

# A Review of Transposition Techniques for Treatment of Complete Abducens Nerve Palsy

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## Abstract

**Purpose:** To review various types of extraocular muscle transposition procedures for management of strabismus in sixth cranial nerve palsy with little lateral rectus (LR) muscle function, along with their pros and cons.

**Methods:** We performed a comprehensive review of transposition procedures in sixth cranial nerve palsy, based on literature published anytime up to March 2021. A thorough search through PubMed and Cochrane databases was performed. All types of clinical studies on different transposition procedures in LR palsy, were included.

**Results:** Eighty-six original articles in English, with full text or abstracts available, were included in the review, among which 16 are prospective studies, 48 retrospective, 3 review articles, 1 randomized clinical trial, 17 case reports, and 1 letter. Vertical rectus transposition has demonstrated promising results, especially in abduction improvement and expansion of binocular diplopia-free visual field, albeit the possible adverse effects such as anterior segment ischemia, especially in the presence of medial rectus contracture, and induced vertical deviation may become troublesome. Partial muscle transposition, single muscle transposition, and also transposition without tenotomy have all been introduced to reduce the risk of multiple muscle manipulation and ischemia. On the other hand, different adjustable transpositions are being utilized to manage concomitant or induced vertical deviations.

**Conclusion:** Transposition procedures are highly effective in the treatment of esotropia caused by complete LR palsy. Various techniques for vertical muscle transposition have been proposed, with each of them having certain advantages and disadvantages.

**Keywords:** Abducens nerve palsy, Rectus muscle transposition, Sixth cranial nerve palsy, Surgical treatment

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## INTRODUCTION

In chronic sixth cranial nerve palsies, surgery is indicated when spontaneous resolution does not take place after 6 months,<sup>1,2</sup> although some studies consider waiting even up to 10 months.<sup>3-5</sup> The amount of residual function of lateral rectus (LR) muscle is very important for determining the surgical plan. A simple way is to score LR function (abduction) deficiency. However, medial rectus (MR) muscle contracture is also an essential consideration, and if significant contracture persists, it may affect the evaluation of LR function and mimic a score of -4 or worse in abduction limitation and

mislead to diagnosis of complete LR palsy. Narrowing of palpebral fissure on attempted abduction may be indicative of a restriction.<sup>6</sup> Moreover, botulinum toxin A (BTA) injection in suspected restricted MR and assessment of postinjection abduction facility can separate the partial LR palsy from the complete one.<sup>7</sup> More reliable and precise tests such as active force generation test or saccadic velocity evaluation are needed in these cases.<sup>7</sup> If some LR function is preserved, surgery on horizontal muscles is usually considered.<sup>8</sup> Ipsilateral MR recession, especially in the

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presence of significant contracture, ipsilateral LR resection, and contralateral MR recession in cases with significant incomitance are usually performed.<sup>8-10</sup> Patients with abduction deficiency of  $-4$  or worse, saccadic velocity of  $<60\%$  of normal, and significantly reduced force generation ( $<50\%$  of the fellow eye) are categorized as complete palsy.<sup>10,11</sup> In these cases, abduction improvement, centration, and expansion of the binocular diplopia-free field are the primary goals of surgical treatment.<sup>8</sup> Supramaximal recession and resection of horizontal muscles are not recommended anymore since the rate of undercorrection and reoperation is high. In this situation, LR muscle surgery is virtually useless and will only damage the ciliary arteries. Nowadays, muscle transposition is the mainstay of treatment for complete form of paralysis. Here, we review different transposition procedures for the management of complete sixth nerve palsy, by considering possible advantages and disadvantages of each procedure.

## METHODS

We designed a review of transposition procedures in sixth cranial nerve palsy based on literature published anytime up to March 2021. A thorough search through PubMed and Cochrane databases was performed using the following MeSH terms and search strategy: (“Abducens Nerve Diseases/diagnosis” [Mesh] OR “Abducens Nerve Diseases/surgery” [Mesh] OR “Abducens Nerve Diseases/therapy” [Mesh]) AND (“vertical rectus” OR “transposition” OR “superior rectus” OR “inferior rectus”). All types of clinical studies on different transposition procedures in LR palsy were included.

