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A comparative multicentric long-term study of un-augmented modified Nishida procedure vs augmentation in unilateral sixth nerve palsy

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PURPOSE: To compare the effectiveness of three procedures: modified Nishida procedure alone vs modified Nishida procedure combined with medial rectus recession (MRc) vs modified Nishida procedure combined with MRc and botulinum toxin (BT) for severe unilateral sixth nerve palsy.
DESIGN: Consecutive, interventional case series.
METHODS: The medical records of a consecutive series of patients with severe unilateral sixth nerve palsy who underwent modified Nishida procedure in multiple centres were reviewed. Surgical technique was decided preoperatively at the surgeon's discretion. The preoperative and postoperative findings were compared.
RESULTS: Of the 43 patients with abducens palsy that received the procedure, 32 were included (mean age 38.6 ± 19.8 years). Mean preoperative deviation was 63.0 ± 27.3 prism dioptres (PD) and mean limitation of abduction −4.5 ± 1.2. Five patients underwent a modified Nishida procedure alone, 24 patients had an additional MRc and 3 patients were also injected with BT. Overall, the average correction of modified Nishida technique by itself was 29.4 ± 6.6 PD (range 20–36) and adding a MRc corrected 62.6 ± 23.8 PD (range 24–120). Modified Nishida procedure, MRc and BT altogether corrected 95.0 ± 18.0 PD (range 75–110). No postoperative complications were observed in any of the patients.
CONCLUSIONS: Excellent outcomes with fewer complications are obtained with modified Nishida procedure alone. The need for additional procedures such as MRc and BT which increase the effect in primary position can be determined depending on passive duction and preoperative horizontal deviation.

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INTRODUCTION

Abducens or sixth cranial nerve palsy is the most common extraocular muscle palsy, causing horizontal diplopia that worsens in ipsilateral gaze and head turn towards the affected side [1]. Treatment in the initial stages of this paralysis is aimed at avoiding diplopia by means of patching, prism glasses or botulinum toxin (BT) injection [2]. When the symptoms do not disappear and the eye misalignment remains stable over time, performing a surgical intervention is considered. In patients with residual action of a partially palsied muscle, recession and resection surgery of the horizontal recti will have greater effect with fewer complications than a transposition. Hence, transposition techniques should be reserved for cases with poor or absent lateral rectus function [3–8].

Various transposition procedures have been described for abducens palsy, classical transposition techniques including partial tendon [9], full tendon [10], and muscle union procedures [11]. Vertical rectus transposition surgery for the treatment of paralytic strabismus was first described by Hummelshein in 1907 [12], it was not until 1959 that full tendon vertical rectus transposition was described by Schillinger [13]. The augmented modalities to increase these procedures' effect include posterior augmentation suture (Foster suture) [6], resection of the transposed muscle [14], and additional medial rectus recession (MRc) or BT injection of the ipsilateral medial rectus muscle [15]. Possible complications following full tendon vertical rectus transposition are residual horizontal deviation, overcorrection, vertical deviation, ocular torsion, and anterior segment ischemia [16], especially if MRc is required or in patients who have undergone previous recess/resect surgery on the horizontal rectus muscles.

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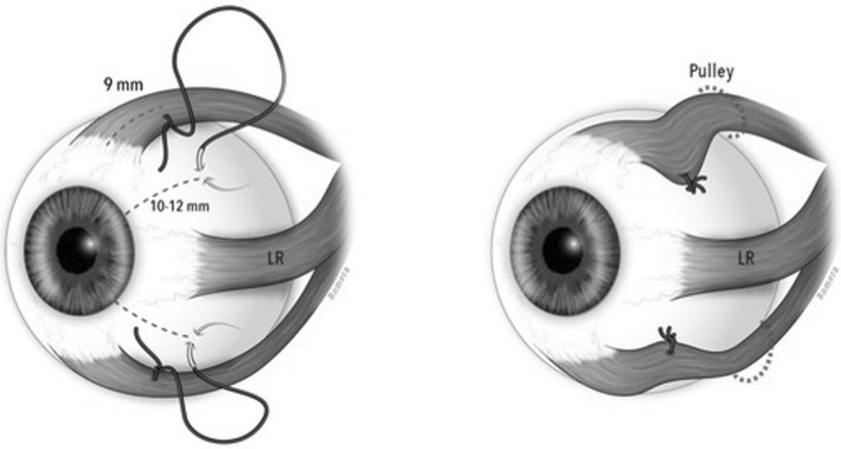

Fig. 1 Modified Nishida procedure. LR lateral rectus.

