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Preliminary Results of New Modification of Vertical Muscle Transposition to Enhance Abducting Force in Sixth Nerve Palsy

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Keywords
Sixth nerve palsy · Vertical muscle transposition · Modification · Abduction

Abstract
Introduction: Since 1907, multiple transposition procedures have been established for the treatment of abducens paralysis. The purpose of the study was to determine where the transposed muscle should be reattached in order to increase the tangential force necessary to improve abduction. ***Methods:*** Retrospective case review of 12 consecutive patients with abducens paralysis who underwent transposition procedures between 2016 and 2019 was conducted. Vertical rectus muscles are transposed to the insertion of lateral rectus muscle; the temporal parts are joined and sutured to the sclera on top of the lateral rectus muscle in the middle of the insertion. The nasal parts are sutured to the sclera following the spiral of Tillaux. The muscle junction suture is placed 8 mm from the insertion, with the temporal parts of the vertical muscles bellies joined and sutured to the lateral rectus muscle. A full-tendon transposition was performed on 11 patients, a half-tendon transposition procedure on 1 patient. The minimum follow-up was 3 months. ***Results:*** The mean preoperative deviation was ET of 37° (range: ET 24° to ET 51°). The mean preoperative abduction limitation was 5 mm from midline (range: 7 to 1 mm). The postoperative mean deviation was ET of 2° (range: 0° to ET 5°). The postoperative mean abduction improvement was 5 mm past midline (range: 2–6 mm). There were no complications or signs of anterior segment ischemia. ***Conclusion:*** To achieve the maximal abductive force from the transposed muscles, we suggest that the vertical muscles be reattached as close as possible to the middle of the lateral rectus insertion.

Introduction

Abducens nerve palsy (6th cranial nerve) is the most common of the isolated ocular motor nerve palsies. For over 100 years, strabismus surgeons have attempted to find the perfect method to improve and normalize abduction weakness induced by the palsy. Since 1907, multiple transposition procedures have been established with good results, yet the search continues to consistently restore fusion and normal ductions [1–7].

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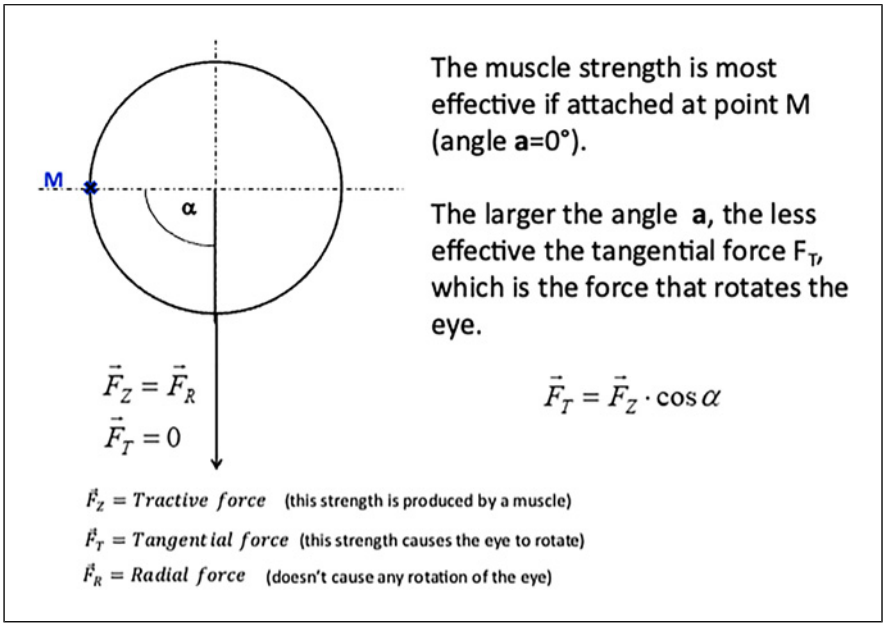

Fig. 1. Tangential force (Prof. Griebenow).

The idea of all transposition procedures is to shift the forces of the vertical muscles to the paralytic lateral rectus muscle. The outcome of the surgery depends not only on the severity of nerve damage, but also on how constricted the medial rectus muscle becomes [1, 8]. When comparing different studies [9], every transposition procedure can achieve a satisfactory outcome in primary position. The major problem is to move the eye past the midline and restore normal duction of the eye.