## RESULTS

Eighty-six original articles in English, with full text or abstracts available, were included in the review, among which 16 are prospective studies, 48 retrospective, 3 review articles, 1 randomized clinical trial, 17 case reports, and 1 letter.

### Vertical rectus transposition

Vertical rectus transposition (VRT) procedures are now first-line surgery for complete sixth nerve palsy. They can improve abducting force and binocular visual field, and preserve LR ciliary arteries.<sup>8</sup> In full-tendon VRT, superior rectus (SR) and inferior rectus (IR) muscles are disinserted and reinserted at the superior and inferior borders of LR tendon. In partial-tendon VRT, only a part of the muscles is transposed to preserve at least one ciliary artery of each vertical muscle. The transposition can only involve one vertical rectus muscle, mostly SR, and less frequently IR.<sup>12</sup>

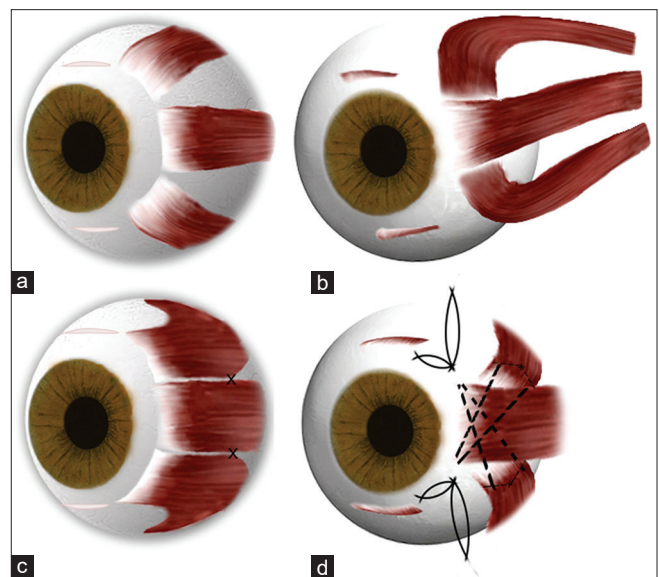
VRT without tenotomy, with or without muscle splitting, is another subtype of VRT. In this method, the muscles are not disinserted while the surgeon pulls the belly of vertical rectus muscles to the desired temporal position and attaches them to the sclera or each other. Herein, we will review the different types of transposition procedures with their special considerations and indications.

### Full-tendon vertical rectus transposition

Full-tendon VRT for management of extraocular muscle palsies was firstly introduced in the 1930s,<sup>13</sup> and it has evolved since then. Surgery has different approaches but usually needs  $120^{\circ}$ – $180^{\circ}$  of conjunctival peritomy or superotemporal and inferotemporal conjunctival fornix incision. At first, IR and SR are separated from adjacent tissues, including tendon of superior oblique muscle and upper and lower lid attachments. Muscles are secured, preferably with 6.0 absorbable stitches, and then disinserted and fixated to the sclera at the superior and inferior borders of LR insertion. The new insertion can be placed along the spiral of Tillaux: the temporal end of SR insertion is fixated at the superior end of LR insertion, and the nasal end of SR insertion is fixated 3–4 mm superiorly at the same distance from limbus. The same procedure will be performed for IR [Figure 1a].<sup>14</sup> They can also be fixated along LR muscle path: the nasal end of SR insertion is fixated at the superior end of LR insertion, and the temporal end of SR insertion is fixated 3–4 mm posteriorly, along the superior border of LR muscle, and the same for IR [Figure 1b].<sup>15</sup> Muscles can also be recessed asymmetrically in their new sites to address preexisting vertical deviation or prevent vertical deviation.<sup>3,11,16,17</sup> Muscle restriction and vertical deviations are potential side effects of transposition surgeries.