In 1964, Jensen introduced a different concept with splitting of the muscle bellies of both the vertical and the lateral rectus. He split the superior and inferior rectus muscles into medial and lateral halves and then united them with the upper and lower halves of the lateral rectus muscle in the equator region [11]. This technique was initially described to protect against anterior segment ischemia but, unfortunately, a case of acute anterior segment ischemia in the immediate postoperative period has been described [17].

More recently, full tendon transposition (FTT) of either the superior rectus or the inferior rectus to the lateral rectus with posterior fixation suture, with or without MRc, has been proposed [18–23].

In order to reduce complications associated with the previously described transposition techniques, mainly ischemia, Nishida described a new transposition technique in 2003. In this technique, the halves of the vertical rectus muscle bellies were divided and sutured onto the sclera without either tenotomy of the vertical rectus muscles, as in Hummelsheim's procedure, or surgical treatment of the lateral rectus muscle, as in Jensen's procedure. Nine patients were evaluated with this technique, obtaining comparable results to those published with other muscle transposition techniques [24]. This technique was then further modified and Nishida et al. reported a muscle transposition procedure in which the vertical rectus were not divided, instead the lateral margin of each vertical rectus muscle was transposed superotemporally or inferotemporally and were sutured onto the sclera without tenotomy or muscle splitting (Fig. 1). This is commonly considered as the modified Nishida technique [25].

The objective of the current study is to compare the effectiveness of three procedures: modified Nishida procedure alone vs modified Nishida procedure combined with medial rectus recession (MRc) vs modified Nishida procedure combined with MRc and botulinum toxin (BT) in a large series of patients with severe unilateral sixth nerve palsy who underwent modified Nishida procedure.

METHODS

In this interventional case series, the preoperative, surgical and postoperative data of patients diagnosed with severe abducens nerve palsy who underwent modified Nishida procedure between January 2017 and December 2019 were reviewed retrospectively and a standardized data collection form was completed by each author for every patient. The following centres were included: SÖ´s private Clinic in Aydin (Turkey), All India Institute of Medical Sciences in New Delhi (India), Instituto de Oftalmología Fundacion Conde de Valenciana in Ciudad de Mexico (Mexico), Hospital Parmenio Piñero in Buenos Aires (Argentina), Kaohsiung Medical University Hospital in Kaohsiung (Taiwan), Omni Hospital in Guayaquil (Ecuador), Hospital Metropolitano in Quito (Ecuador) and Hospital Clínico San Carlos in Madrid (Spain).

Patients with abduction defects due to severe acquired unilateral sixth nerve paralysis and no recovery within six months after onset were included in the study. Those patients who had undergone previous surgery, presented with bilateral or moderate sixth nerve paralysis and patients with under 6 months postoperative follow-up were excluded.

Data collected included age, sex, aetiology of the abducens nerve palsy, laterality (specifically whether the surgery was performed on the affected or the unaffected eye), preoperative deviation in the primary position (horizontal and vertical deviations considered separately, for both far and near), preoperative abduction deficit and diplopia. The ophthalmologists measured the horizontal and vertical deviations in prism dioptres (PD) by alternate prism cover test. Limitation of ductions was measured on a scale from 0 to −8, with 0 indicating full rotation up to canthus, −4 for abduction as far as primary position and −8 for globe immobilized in extreme adduction.

Patients with Nishida modified procedure were divided into three groups according to the surgical technique: those with Nishida modified procedure alone, those with a MRc added to the Nishida procedure and a group of patients in which BT was injected to the recessed medial rectus muscle. In cases with muscle recession, the amount in millimetres was recorded.