Physics can calculate where a pulling string should be attached to a ball in order to achieve a maximal tractive force. A two-dimensional case can be utilized to understand the distribution forces on a ball. Figure 1 shows a virtual eye with the muscle attached at point M. F_Z represents the tractive force produced by the muscle. F_T represents the tangential force causing the eye to rotate, whereas F_R equals a radial force and does not result in any rotation. The muscle strength is therefore most effective if attached at point M (angle $\alpha = 0°$). The larger the angle α, the less effective is the tangential force F_T.

The two-dimensional case supports the idea that the most effective tangential force would be achieved if a transposed muscle is attached to the middle of the lateral rectus muscle insertion or as described in the case, at point M. The main objective of this study was to evaluate the abduction achieved after a modified transposition procedure.

Study Design

A new modification of transposition procedure for abducens palsy was created and performed by surgeon S.H. During the 15th congress "Ophthalmologicum Balticum 2016," the procedure was introduced and discussed with surgeons W.A., I.K., and S.V. To create a sufficient cluster of patients, a decision was made to perform the new modification in different countries by different surgeons: S.H., W.A., and I.K.

A retrospective case review of 12 consecutive patients with sixth nerve paralysis was conducted. Each patient presenting with sixth nerve paralysis received the new modification. Each surgeon was at liberty to augment the transposition with additional procedures if needed, such as Botox injection in medial rectus muscle, an additional lateral rectus resection, or a half-tendon transposition, if deemed necessary.

All patients underwent the transposition procedure between 2016 and 2019. The surgeries were performed at the Children's Clinical University Hospital in Riga (Latvia), the Military Medical Academy, St Petersburg (Russian Federation), and the Alberta Children's Hospital Calgary, Canada. The data have been collected and analyzed.

Methods

Approval was obtained from the Research Ethics Committee of Riga Stradins University in Latvia, and the medical records were retrospectively reviewed. Twelve patients with abducens nerve palsy and limited abduction that did not reach the midline were included. The patients ranged in age from 8 to 63 years.

Nine patients developed abducens palsy following trauma, 1 patient secondary to a brain tumor, and 1 patient due to alcoholic neuropathy. One patient developed a pseudo palsy due to a lost muscle, after strabismus surgery in childhood (Table 1).

Table 1. Patient characteristics

Patient/ gender	Age, years	Etiology	pre-OP/ distance	post-OP/ distance	post-OP/ HP, DB	pre-OP/ abd./mm	post-OP/ abd./mm	Surgery
1/m	8	Trauma	ET 51°	ET 2° EP 7° –VD 2°	HP 5°, no DB	–7	+4	f. Tx + Botox
2/m	49	Trauma	ET 37°	ET 3°, +VD 6°	–	–7	+3	f. Tx + Botox
3/m	51	Lost muscle	ET 41°	ET 5°, EP 20°	–	–6	+5	h. Tx + Botox
4/m	59	Alcoholic neuropathy	ET 43°	ET 2°	HP 5°, DB	–7	+4	*f. Tx
5/f	63	Brain tumor	ET 25°	ET 1°	–	–6	+4	**f. Tx
6/m	51	Trauma	ET 40°	ET 0, EP 5°	–	–1	+6	f. Tx + Botox
7/f	39	Trauma	ET 31°	ET 0, EP 2°	–	–4	+5	***f. Tx
8/f	58	Trauma	ET 33°	ET 3°	HP <5°	–3	+2	**f. Tx
9/m	49	Trauma	ET 24°	ET 3°	–	–3	+4	f. Tx
10/f	62	Trauma	ET 42°	ET 0, EP 7°	–	–7	+6	****f. Tx
11/m	35	Trauma	ET 50°	ET 0, EP 5°	–	OD: –3 OS: +5	OD: +5 OS: +9	OD: v. Tx OS: R/R
12/m	30	Trauma	ET 31°	ET 1°	–	–3	+6	f. Tx

m, male; f, female; pre-OP, preoperative; post-OP, postoperative; distance, primary deviation angle, measured in prism diopters for distance, recalculated in degrees; ET, esotropia; EP, esophoria; XP, exophoria; –VD, right eye hypotropic; +VD, right eye hypertropic; abd./mm, abduction measured in millimeters; OD, right eye; OS, left eye; HP, head posture; DB, diplopia; –, no HP, no DB; f. Tx, modified full-tendon transposition; h. Tx, modified half-tendon transposition. * = years before resection-recession procedure. ** = transposition combined with lateral rectus resection. *** = botox injection a year before. **** = a year before medial rectus recession.

