. However, it has several important limitations due to its retrospective design. Detailed data regarding the specific neurosurgical procedures performed, comprehensive systemic findings in syndromic cases, and systematic orbital imaging were not uniformly available. Consequently, we could not analyze potential outcome differences between syndromic and non-syndromic subgroups or quantitatively assess anatomical variables such as globe extorsion. Furthermore, operative notes did not consistently document the intraoperative anatomy of the extraocular muscles, including anomalies like hypoplasia or insertion displacement, which may influence surgical planning and outcomes. These limitations highlight the need for prospective studies with standardized preoperative imaging and systematic surgical documentation to better elucidate the structure-function relationships in this complex population.

Conclusion

Strabismus management in patients with craniosynostosis presents distinct surgical challenges. While standard rectus muscle procedures are recommended for horizontal deviations, surgeons must anticipate a higher rate of long-term exotropic drift and lower stability compared to the general strabismus population, necessitating indefinite follow-up. For the characteristic V-pattern and over-elevation in adduction, aggressive IO weakening techniques combined with rectus muscle transposition can be effective. Crucially, preoperative counseling must address the substantial risk of late-onset contralateral IOOA and the potential need for reoperation, even following initially successful alignment. A comprehensive, long-term management strategy is therefore essential for optimizing outcomes in this complex cohort.

Abbreviations

N
patient number
M
male
F

female
R
right
L
left
B
bilateral
OU
oculus uterque
BCVA
best corrected visual acuity
D
diopter
PD
prism diopter
XT
exotropia
ET
esotropia
HT
hypertropia
PP
primary position
LR
lateral rectus
MR
medial rectus
IO
inferior oblique
IOOA
inferior oblique muscle over-action
mm
millimeters
IQR
interquartile range

Declarations

Ethics approval and consent to participate:

The current study was supported by Shiraz University of Medical Sciences, Shiraz, Iran (Grant No. 34553). The study was approved by the Ethics Committee of Shiraz University of Medical Sciences. The research adhered to the ethical guidelines stipulated in the Declaration of Helsinki. Before undergoing surgery and enrollment in the study, Written informed consent was obtained from all participants. In cases of minors, which refer to patients younger than 16 years, written informed consent was obtained from the parents or their legal guardians.

Consent for publication:

Written informed consent for publication of the patients' clinical and surgical details and any identifying images was obtained from all participants. For participants under 18 years of age, written informed consent was obtained from their parents or legal guardians. Copies of the signed consent forms are available for review by the Editor-in-Chief on request.

Availability of data and materials:

The datasets analyzed during the current study are not publicly available due to confidentiality, but they can be obtained from the corresponding author upon reasonable request.

Competing interests:

The authors state that they have no competing interests, and none has a financial interest in the subject matter of this paper.

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Authors' contributions:

- Majid Farvardin: Conceptualization, methodology, data curation, formal analysis, writing the manuscript (original draft)
- Maryam Shahmohammadi: Data curation, formal analysis, funding acquisition, writing the manuscript (original draft)
- Hajar Farvardin: Conceptualization, methodology, data interpretation, funding acquisition supervision, writing the manuscript (original draft, review and editing)

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Figures



Figure 1

Preoperative (upper) and 1-year postoperative (lower) deviograms of patient 16

Note the exotropia, hypertropia, and 4+ IOOA in the right eye that were corrected after unilateral recess-resect surgery combined with IO anterior transposition in the right eye.