Briefly, the surgical procedure performed, modified Nishida procedure, consisted of a 10 mm transposition of the superior and inferior rectus temporally at 12 mm from the limbus, equidistant to the lateral rectus and superior or inferior rectus. The amount of MRc was based on the amount of deviation in primary position, tightness of the medial rectus as judged subjectively by preoperative forced duction testing, and standard tables were used to calculate dosage. When BT was added, a standard dose of 5 units in 0.1 mL was injected in all cases.

Postoperative follow-up examinations were performed at 1 and 6 months. Postoperative deviation in the primary position (horizontal and vertical deviations considered separately) and postoperative abduction deficit were recorded in the same manner as the preoperative examinations.

Outcome measures studied included change in horizontal esodeviation in primary position fixing on a distant target (in PD and percentage of preoperative deviation corrected), diplopia, complications and the need for further surgery. Surgical success was defined as the absence of diplopia in primary position with postoperative primary position deviation of 10PD or less. Overcorrection and undercorrection were defined as deviations of more than 10PD in the appropriate directions.

Statistical analysis was performed by the Hospital Clinico San Carlos team using SPSS software (Version 22.0 SPSS Inc., Chicago, IL) to summarize baseline characteristics and outcomes and to compare pre- and postoperative deviations. Continuous variables are presented as mean and standard deviation (SD) with range, while categorical variables are presented as numbers and percentages. The paired *t* test was used to analyse the preoperative and postoperative changes in esotropia in primary position. $P < 0.05$ was considered statistically significant.

Table 1. Demographic, clinical, preoperative and postoperative characteristics of the patients included in the study.

	All ($n = 32$)	Nishida ($n = 5$)	Nishida + MRc ($n = 24$)	Nishida + MRc + BT ($n = 3$)
Age (years)	38.6 ± 19.8 (3–82)	43.6 ± 24.2 (16–74)	39.0 ± 16.6 (21–82)	26.8 ± 38.3 (3–71)
Sex.				
Male	56%	40%	63%	33%
Female	44%	60%	37%	67%
Aetiology.				
Idiopathic	47%	20%	58%	0%
Trauma	31%	20%	33%	33%
Congenital	6%	20%	0%	33%
Haemorrhage	6%	20%	0%	33%
Infection	3%	0%	4%	0%
Tumour	6%	20%	4%	0%
Preoperative deviation in PP (PD)	63.0 ± 27.3 (24–125)	33.0 ± 4.5 (30–40)	64.1 ± 23.1 (24–95)	106.7 ± 16.1 (95–125)
Preoperative limitation of abduction	−4.5 ± 1.2 (−8 – −4)	−4.2 ± 0.5 (−5 – −4)	−4.6 ± 1.4 (−8 – −4)	−4.7 ± 0.5 (−5 – −4)
Preoperative vertical deviation	0 ± 0	0 ± 0	0 ± 0	0 ± 0
Preoperative diplopia	88%	100%	92%	33%
MRc (mm)	–	–	6.1 ± 1.3 (5–10)	8.0 ± 3.6 (5–13)
1-month deviation in PP (PD)	−4.2 ± 16.3 (−70–10)	3.6 ± 4.1 (0–10)	−3.6 ± 17.4 (−70–10)	−21.7 ± 7.6 (−30 – −15)
1-month vertical deviation (PD)	1.4 ± 2.8 (0–10)	0.8 ± 1.8 (0–4)	1.2 ± 2.5 (0–8)	3.3 ± 5.8 (0–10)
6-months deviation in PP (PD)	2.8 ± 9.2 (−30–20)	3.6 ± 4.1 (0–10)	1.5 ± 9.4 (−30–20)	11.7 ± 10.4 (0–20)
6-months limitation of abduction	−2.8 ± 0.8 (−4–0)	−2.6 ± 0.5 (−3 – −2)	−2.7 ± 0.8 (−3–0)	−3.7 ± 0.6 (−4 – −3)
6-months vertical deviation (PD)	0.7 ± 1.6 (0–6)	0 ± 0	0.9 ± 1.8 (0–6)	0 ± 0
6-months diplopia	22%	0%	25%	33%
Surgical complications	0%	0%	0%	0%
Need for further surgery	16%	0%	21%	0%
Deviation correction (PD)	60.4 ± 26.8 (20–120)	29.4 ± 6.6 (20–36)	62.6 ± 23.8 (24–120)	95.0 ± 18.0 (75–110)
Deviation correction (%)	95.6 ± 13.0 (67–133)	88.7 ± 13.7 (67–100)	97.9 ± 12.9 (78–133)	89.0 ± 10.6 (79–100)
Surgical success	75%	100%	75%	33%

PD prism dioptres, *PP* primary position, *MRc* medial rectus recession, *BT* botulinum toxin.