Orthoptic Measurements

All patients underwent full ophthalmological (best corrected vision at distance, slit-lamp, and fundus examination) and orthoptic assessments. The primary angle of deviation was measured in prism diopters with straight gaze, at both distance and at near. For statistical evaluation, the values of prism diopters were converted into degrees. A fixation target was used. Motility was measured binocularly in millimeters, using Kestenbaum-Glasses. Both eyes were illuminated with a light source positioned at the root of the nose at a distance of 40 cm. The resulting corneal light reflex was set as point zero or midline. The patient was then asked to maximally abduct, attempting to look to the paralytic side. The difference between point zero and the middle of pupil (slightly nasally) during maximal abduction was measured, in millimeters, using the Kestenbaum-Glasses. If the middle of pupil did not reach the midline, the inability to abduct was labeled with a minus sign (–), in millimeters. If the eye passed the midline, the abduction was labeled with a plus sign (+).

Surgical Technique

All surgeries were performed under general anesthesia by one of three surgeons: S.H., W.A., or I.K. Forced duction testing under anesthesia was performed prior to the transposition procedure. The surgical technique included either a full-tendon or half-tendon transposition of the vertical recti muscles, to the palsied lateral rectus muscle, following the spiral of Tillaux. The conjunctival incision was made from the 12 to 6 o'clock positions, parallel to the limbus and 4 mm from limbus. The frenulum between the superior oblique and superior rectus was carefully freed, as well as the connection between the inferior rectus and lower lid retractors. Both vertical rectus muscles were dissected free for 15 mm. In a half-tendon transposition, a short muscle hook was used to bluntly dissect the vertical muscles into two parts. Prior to the dissection, both anterior ciliary vessels were inspected to be sure that each part of the muscle contained one. The vertical muscles were then transposed to the insertion of lateral rectus muscle: The temporal parts were joined and sutured to the sclera, on top of the lateral rectus muscle, in the middle of the insertion. The nasal parts of the transposed muscled were then sutured to the sclera, following the spiral of Tillaux.

The muscle junction suture was placed 8 mm from the insertion of lateral, and in the middle of the lateral rectus muscle: The temporal parts of the vertical muscles bellies were joined and sutured to the lateral rectus muscle. Double-armed 6–0 polyglactin (Vicryl) sutures were used (Fig. 2a, b). If required 2.5 units of Botox were injected into the belly of the medial rectus muscle.

All patients received the modified transposition procedure: 11 patients received a full-tendon transposition. One patient received a half-tendon transposition when absence of the lateral rectus muscle was discovered. To decrease the risk of anterior segment ischemia, a half-tendon transposition was performed.

Five patients received botulinum toxin A injections into the medial rectus muscle: four intraoperatively, and 1 patient 1 year

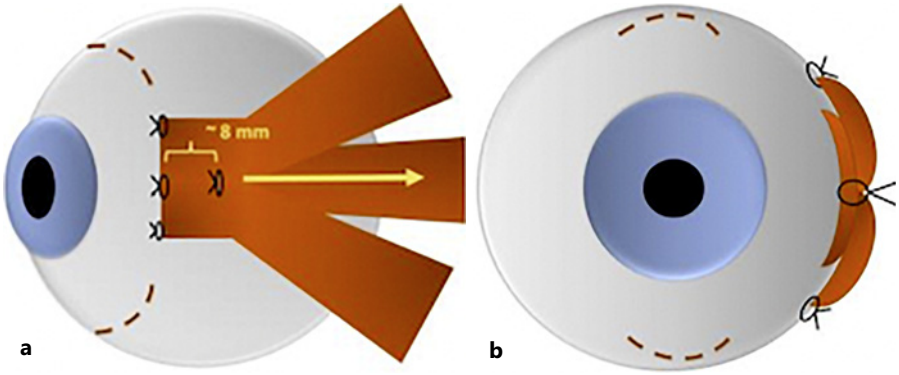

Fig. 2. a Side view of simplified representation without detailed anatomy of modified full-tendon transposition (Santa Heede). **b** Front view of simplified representation without detailed anatomy of modified full-tendon transposition (Santa Heede).

prior to surgery. The decision for Botox injection during surgery was made following positive forced duction testing, secondary to a tight medial rectus muscle.