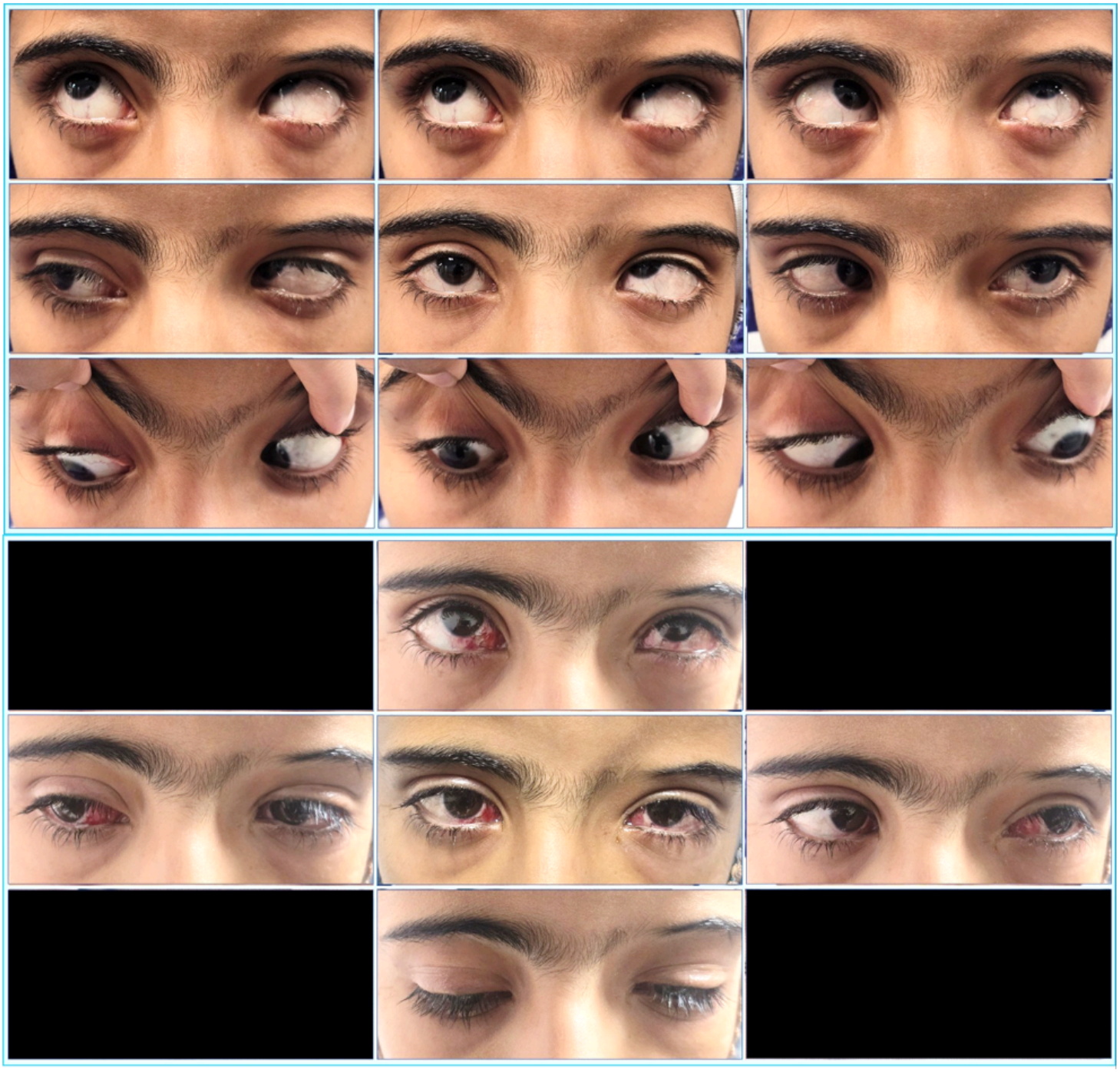


Figure 2

Preoperative (upper) and 1-week postoperative (lower) deviograms of patient 17

Note the esotropia, hypertropia, and 4+ IOOA in the left eye that were resolved after bilateral MR recession and IO anterior transposition in the left eye.