RESULTS

A total of 43 patients with modified Nishida operated at the centres included were initially selected. However, 3 were excluded due to previous surgery, 4 to incomplete follow-up and 4 because they were bilateral. Hence, the final study population comprised 32 patients of mean age 38.6 ± 19.8 years (range 3–82); 56% male and 44% female patients.

Table 1 shows the demographic, preoperative and postoperative features of the patients. Most participants (15 patients, 47%) presented with idiopathic abducens nerve palsy. Mean preoperative deviation was 63.0 ± 27.3 PD (range 24–125) and mean limitation of abduction −4.5 ± 1.2 (range −8 to −4), 88% of patients referring diplopia.

Regarding surgical technique, 5 patients underwent a modified Nishida procedure alone, 24 patients had an additional MRc, and 3 patients were also injected with BT. Surgical technique was decided preoperatively at the surgeon's discretion. In all of the patients, the Nishida modified procedure, MRc and BT injection were all performed in the affected eye, except for 3 patients who underwent Nishida modified procedure combined with MRc in whom the procedure was performed on the unaffected eye. The patients with Nishida modified procedure and MRc are detailed in Table 2, mean MRc being 6.1 ± 1.3 mm (range 5–10) in this group. In patients with modified Nishida procedure, MRc and BT the mean MRc was 8.0 ± 3.6 mm (range 5–13).

Mean horizontal deviation preoperative, at 1 month and 6 months with the different techniques are illustrated in Fig. 2. All postoperative results were statistically significant ($p < 0.05$). The changes in horizontal deviation in primary position stratified by technique and preoperative deviation (<40, 41–79 and >80 PD preoperatively) are shown in Fig. 3. Patients with BT were followed up to 12 months, obtaining similar results to those at 6 months.

Overall, the modified Nishida technique by itself corrected 29.4 ± 6.6 PD (range 20–36), whereas adding a MRc corrected 62.6 ± 23.8 PD (range 24–120). Modified Nishida procedure, MRc and BT altogether corrected 95.0 ± 18.0 PD (range 75–110). Surgical success was overall 75%; 100% with modified Nishida procedure, 75% with an additional rectus muscle recession and 33% in the group with BT. 16% of patients required further surgery, but no surgical complications were noted. At the 6-month follow-up 22% of all the included patients presented diplopia: none from the modified Nishida procedure alone, 25% of the augmented technique and 33% of the patients with BT. None of the patients lost vision or had anterior chamber signs of ischemia. Other results from similar studies using the Nishida procedure, along with those with an additional rectus muscle recession are provided in a Supplemental Table.

DISCUSSION

Various vertical rectus muscle transposition procedures have been described for abducens palsy. We hereby present the results of the modified Nishida technique in a considerably large sample of patients. Before it was described, other techniques with higher associated risks were used.

Table 2. Characteristics of the patients who underwent modified Nishida procedure and medial rectus recession.