Two patients received lateral rectus resection during surgery based on discovering a saggy and thin lateral rectus muscle at the time of dissection. Two patients received a medial rectus recession 1 year prior to the transposition procedure. One patient had a bilateral abducens palsy and received a recession/resection procedure in one eye, and a modified transposition in other eye. For analysis, we included only the motility results of the eye undergoing the transposition (Table 1).

Postoperative Examination

An examination under slit lamp was performed within 3 weeks after surgery to detect any signs of anterior segment ischemia. Minimum follow-up was 3 months postoperatively (range: 3 months to 2 years).

Results

Abduction

For assessing abduction improvement postoperatively, the data from 12 patients were reviewed. The augmented transposition improved the abduction of all 12 patients from mean −5 mm (range: −7 to −1 mm) to +5 mm (range: 2–6 mm). The paralytic eyes of all patients gained an additional 5–13 mm of horizontal motility postoperatively (median: 9 mm) (Table 1; Fig. 3).

Deviation

Pre-operatively the mean distance primary deviation for eleven eyes was 37° (75 PD) esotropia (range: 24° [45 PD] to 51° [123 PD]), with a mean near primary deviation of 31° (60 PD) esotropia (range: 20° [35 PD] to 51° [123 PD]). Three months post-surgery, the mean distance primary deviation was 2° (3.3 PD) ET [range: 0°–5° [8 PD]), and the near primary deviation 1° (2 PD) ET (range: ET 3° (6 PD) to XT 1° [2 PD]).

Four patients had an esophoria, no manifest esotropia (range: EP 2° (4 PD) to EP 7° [12 PD]) postoperatively. After surgery, 3 patients had a head posture of 5° or less to avoid the remaining esotropia.

One patient (No. 4, Table 1) had diplopia in primary position but was diplopia free adopting a head posture of 5°. This patient received prisms to achieve fusion in primary position.

Two patients developed a vertical deviation postoperatively with a phoria of 2° (4 PD) and 6° (11 PD), respectively. In both cases, the operated eye was hypotropic. Both patients did not have any symptoms or cosmetic concerns with the vertical deviation. No patients complained of torsional diplopia.

Complications

There were no complications during or after surgery. There were no signs of anterior segment ischemia.

Discussion

Sen and colleagues published an extensive literature review of 27 surgical studies with different transposition procedures for abducens palsy in 2019 [9]. All techniques achieved good postoperative results for deviations in primary position: range from slight esotropia of 0.7 PD to esotropia of 32 PD.

Our postoperative results correspond with the majority of other studies: the mean primary deviation at distance postoperatively in 11 patients (No. 11 was excluded due to bilateral surgery) was ET of 2° (range: 0°–5°).

In this study, strabismus angle measurements were carried out using degrees, since this procedure follows a linear pattern. PD is mathematically defined by a trigonometric function: PD = 100· tan α, where PD denotes