### Full-tendon vertical rectus transposition with medial rectus weakening

In patients planned for VRT procedure, performing forced duction test for assessment of MR contracture is essential.<sup>8</sup> This test is better to be performed while the patient is awake. The point in abduction where restriction begins shows how much we should expect the transposition alone to work.<sup>18</sup> In chronic



**Figure 1:** Transposition procedures for abduction deficit, (a) Full-tendon vertical rectus transposition along the spiral of Tillaux, (b) Full-tendon vertical rectus transposition along lateral rectus path, (c) Full-tendon vertical rectus transposition with posterior augmentation suture, (d) Crossed-adjustable vertical rectus transposition

sixth nerve palsies, especially when esotropia is more than 25 prism diopter (PD), moderate-to-severe MR contracture is often seen. It needs to be addressed to gain optimal results from transposition; otherwise, undercorrection or recurrence of esotropia is to be expected.<sup>19-21</sup>

With full-tendon VRT, simultaneous MR recession is not recommended due to the possible risk of anterior segment ischemia (ASI).<sup>22,23</sup> The next low-risk choice is BTA injection into the contracted MR,<sup>3,11,16,24,25</sup> albeit some cases of ASI have been reported.<sup>22</sup> It will cause temporary paralysis of MR. Therefore, transposed muscles can bring the eye back to the center easier. An early exoshift and significant reduction in esotropia will often appear but usually resolve within 8–12 weeks, with final 40–50 PD reduction of esotropia when the effects of BTA wear off.<sup>11,16,24,26</sup> In patients with residual diplopia and remarkable face turn after transposition, injection or reinjection of BTA is valuable.<sup>27</sup> It can be done before or at the time of surgery and in multiple sessions.<sup>16,24-27</sup> Botulinum toxin injection before surgery will decrease MR tightness and make vertical muscle manipulation easier. However, since simultaneous injection and transposition may mask vertical deviations induced by VRT (discussed later in this article), or over and undercorrections,<sup>11</sup> postoperative injection within 2 weeks is preferred by some surgeons, especially when adjustable sutures are utilized.<sup>11,17,18</sup> The recommended drug dosage varies from 2.5 to 5 IU of Botox equal to 7–15 IU of Dysport.<sup>11,16,27,28</sup>

Some authors prefer to do VRT and MR recession in two separate steps with an interval of at least 6 months.<sup>29,30</sup> The amount of MR recession is calculated using surgical tables in particular situations. For example, for deviations up to 75 PD, 4.5–6 mm of recession seems appropriate.<sup>18</sup> Furthermore, the surgeon can allow MR to find its proper neutral position after disinsertion and fix it there. However, this method does not seem appropriate for large amounts of recession.<sup>31,32</sup>

Another uncommon method is ciliary vessel sparing.<sup>20,30</sup> MR can be recessed with a complete saving of ciliary arteries or that the central of two-thirds the tendon width is recessed and the upper and lower 1.5 mm of the tendon, which contains the ciliary vessels, are preserved.<sup>33</sup> When forced duction test is negative and significant incomitance presents, contralateral MR recession can be added to the VRT procedure.<sup>34</sup>

In large and long-standing deviations, static orbital forces may adapt to globe position. Hence, after transposition, a temporary globe traction suture can be placed to fix the eye in the new position. The surgical procedure is as follows: a 5.0 nonabsorbable suture that passes through the medial limbus or MR insertion will attach to the lateral canthus over tarsorrhaphy bolsters.<sup>29</sup>

The results of full-tendon VRT with different types of MR weakening are shown in Table 1.

### **Full-tendon vertical rectus transposition with Foster augmentation suture**

Magnetic resonance imaging (MRI) pictures taken after VRT show that only insertions of the vertical muscles are transposed, while the position of muscles belly, posterior to the equator, remains almost intact, probably due to muscle attachments to the pulley system.<sup>36</sup> That is why simple muscle transposition might not always have optimal results and causes undercorrection and little change in abducting force. Various augmentation methods have been proposed for VRT procedure, which can be used separately or in combination.<sup>31,34</sup>