Nishida + MRc	<40 PD ($n = 6$)	41–79 PD ($n = 8$)	>80 PD ($n = 7$)	>80 PD (fixating eye) ($n = 3$)
Preoperative deviation in PP (PD)	35.7 ± 6.2 (24–40)	54.4 ± 5.0 (50–60)	90.0 ± 2.9 (85–95)	86.7 ± 5.8 (80–90)
Preoperative limitation of abduction	−4.3 ± 0.8 (−6 – −4)	−4 ± 0	−4 ± 0	−8 ± 0
Preoperative vertical deviation	0 ± 0	0 ± 0	0 ± 0	0 ± 0
Preoperative diplopia	100%	87%	100%	67%
MRc (mm)	5.3 ± 0.5 (5–6)	5.5 ± 0.4 (5–6)	7.2 ± 1.6 (6–10)	6.0 ± 1.0 (5–7)
1-month deviation in PP (PD)	−12.6 ± 32.2 (−70–5)	−0.5 ± 6.8 (−10–8)	0.0 ± 15.9 (−32–10)	−4.0 ± 4.0 (−8 – −4)
1-month vertical deviation (PD)	0 ± 0	0.3 ± 0.7 (0–2)	2.7 ± 3.0 (0–6)	2.7 ± 4.6 (0–8)
6-months deviation in PP (PD)	1.2 ± 4.1 (−3–8)	−0.5 ± 6.8 (−10–8)	0.3 ± 13.8 (−30–10)	10.7 ± 10.1 (0–20)
6-months limitation of abduction	−2.5 ± 1.0 (−3 – −1)	−3 ± 0	−2.8 ± 0.4 (−3 – −2)	−1.5 ± 2.1 (−3–0)
6-months vertical deviation (PD)	0 ± 0	0.3 ± 0.7 (0–2)	2.8 ± 2.6 (0–6)	0 ± 0
6-months diplopia	17%	13%	29%	66%
Surgical complications	0%	0%	0%	0%
Need for further surgery	17%	13%	29%	33%
Deviation correction (PD)	34.5 ± 6.9 (24–43)	54.9 ± 8.8 (44–66)	89.7 ± 14.4 (79–120)	76.0 ± 5.3 (70–80)
Deviation correction (%)	97.0 ± 10.6 (80–108)	100.8 ± 13.1 (85–120)	99.6 ± 15.3 (91–133)	88.1 ± 11.2 (78–100)
Surgical success	83%	88%	71%	33%
Undercorrection (>10 PD)	0%	0%	0%	66%
Overcorrection (<10 PD)	0%	0%	14%	0%

MRc medial rectus recession, *PD* prism dioptres, *PP* primary position.

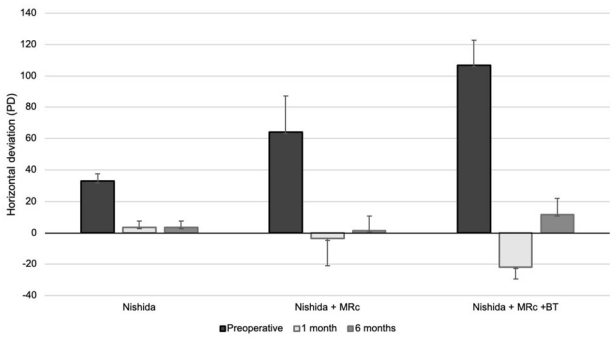

Fig. 2 Long-term outcomes of horizontal deviation in primary position with the different surgical techniques. Mean measurements with standard deviation are shown. PD prism dioptres, MRc medial rectus recession, BT botulinum toxin.

One of the most effective surgical methods available for large-angle strabismus with minimal or absent muscle force is FTT augmented with posterior fixation [6, 26, 27]. González et al. [28] compared three different transposition procedures without simultaneous medial rectus weakening: FTT, FTT with 4 mm resections before reinsertion, and FTT with myopexy sutures. FTT with 4 mm resections before reinsertion corrected the most esotropia (mean correction 46.4 PD; range 33–64) and improved abduction to the greatest degree. Complications following full tendon vertical rectus transposition included residual horizontal deviation, vertical deviation, ocular torsion, and anterior segment ischemia [16].

Until Jensen's technique was described [11], transposition techniques required the performing of tenotomy with the subsequent risk of ischemia. Jensen's procedure is thus considered safer because it reduces the risk of anterior segment ischemia. However splitting of 3 rectus muscles is required and cases of anterior segment ischemia have been described [17].

In 2003 Nishida et al. [24] reported ten cases of abducens palsy treated using a muscle transposition procedure in which the split halves of the vertical rectus muscle bellies were sutured onto the sclera without performing a tenotomy of the vertical rectus muscles. They concluded that it achieved similar postoperative results as vertical rectus transposition. In 2005, the authors reported the results of a series of three cases with this procedure but without splitting the vertical recti [29] and later described the outcomes of nine more patients [25]. This modified Nishida technique was performed by suturing the lateral muscle belly margins of vertical recti onto the superotemporal or inferotemporal sclera to transfer the lateral muscle bellies temporally and create additional muscle insertions as new points of action which can generate abductional forces.