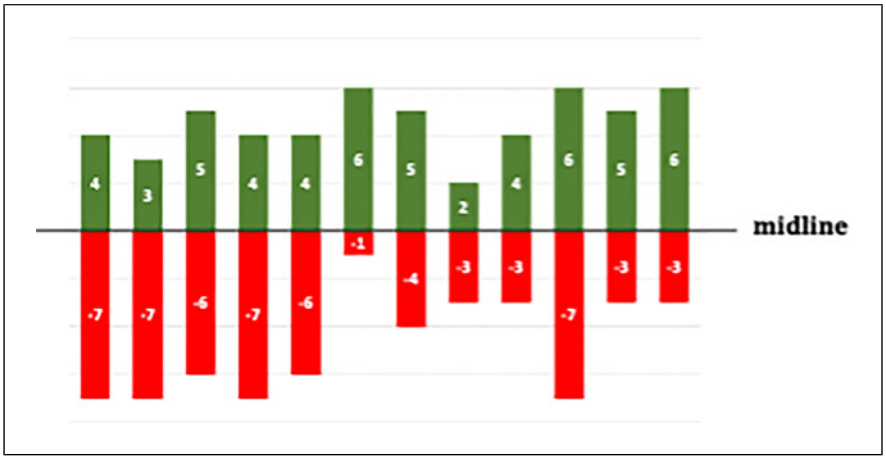

Fig. 3. Pre- and postoperative motility in millimeters. Red = before surgery, motility in millimeters before midline; green = after surgery, motility in millimeters beyond midline.

the prismatic effect in prism diopters and α as the angle of the prism in degrees. For example, for a strabismus angle of up to 45°, one degree corresponds to about two PD. For strabismus angles greater than 45°, this ratio is no longer given and for angles at 90°, the converted values of the PD approach infinity [10].

The comparison of surgical results – measured in degrees – would be more accurate after strabismus operations are conducted with widely different starting angles. To better compare this study's results to other international studies, the PD values were provided in the Results section.

In 1997, Foster presented a new modification of vertical muscle transposition [4]. With a posterior fixation suture 8 mm posterior to the palsied lateral rectus insertion, the abducting force was improved postoperatively. The premise of the Foster procedure is to reduce the space between the transposed vertical muscles and the lateral rectus muscle which then alters the force vectors of the transposed muscles.

The difference in our modified transposition technique is that maximal traction is achieved by attaching the transposed muscles exactly over the middle of the lateral rectus muscle, rather than on each side of the palsied lateral. A muscle junction suture placed in the middle and about 8 mm from the insertion, like Foster suggested, could potentially extend the force vector even more. This simplified two-dimensional calculation supported our idea to modify the transposition procedure as noted (Fig. 1).

Our results demonstrate that our modified transposition procedure leads to a good improvement in abduction ability (Fig. 4–9). The mean abduction after surgery was 5 mm beyond midline (range: 2–6 mm). The paralytic eyes of all patients gained an additional 5–13 mm of maximally possible horizontal motility (median: 9 mm) (Table 1; Fig. 3).

To determine, the motility we used Kestenbaum-Glasses, making comparison with other studies difficult. The majority of studies use a 6 point scale, with 0 indicating full abduction and −6 indicating no abduction at all. Alternatively, there are also 5 point scales or 8 point scales in use [11, 12]. Many surgical studies report achieving an abduction of about −3 postoperatively, which would correspond to 2–3 mm beyond midline [4, 5, 12–16]. Utilizing his modified transposition, Foster achieved abduction of −3.5 to −3.0 point scale Flanders and colleagues combined the full-tendon transposition with Botox injection in the medial rectus muscle, achieving a postoperative mean abduction of −1.7 point scale [11].

There are different augmentations of transposition procedure discussed in the literature. The augmentation of transposition beside the posterior suture and Botox injection in the medial rectus muscle includes the resection of the transposed tendons [5], as well as the joining and suturing of lateral strips of vertical rectus muscles to the lateral rectus muscle [6]. In this "crossed-adjustable transposition," the adjustable sutures are placed under the lateral rectus muscle in order to reattach the vertical rectus muscles at its opposite corners [17].

The lateral rectus muscle has only one ciliary arteria in comparison to medial rectus muscle. The risk in developing ischemia after resecting the lateral rectus is lower than after recessing the medial rectus [18–22]. Plication of lateral rectus would reduce the risk of ischemia even more but considering the additional