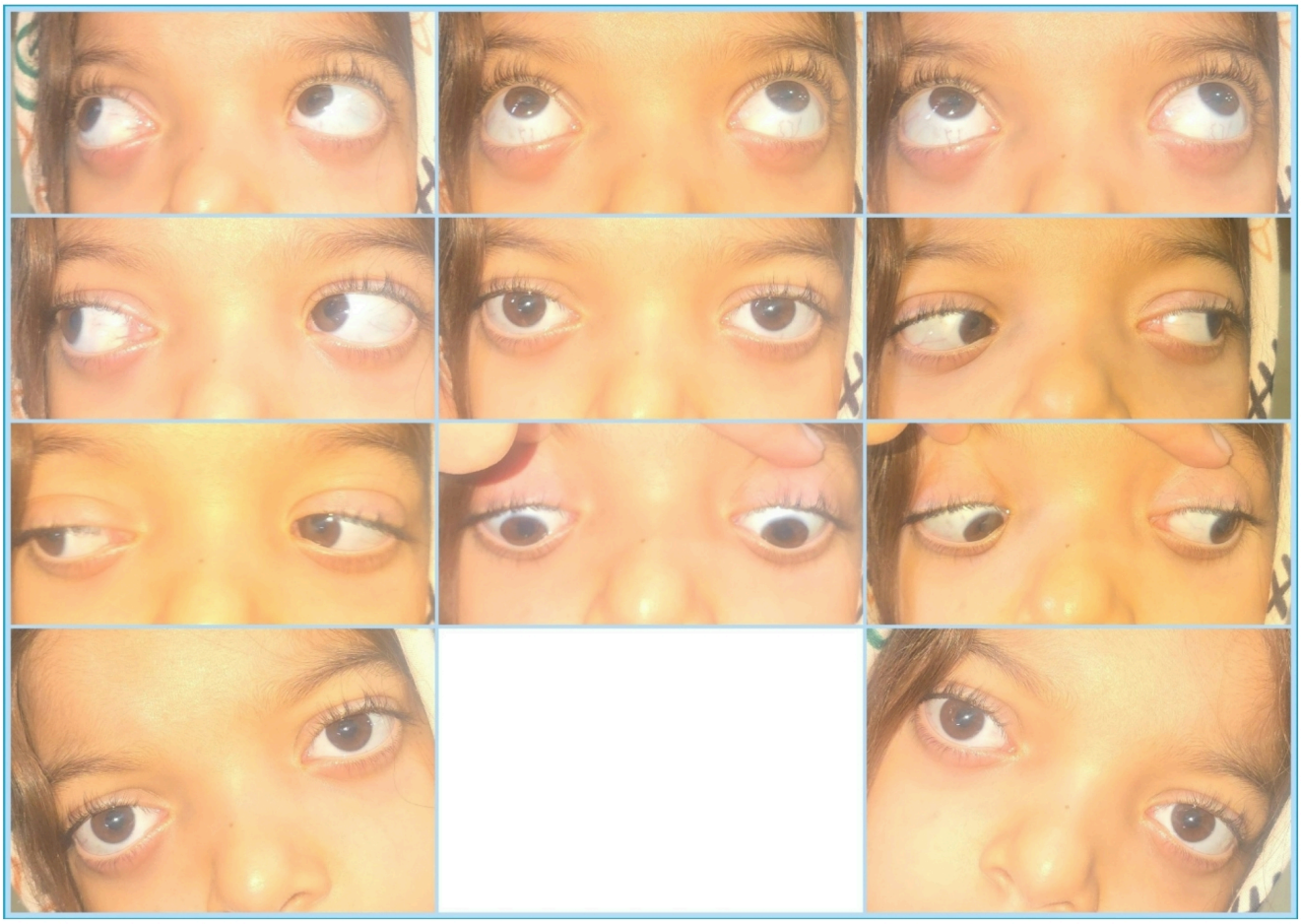


Figure 3

Preoperative deviogram of patient 2

Mild hypertropia in the left eye, increasing with gaze to the right and tilt to the left, accompanied by IOOA 2+ in the left eye