In Nishida's initial study, data from patients with unilateral and bilateral paralysis was discussed together, as well as that of patients with and without previous surgeries and with and without recession of the middle rectus muscle. No separate analysis was performed so as to reach specific recommendations depending on preoperative deviation and the technique used was the initially described with vertical recti splitting. If we exclude bilateral cases reported in Nishida's first paper and analyse the results of the technique by itself in five patients, preoperative mean deviation was 42 PD with a postoperative deviation of 3.4 PD (average correction 38.6 PD).

Using the modified Nishida technique, Nishida et al. reported nine cases of severe abducens palsy, six unilateral and three bilateral. In cases where muscle transposition alone was performed, a correction of 24–36 PD was noted. Our results show a mean correction of 29.4 ± 6.6 PD (range 20–36), being thus comparable. In the group of augmented modified Nishida with MRc (patients with the same selection criteria as ours), deviation improved by 50–56 PD. Abduction improved beyond midline in all cases and none had anterior segment ischemia. Our results demonstrate the resolution of diplopia in most patients, as well as the improvement of the limitation of abduction. Therefore, this procedure seems to achieve similar results to other published procedures, and it is simple to perform as it requires only a suture from muscle to sclera, with tenotomy or muscle splitting being unnecessary.

In addition, Sabermoghadam et al. [30] provided a series of ten patients undergoing Nishida's transposition combined with MRc

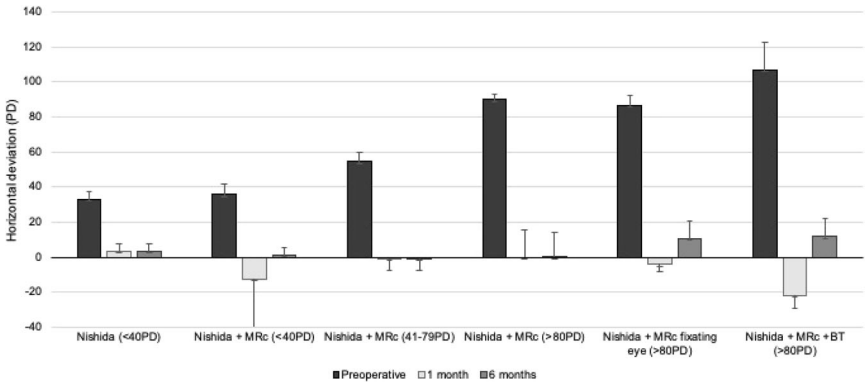

Fig. 3 Long-term outcomes of mean horizontal deviation in primary position with the Nishida modified procedure and medial rectus recession stratified by technique and preoperative deviation. PD prism dioptres, MRc medial rectus recession, BT botulinum toxin.

with a mean preoperative deviation of 49.5 ± 9 PD (range 40–65). Postoperative deviation ranged from orthotropia to 12 PD of esotropia and all the patients obtained abduction at least beyond the midline. No vertical ductional disturbances or deviations were developed, adduction was not compromised in any patient and no patient developed anterior segment ischemia. In all of the patients, this transposition was combined with MRc of 5–6.5 mm regardless of result of forced duction test. The amount of MR recession was 5 mm in 40 PD esotropia and increased in steps of 0.5 mm for each 5 PD increase in esotropia. These results are comparable to those found in patients in our series, but the follow-up time was relatively short and they did not evaluate separately patients with and without BT injection.

Regarding muscle transpositions combined with BT injection, only Flanders et al. [15] reported five patients who were given BT before surgery, correcting a mean deviation of 66 PD when combined with complete transposition of vertical rectus. In our work we present three patients with Nishida's transposition combined with MRc and BT with an average correction of 95 DP, along with improvement of abduction and diplopia in 2 of the 3 patients.

Based on Nishida's technique, Marcon et al. [31] described in 2013 a muscle union procedure in which a single non adsorbable suture was used to unify the muscle belly of two recti muscles supplying the action of the paretic muscle without scleral pass nor muscle splitting. Its mean effect in isolation was 35 PD (range 25–40) in 39 patients and results seemed to be satisfactory. However, Marcon's series is heterogeneous with joint analysis of all patients including those with previous surgeries, BT injections, and with various aetiologies.