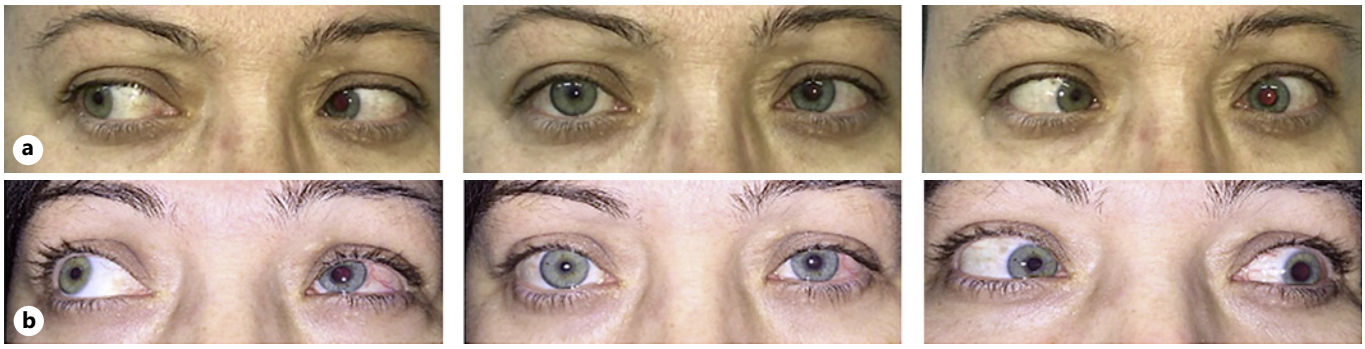

Fig. 4. a Patient No 7. Prior-surgery, VI palsy left eye. **b** Patient No 7. One month after surgery.

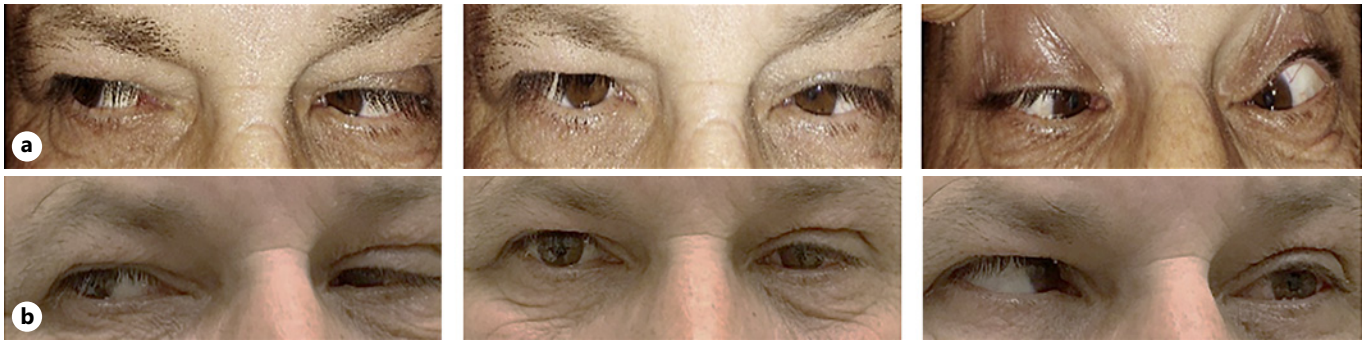

Fig. 5. a Patient No. 2. Prior-surgery, VI palsy left eye. **b** Patient No. 2. One year after surgery.

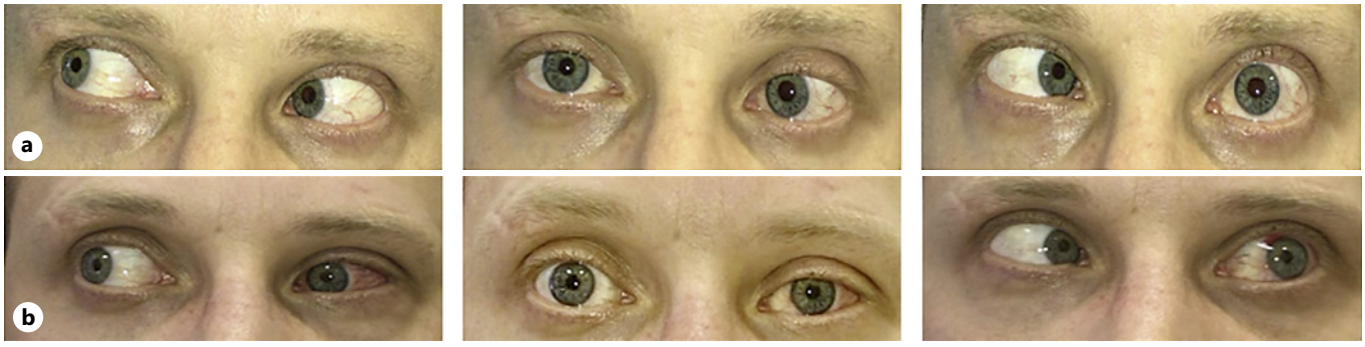

Fig. 6. a Patient No. 12. Prior-surgery, VI palsy left eye. **b** Patient No. 12. One month after surgery.

overlying of vertical rectus muscle the thickening could be too excessive.