Foster introduced posterior fixation of transposed muscles in 1997 (Foster modification).<sup>14</sup> The concept is to change the muscle path posteriorly in the pulley region, as shown by MRI.<sup>37</sup> After securing and disinsertion of vertical rectus muscles, two 5.0 or 6.0 nonabsorbable sutures are passed through the sclera, separately, at the inferior and superior borders of LR, 16 mm from limbus or 8 mm from LR insertion. Vertical muscle insertions are then fixated along the spiral of Tillaux, and posterior scleral sutures will pass through the lateral border of each vertical muscle, containing one-fourth to one-third muscle width, and then, the muscle belly will be fixated to the sclera [Figure 1c]. This type of augmentation has had superior effects than VRT alone and has enhanced abduction force by 50%.<sup>14,38</sup> It has been said that if IR belly apposes LR belly, it might become too tight and increase the risk of extorsion and hypotropia, so leaving 1–3-mm space between LR and IR bellies is recommended by some authors.<sup>39</sup> Posterior fixation can also contain both vertical muscles in a single suture. In this modification, a 3-mm width single nonabsorbable suture is passed 15 mm from limbus, under LR muscle, and imbricates one-fourth to one-third of both inferior and SR width.<sup>40</sup> However, it may cause vertical deviation due to cheese wiring and migration or breakage of this one suture. Severe contracture of MR should also be addressed before or during transposition to gain optimal results. The effects of Foster suture did not decline during 1–2-year follow-up, and the new path of muscle and its force remained stable.<sup>20,41</sup>

The results of various studies on VRT with Foster augmentation suture are listed in Table 2.

### **Full-tendon vertical rectus transposition with intermuscular augmentation suture**

Intermuscular augmentation suture, or Wright modification, is when temporal one-fourth width of SR and IR bellies are fixated to upper and lower one-fourth width of LR belly, respectively, using 5.0 nonabsorbable sutures at 7–8 mm posterior to LR insertion. The method avoids scleral manipulation. Therefore, it may decrease scleral complications and can prevent unwanted limitation of elevation and depression.<sup>10</sup> The results of this method, combined with MR weakening, are comparable to Foster augmentation [Table 2]. However, the improvement of abduction is not as much, and over time, the intermuscular fixation may cause LR to stretch, and the vertical muscles will be dragged back to superior and inferior quadrants.<sup>31</sup>

**Table 1: Effects of full-tendon vertical rectus transposition with or without medial rectus weakening on deviation, binocular single vision field, and abduction**

Study	Number of patients	Preoperative deviation (PD/mean±SD)	Duration of deviation (months/mean±SD)	Transposition	Adjunctive procedure	Follow-up (months/mean±SD)	Outcome (EC, BSV, DC)
Fitzsimons <i>et al.</i> , 1988 <sup>26</sup>	8	53.7±19.7	40	Full-tendon VRT	MR BTA injection	3	EC 42
Rosenbaum <i>et al.</i> , 1989 <sup>11</sup>	10	55±21.2	14.2±8.5	Full-tendon VRT	MR BTA injection	17.4±13.9	EC 55 BSV 51
McManaway <i>et al.</i> , 1990 <sup>24</sup>	6	34.1±8.01	13.3±6.8	Full-tendon VRT	MR BTA injection	12	EC 32 BSV 69
Laby and Rosenbaum, 1994 <sup>19</sup>	7	-	-	Adjustable full-tendon VRT	None	-	EC 25-30
Flanders <i>et al.</i> , 2001 <sup>16</sup>	5	52±24.1	14.4±5.6	Full-tendon VRT	Pre and perioperative MR BTA injection	21.4±16.27	EC 66 BSV 55 DC 4.3
Bansal <i>et al.</i> , 2006 <sup>35</sup>	18	46.7±21.6	-	Full-tendon VRT	MR BTA injection	4	EC 32.1
Phamonvaechavan <i>et al.</i> , 2010 <sup>30</sup>	23	45.2±22.2	-	Full-tendon VRT	Adjustable MR recession 4.35 mm average	12±22.7	EC 39.3 DC 1.39
Phamonvaechavan <i>et al.</i> , 2010 <sup>30</sup>	19	47.5±24.9	-	Crossed-adjustable full-tendon VRT	Adjustable MR recession 8.25 mm average	11.7±25.8	EC 48.5 DC 1.17
Yurdakul <i>et al.</i> , 2011 <sup>29</sup>	17	64.1±14.3	16.8±19.2	Full-tendon VRT	MR recession with or without traction suture	18.7±12	EC 50 (73 in traction suture group) DC 1.3
Leiba <i>et al.</i> , 2010 <sup>3</sup>	22	38.1±11.6	12	Full-tendon VRT	MR BTA injection	44.2±37.4	EC 30 BSV 61