Limitations of our study include that multiple surgeons were involved and there may have been minor variations in the surgical procedure; measurement of binocular field of vision would have also been useful in these patients and the procedure was not randomly selected, but instead decided by the surgeon depending on preoperative deviation. Notwithstanding, in most published works, the number of cases described is low and the analysis of the data is very heterogeneous without results being grouped according to surgical technique. To the best of our knowledge, this is the largest and most homogeneous series of patients receiving Nishida's procedure for severe sixth nerve palsy. In addition, patients were subdivided into three groups for a more accurate analysis of the results.

In our series, high success rate was achieved in patients with the modified Nishida procedure, regardless of baseline deviation magnitude, although the deviation amount corrected varies with the procedures. There was also an improvement in the limitation of abduction and resolution of diplopia in most patients with no complications associated with surgery being noted. Therefore, modified Nishida procedure alone is an excellent surgical option for treating severe sixth nerve palsy.

Summary

What was known before

- Transposition techniques are reserved for cases of sixth nerve palsy with poor or absent lateral rectus function.

What this study adds

- Excellent outcomes with fewer complications are obtained with modified Nishida procedure.
- The need for additional procedures such as medial rectus recession and botulinum toxin which increase the effect in primary position can be determined depending on passive duction and preoperative horizontal deviation.

REFERENCES

1. Yurdakul NS, Ugurlu S, Maden A. Surgical management of chronic complete sixth nerve palsy. Ophthalmic Surg Lasers Imaging. 2011;42:72–7.
2. Holmes JM, Leske DA, Christiansen SP. Initial treatment outcomes in chronic sixth nerve palsy. J AAPOS Publ Am Assoc Pediatr Ophthalmol Strabismus. 2001;5:370–6.
3. Bansal S, Khan J, Marsh IB. Unaugmented vertical muscle transposition surgery for chronic sixth nerve paralysis. Strabismus.2006;14:177–81.
4. Holmes JM, Leske DA. Long-term outcomes after surgical management of chronic sixth nerve palsy. J AAPOS Publ Am Assoc Pediatr Ophthalmol Strabismus. 2002;6:283–8.
5. Simons BD, Siatkowski RM, Neff AG. Posterior fixation suture augmentation of full-tendon vertical rectus muscle transposition for abducens palsy. J Neuroophthalmol. 2000;20:119–22.
6. Foster RS. Vertical muscle transposition augmented with lateral fixation. J AAPOS Publ Am Assoc Pediatr Ophthalmol Strabismus. 1997;1:20–30.
7. Britt MT, Velez FG, Thacker N, Alcorn D, Foster RS, Rosenbaum AL. Partial rectus muscle-augmented transpositions in abduction deficiency. J AAPOS Publ Am Assoc Pediatr Ophthalmol Strabismus. 2003;7:325–32.
8. Gunton KB. Vertical rectus transpositions in sixth nerve palsies. Curr Opin Ophthalmol. 2015;26:366–70.
9. Hummelsheim E. Weitere Erfahrungen mit partieller Sehnenuberpflanzung an den Augenmuskeln. Arch Augenheilkd. 1908;62:71.
10. O'Connor R. Transplantation of ocular muscles. Am J Ophthalmol. 1921;4:838.
11. Jensen CD. Rectus muscle union: a new operation for paralysis of the rectus muscles. Trans Pac Coast Otoophthalmol Soc Annu Meet. 1964;45:359–87.
12. Hummelshein E. Über Schnentransplantation am Auge. Ophthal Gesselschaft. 1907;34:248.
13. SCHILLINGER RJ. A new type of tendon transplant operation for abducens paralysis. J Int Coll Surg. 1959;31:593–600.