Unfortunately, our patient group is not homogenous regarding the surgery procedure: only 3 patients received a single modified full-tendon transposition. The abduction beyond the midline after surgery for those 3 patients was 4 mm, 5 mm, and 6 mm, respectively.

The combination of vertical muscle transposition augmented with a Botox injection into the medial rectus could further improve surgical results. One of the most important factors in determining the effectiveness of vertical muscle transposition is how restricted the antagonist medial rectus muscle has become over time. Since an additional recession would increase the risk of ischemia, chemodenervation is a

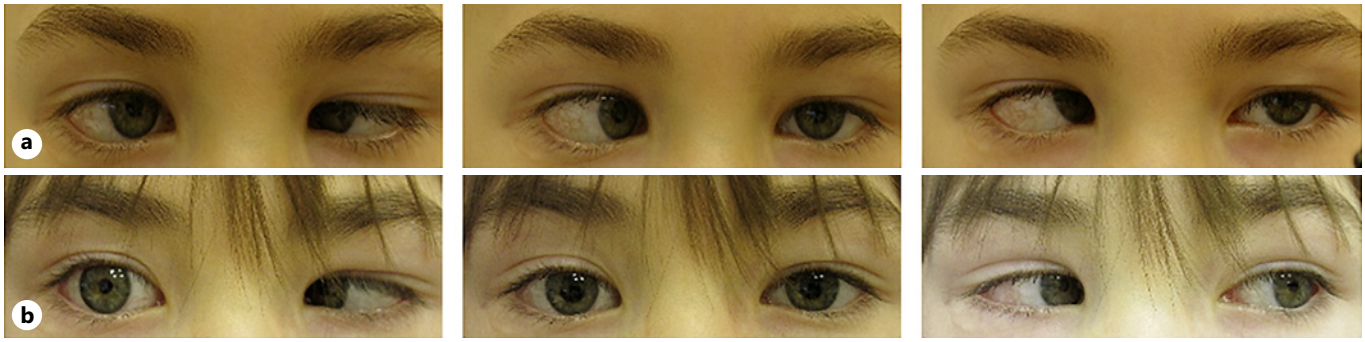

Fig. 7. a Patient No. 1. Prior-surgery, VI palsy right eye. **b** Patient No. 1. Two years after surgery.

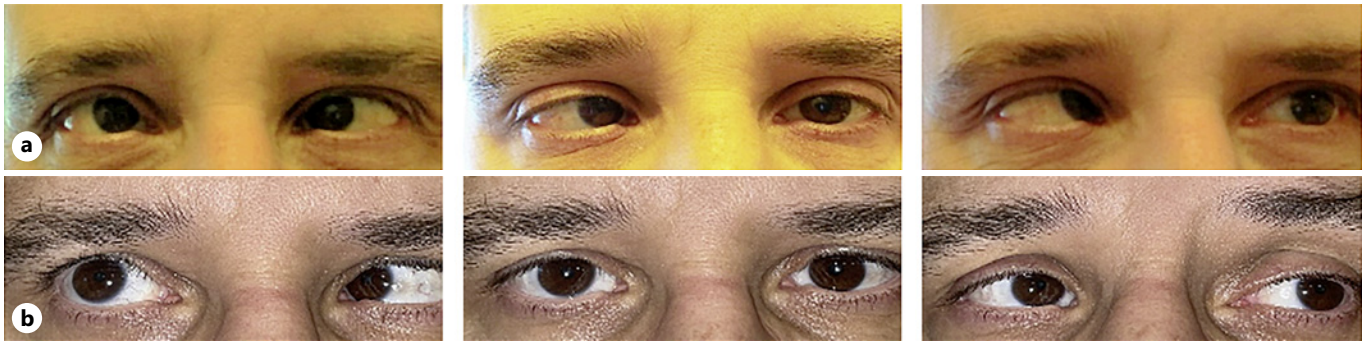

Fig. 8. a Patient No 3. Prior-surgery, lost muscle after previous strabismus surgery, right eye. **b** Patient No. 3. Two years after surgery.