PD: Prism diopter, SD: Standard deviation, EC: Esotropia correction (PD), BSV: Binocular single vision field improvement (°), DC: Duction correction, VRT: Vertical rectus transposition, MR: Medial rectus, BTA: Botulinum toxin A

### Full-tendon vertical rectus transposition with resection augmentation

Resection of vertical muscles before transposition has also been used to augment the results of surgery.<sup>30,32</sup> In this procedure, vertical muscle sutures are placed at 4–8 mm posterior to the insertion, and muscle will be resected before transposition. This method has the advantage of avoiding scleral complications and the potential to use adjustable sutures. Furthermore, it is possible to calculate the amount of augmentation based on the amount of muscle resection. The resection can be planned asymmetrically or only in one muscle, to correct the preexisting vertical deviation.<sup>32</sup> Results are comparable to other types of augmentation [Table 2].

### Complications of full-tendon vertical rectus transposition

#### Adduction limitation

Although VRT with augmentation, combined with MR weakening, can result in acceptable improvement in abduction, it can cause some degrees of adduction limitation and decrease in the single binocular vision field with a probability of 13%–43%. However, it has not shown any clinical significance or patient dissatisfaction in most situations.<sup>31,32</sup>

#### Vertical and torsional tropia

New vertical deviations have been observed in 0%–40% of

conventional VRT procedures,<sup>3,11,16,19,24,26,29,30,35</sup> and 0%–30% of VRT procedures with posterior scleral augmentation suture.<sup>14,20,25,27,33,40,42,44</sup> It is mostly due to final imbalance between transposed vertical muscle forces in the new position, originating from anatomical differences, attachments to surrounding tissues and eyelids, and even different changes of tension between the nasal and temporal portions of muscles.<sup>19</sup> Based on a hypothesis, preexisting vertical deviations due to unexplained concomitant fourth nerve palsy or skew deviation, which has not been diagnosed because of MR tightness, can cause this complication.<sup>26</sup> Excessive temporal displacement of vertical muscles may rarely happen, due to weak elastic tissues or pulleys, especially when posterior fixation suture is placed, which can decrease their vertical function.

During surgery, vertical muscles can be asymmetrically recessed in their new sites to address preexisting vertical deviation.<sup>18</sup> Performing forced duction test for vertical rectus muscles before and after transposition is an essential step of surgery. If it is positive, removal of augmentation sutures, and if needed, recession of the restricted muscle is recommended until forced duction becomes free. However, prolonged operation time may cause globe hypotonia that results in false negative for forced duction test.<sup>18,45</sup> Careful



**Table 2: Effects of full-tendon vertical rectus transposition with various augmentations on deviation, binocular single vision field, and abduction**

Study	Number of patients	Preoperative deviation (PD/mean ± SD)	Duration of deviation (months/mean ± SD)	Transposition	Adjunctive procedure	Follow-up (months/mean ± SD)	Outcome (EC, BSV, DC)
Foster, 1997 <sup>14</sup>	7	52.1±26.9	-	Full-tendon VRT	Foster augmentation MR recession	12±16.6	EC 55 DC 1.9 BSV 72
Simons <i>et al.</i> , 2000 <sup>42</sup>	7	36.7±12.7	6	Full-tendon VRT	Foster augmentation	7.2±5.1	EC 41 DC 1.2
Hong <i>et al.</i> , 2005 <sup>43</sup>	11	59±22	74±80	Full-tendon VRT	Intermuscular augmentation	19.7±20	EC 44 DC 0.4 BSV 68
Struck, 2009 <sup>40</sup>	5	44±13	-	Full-tendon VRT	Single foster augmentation	-	EC 49.4 DC 2.1
Yazdian <i>et al.</i> , 2010 <sup>44</sup>	24	44.7±7.2	-	Full-tendon VRT	Foster augmentation	18±9	EC 32 DC 1.9
Akar <i>et al.</i> , 2013 <sup>20</sup>	47	42.2±14.1	-	Full-tendon VRT	Foster augmentation MR BTA injection or recession	38±13.7	EC 41 DC 2.3 BSV 71
Lee and Lambert, 2017 <sup>27</sup>	8	55.6±21.8	51.1±60.4	Full-tendon VRT	Foster augmentation Preoperative MR BTA injection MR recession 5-6 mm	17.3	EC 45.4 DC 0.7
Nabie and Andalib, 2017 <sup>25</sup>	29	45±17.5	-	Full-tendon VRT	Foster augmentation MR BTA injection	24.2±24.3	EC 48.1 DC 2.6
Kozeis <i>et al.</i> , 2018 <sup>33</sup>	20	64.25±10.9	6	Full-tendon VRT	Foster augmentation Modified MR recession	12	DC 2.8 EC 56