14. Brooks SE, Olitsky SE, deB Ribeiro G. Augmented Hummelsheim procedure for paralytic strabismus. J Pediatr Ophthalmol Strabismus. 2000;37:189–95; quiz 226–7.
15. Flanders M, Qahtani F, Gans M, Beneish R. Vertical rectus muscle transposition and botulinum toxin for complete sixth nerve palsy. Can J Ophthalmol. 2001;36:18–25.
16. Simon JW, Grajny A. Anterior segment ischemia following augmented 2-muscle transposition surgery. J AAPOS Publ Am Assoc Pediatr Ophthalmol Strabismus. 2004;8:586–7.
17. von Noorden GK. Anterior segment ischemia following the Jensen procedure. Arch Ophthalmol (Chic, Ill 1960). 1976;94:845–7.
18. Mehendale RA, Dagi LR, Wu C, Ledoux D, Johnston S, Hunter DG. Superior rectus transposition and medial rectus recession for Duane syndrome and sixth nerve palsy. Arch Ophthalmol (Chic, Ill 1960). 2012;130:195–201.
19. Velez FG, Oltra E, Isenberg SJ, Pineles SL. Assessment of torsion after superior rectus transposition with or without medial rectus recession for Duane syndrome and abducens nerve palsy. J AAPOS Publ Am Assoc Pediatr Ophthalmol Strabismus. 2014;18:457–60.
20. Patil-Chhablani P, Kothamasu K, Kekunnaya R, Sachdeva V, Warkad V. Augmented superior rectus transposition with medial rectus recession in patients with abducens nerve palsy. J AAPOS Publ Am Assoc Pediatr Ophthalmol Strabismus. 2016;20:496–500.
21. Agarwal R, Sharma M, Saxena R, Sharma P. Surgical outcome of superior rectus transposition in esotropic Duane syndrome and abducens nerve palsy. J AAPOS Publ Am Assoc Pediatr Ophthalmol Strabismus. 2018;22:12–16.e1.
22. Velez FG, Chang MY, Pineles SL. Inferior rectus transposition: a novel procedure for abducens palsy. Am J Ophthalmol. 2017;177:126–30.
23. Lee Y-H, Lambert SR. Outcomes after superior rectus transposition and medial rectus recession versus vertical recti transposition for sixth nerve palsy. Am J Ophthalmol. 2017;177:100–5.
24. Nishida Y, Inatomi A, Aoki Y, Hayashi O, Iwami T, Oda S, et al. A muscle transposition procedure for abducens palsy, in which the halves of the vertical rectus muscle bellies are sutured onto the sclera. Jpn J Ophthalmol. 2003;47:281–6.
25. Muraki S, Nishida Y, Ohji M. Surgical results of a muscle transposition procedure for abducens palsy without tenotomy and muscle splitting. Am J Ophthalmol 2013;156:819–24.
26. Clark RA, Demer JL. Rectus extraocular muscle pulley displacement after surgical transposition and posterior fixation for treatment of paralytic strabismus. Am J Ophthalmol. 2002;133:119–28.
27. Hussein MAW, Coats DK. Limitation of opposing ductions following augmented horizontal rectus muscle transposition. Am J Ophthalmol. 2003;136:947–9.
28. González M, del P, Kraft SP. Outcomes of three different vertical rectus muscle transposition procedures for complete abducens nerve palsy. J AAPOS Publ Am Assoc Pediatr Ophthalmol Strabismus. 2015;19:150–6.
29. Nishida Y, Hayashi O, Oda S, Kakinoki M, Miyake T, Inoki Y, et al. A simple muscle transposition procedure for abducens palsy without tenotomy or splitting muscles. Jpn J Ophthalmol. 2005;49:179–80.
30. Sabermoghadam A, Etezad Razavi M, Sharifi M, Kiarudi MY, Ghafarian S. A modified vertical muscle transposition for the treatment of large-angle esotropia due to sixth nerve palsy. Strabismus.2018;26:145–9.
31. Marcon GB, Pittino R, Paris V, Göky B, De Liaño RG. Muscle union technique for correction of complex paralytic strabismus: a multicenter, multicountry study. Trans 36° Meet. Eur. Strabismological Assoc. Marseille: 3–7.

AUTHOR CONTRIBUTIONS

EHG, BBB and RGDL contributed to the conception, design, acquisition, analysis and interpretation of the work. SBO, PS, AAR, DPD, YHL, DCC and AM contributed to the acquisition of the data. EHG, BBB and RGDL drafted the work. All authors revised the manuscript and approved the final version to be published.

COMPETING INTERESTS

The authors declare no competing interests.

ADDITIONAL INFORMATION

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