Figure 4

Preoperative deviogram of patient 21

Large-angle exotropia, accompanied by 3+ IOOA in both eyes

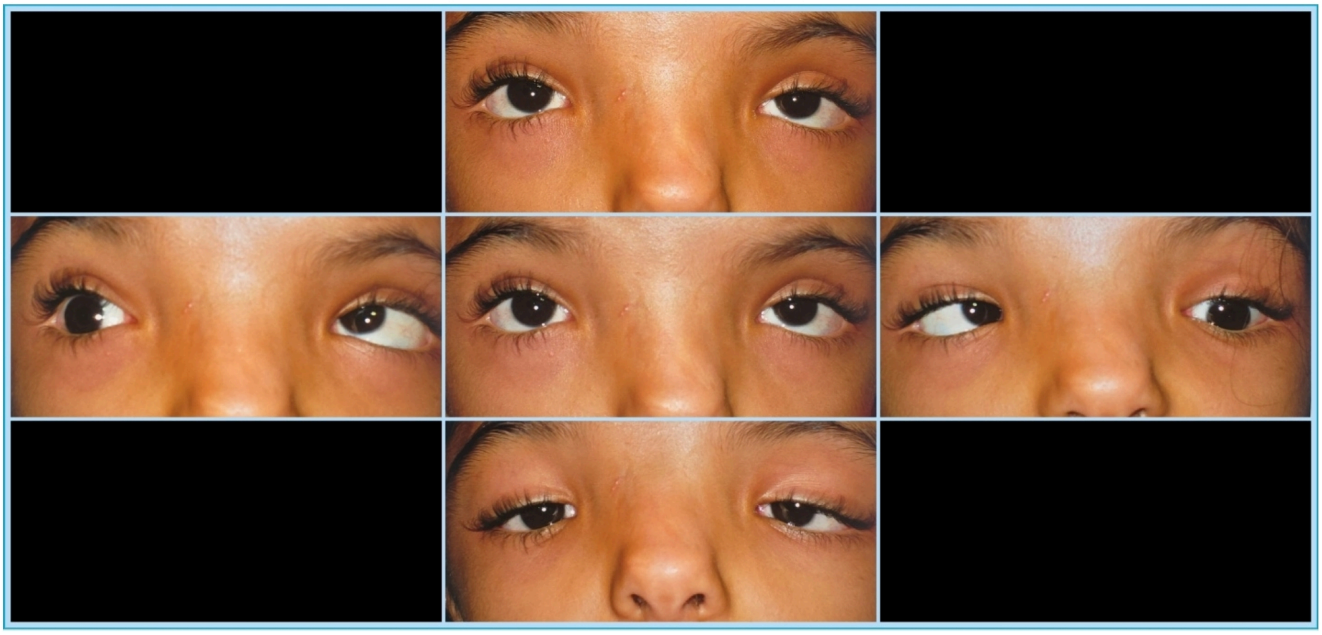


Figure 5

Preoperative deviogram of patient 27

V-pattern esotropia accompanied by 3+ IOOA in both eyes

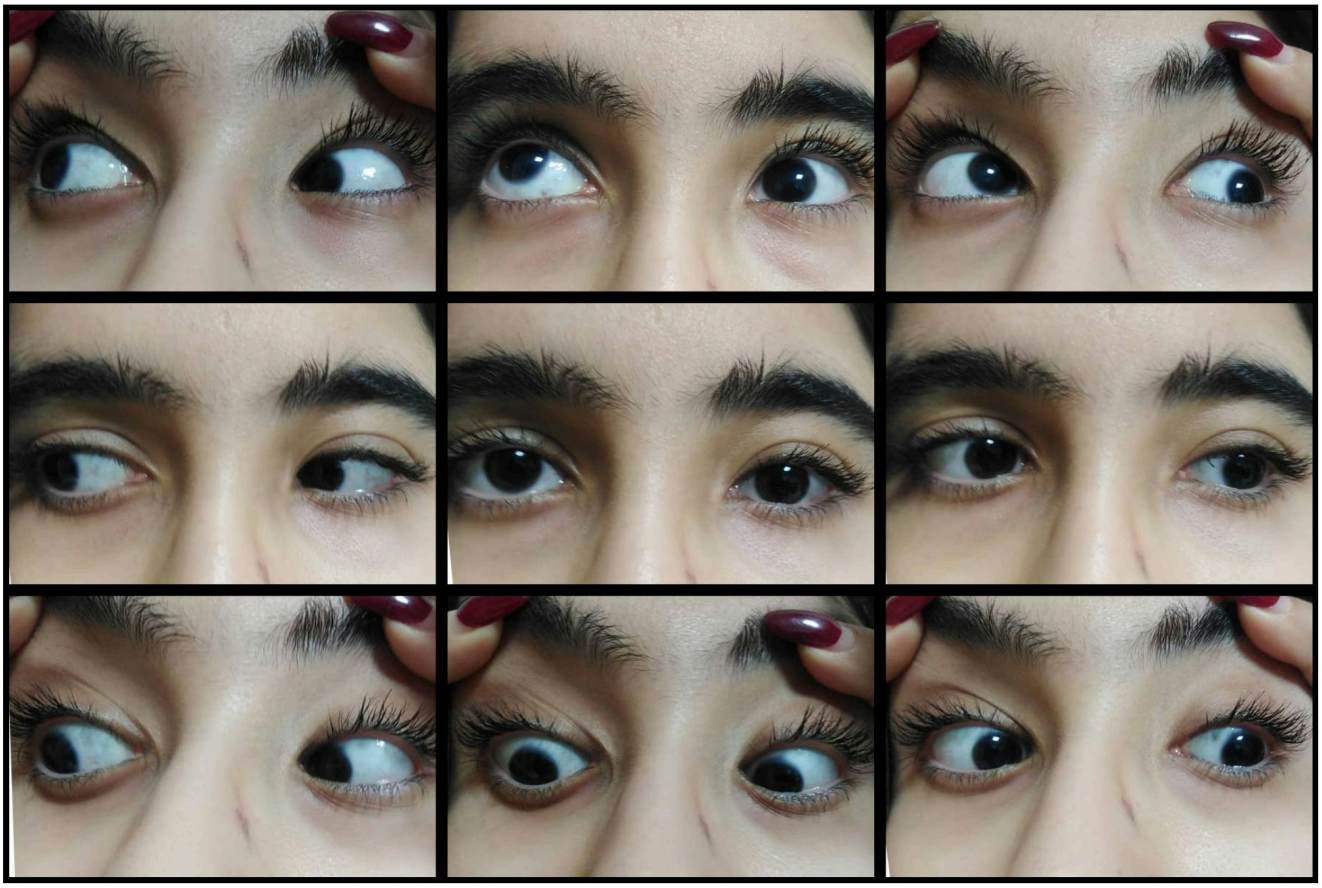


Figure 6

Postoperative anti-elevation syndrome in patient 11

This patient underwent left IO anterior transposition combined with right IR recession for left hypertropia of 30 PD. After surgery, she developed mild hypotropia of the left eye. Note under-elevation of the left eye, particularly on abduction, which confirms the diagnosis of anti-elevation syndrome.