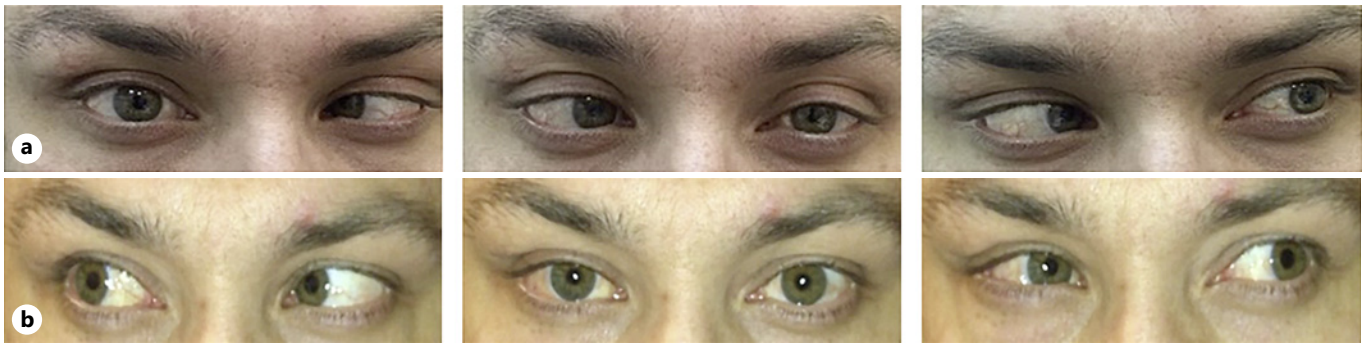

Fig. 9. a Patient No. 11. Prior-surgery, bilateral palsy. **b** Patient No. 11. Three months after surgery, right eye received the modified transposition.

solution to this problem. Two possibilities discussed in the literature include Botox injection either 2–8 months before surgery [11] or intraoperatively with the transposition [23, 24]. As with any vertical muscle transposition, potential complications such as loss of vertical movement, limitation of adduction, and the potential for inducing globe retraction or eyelid anomalies should be considered carefully.

Conclusions

Our results suggest that the best location for re-attaching transposed vertical muscles in order to increase the abductive force in patients with abducens palsy is over the insertion of lateral rectus muscle, joining the temporal parts of the vertical muscles on top of the lateral rectus muscle in the middle of the insertion.

Fear of overlapping muscles and potential scarring could be unfounded. Long-term effects cannot be determined as not all patients were seen for follow-up after 6 months. This series of patients demonstrates that the transposition procedure described should be considered as a viable surgical alternative for this complex group of patients.

Statement of Ethics

This study protocol and all procedures performed involving human participants were reviewed and approved by the Research Ethics Committee of Riga Stradins University in Latvia, approval number 6-1/02/74, and with the 1964 Helsinki Declaration and its later amendments or comparable ethical standards. Written informed consent was obtained from all participants. For participants under 18 years of age, written informed consent to participate was obtained from their parent/legal guardian/next of kin.

Written informed consent was obtained from all participants. For participants under 18 years of age, written informed consent for the publication of details regarding their medical case and any accompanying images was obtained from their parent/legal guardian/next of kin.

Conflict of Interest Statement

The authors declare that they have no competing interests.

Funding Sources

No funding was received for this research.

Author Contributions

S.H. was involved in the conception, design, acquisition of data, analysis and interpretation of data, and drafted the manuscript. W.A. was involved in the conception and design of the study and contributed to the acquisition of data and revision of the manuscript. E.S. was involved in analysis of data and revision of the manuscript. I.K. and S.V. were involved in the conception of the study and contributed to the acquisition of data. U.W. was involved in creating the mathematical formulas and analysis. All authors read and approved the final manuscript.

Data Availability Statement

Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study. The data that support the findings of this study are not publicly available to protect the privacy and confidentiality of the patients as required by the ethics board. Further inquiries can be directed to the corresponding author.

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