PD: Prism diopter, SD: Standard deviation, EC: Esotropia correction (PD), BSV: Binocular single vision field improvement (°), DC: Duction correction, VRT: Vertical rectus transposition, MR: Medial rectus, BTA: Botulinum toxin A

dissection of muscles not more than 10 mm from insertion was suggested. In addition, the muscle path is better to be observed after suture fixation to be sure that it has not displaced laterally too much.<sup>18</sup>

As for torsional effects of transposition procedures, lateral transposition of SR muscles theoretically leads to some degrees of intorsion, and transposition of IR causes extorsion. However, the exact torsional changes with different transposition procedures and different augmentation methods are unknown. Therefore, different methods of torsion monitoring, like intraoperative monitoring with limbus marking for adjustment or removal of the posterior fixation sutures, or performing adjustable VRT for postoperative adjustment, are also applicable.<sup>39,46,47</sup>

Postoperatively, in most cases, a small amount of induced tropia will spontaneously resolve or can be managed simply with vertical prisms.<sup>3</sup> If significant vertical tropia is present, it will often accompany a positive forced duction test. Therefore, early removal of posterior fixation sutures and recession of responsible transposed muscle is indicated. Augmentation sutures can be replaced at their original situation, or some millimeters away from LR, or even omitted.<sup>3,19,45,46</sup>

Adjustable VRT is performed primarily to gain the most abducting force without causing significant unwanted

vertical or torsional deviation. It can also correct over and undercorrections of horizontal deviation. It is easier to adjust vertical muscles postoperatively if posterior fixation sutures are not applied. Several methods are available. The disinserted vertical rectus muscles can be reattached with adjustable sutures at their typical side of LR insertion.<sup>17,21</sup> Furthermore, a crossed-adjustable method has been introduced in which SR suture is passed beneath LR and is fixated to the sclera at the inferior border of LR insertion with sliding-noose technique. The mirror procedure of the above surgery will also be performed for IR [Figure 1d].<sup>30</sup> The transposed vertical rectus muscles can be sutured to each other before fixation to the sclera (named Carlson–Jampolsky transposition technique in partial-tendon VRT). In this method, the muscles are allowed to balance their vertical vector force and determine their site of scleral attachment and then fixate to the sclera on adjustable suture, beneath or above LR muscle.<sup>48-50</sup>

### **Anterior segment ischemia**

ASI is a rare but major complication of transposition procedures, especially if multiple rectus muscles are involved in the surgery, since in most cases of sixth nerve palsy, MR contracture is present and needs intervention.<sup>23</sup> It has been reported in all types of VRT when combined with MR recession or BTA injection, even months after the procedure,

and also when it is not combined with MR manipulation.<sup>22,51</sup> Other than severing rectus muscle ciliary arteries, other possible reasons include disturbing MR blood flow with BTA injection, disturbing ciliary flow with stretching the remaining untouched muscle (in partial transpositions), and compromising anterior ciliary circulation when placing posterior fixation sutures.<sup>22,23,52</sup> Apparently, fornix incisions might be superior to limbal peritomy in saving limbal conjunctival vessels.<sup>53</sup>

Surgery is better to be performed with a vessel-sparing method in at least one of the vertical or MRs, especially in old and diabetic patients in whom the risk of ASI is high.<sup>21,30</sup>

Other than vessel-sparing VRT, there are several methods of transposition that are introduced primarily to prevent three-muscle surgeries in one session. Partial-tendon transposition, surgery on one vertical muscle, and surgery without tenotomy will be discussed here.