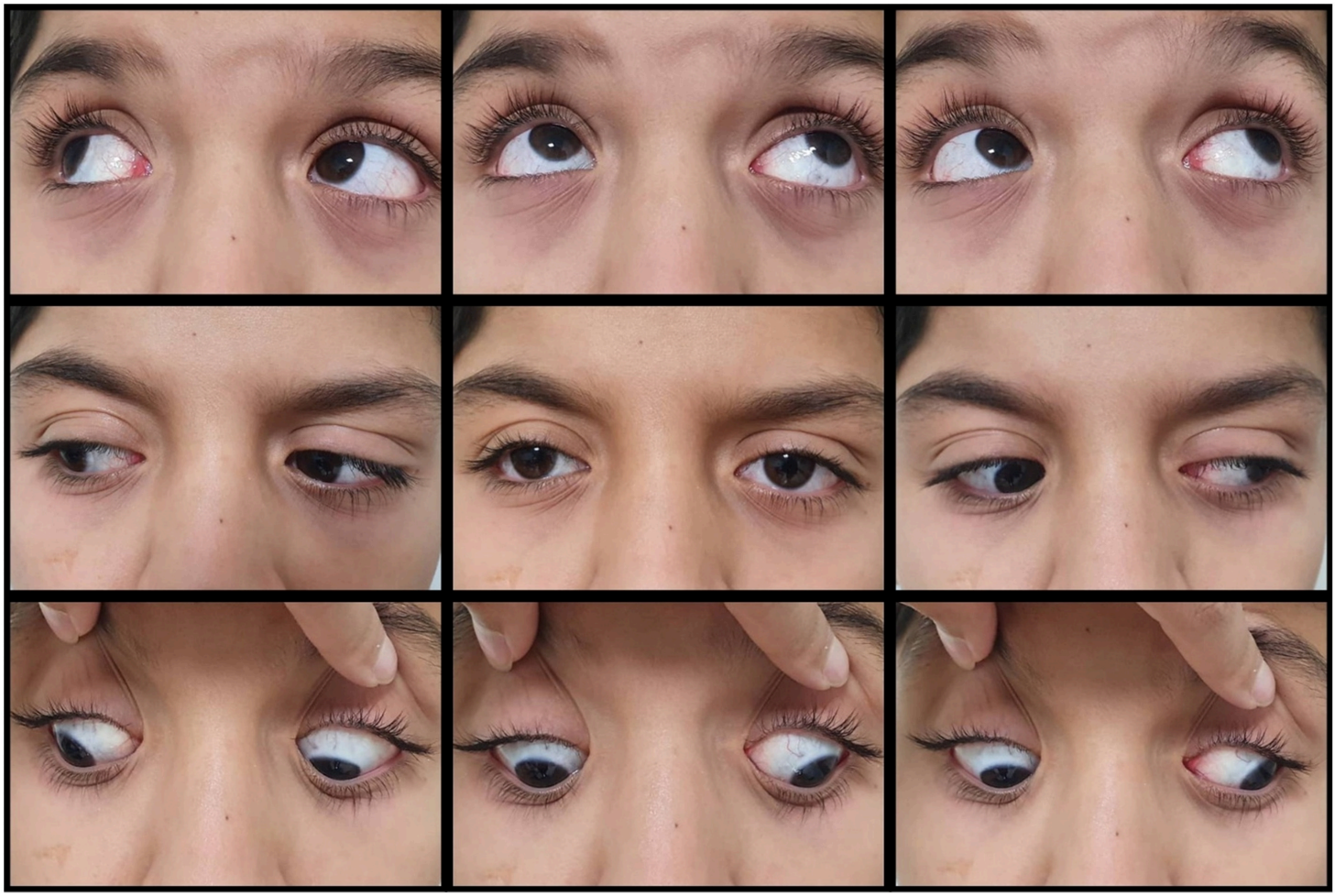


Figure 7

Postoperative recurrence of exotropia in patient 13

This patient developed an exotropic drift despite multiple strabismus surgeries. Note the resolution of IOOA in both eyes.