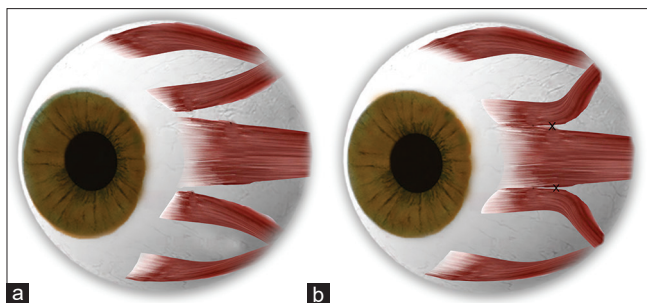
### **Partial-tendon vertical rectus transposition**

In partial-tendon VRT (Hummelsheim procedure), vertical muscles are divided into two parts, up to 9–15 mm posteriorly, and only the temporal halves are transposed. The transposed parts can be reattached to the sclera along the spiral of Tillaux or LR tendon path [Figure 2a]. The goal of this method is to preserve at least one ciliary artery in each vertical muscle. With great care to save the nasal ciliary arteries, even more than half of each muscle width can be transposed.<sup>54-56</sup> This procedure is indicated when previous recession–resection surgery has been performed for a patient or when MR weakening is necessary due to significant contracture of MR muscle.<sup>48</sup> However, ASI has still been reported.<sup>7,57</sup>

All three methods of augmentation (Foster augmentation suture, intermuscular augmentation suture, and resection augmentation) can be added to partial-tendon VRT, separately or in combination [Figure 2b].<sup>32,54,58,59</sup> Furthermore, since vertical deviation can be the complication of any transposition procedure, partial-tendon VRT can also be performed on adjustable sutures.<sup>21,48-50</sup> The results of published studies are available in Table 3.

### **Single muscle transposition**

The advantage of this method is the possibility of simultaneous



**Figure 2:** Transposition procedures for abduction deficit, (a) Partial-tendon vertical rectus transposition, (b) Partial-tendon vertical rectus transposition with posterior augmentation suture

transposition and MR weakening without increasing the risk of ASI. Moreover, an intact vertical rectus muscle will be preserved for the situation of undercorrection.<sup>12,61</sup> In most cases, SR is transposed; however, this surgical procedure can also be performed for IR.<sup>62</sup> The surgical procedure is quite similar to conventional VRT and can be combined with one or multiple augmentation procedures.

### **Superior rectus transposition**

The degree of preoperative abduction deficiency seems to be the most important prognostic factor for the success of SR transposition (SRT).<sup>61</sup> Nevertheless, since simultaneous recession of MR is applicable, better improvement of abduction deficiency has been reported in some studies in comparison to conventional VRT. Postoperative esodrift was <1 PD in 7 months of follow-up.<sup>12,27</sup> The results of previous studies are presented in Table 4.

Theoretically, single muscle transposition may induce a significant vertical or torsional diplopia. SRT procedure with or without augmentation sutures has induced vertical deviation, in 7%–28% of cases,<sup>12,27,61,64,66-69</sup> which is comparable to VRT. Although transposition may reduce SR vertical force, it might not change the muscle force vector (nearly 23° into abduction). Instead, it causes a small amount of advancement of muscle to fix on the temporal sclera. This combination may change the balance of vertical alignment into hypo or hypertropia or even no vertical deviation.<sup>12,18</sup> SRT may cause intorsion, but despite 1°–5° of postoperative fundus intorsion, it is not usually clinically significant, and subjective complaint of torsional diplopia is rare.<sup>27,63,64,66,67</sup> However, one should be cautious about performing SRT when preoperative intorsion or even no torsion exists. Using adjustable sutures can prevent postoperative vertical or torsional deviation.<sup>70</sup>

Management of postoperative induced vertical or torsional diplopia after SRT is the same as VRT. Performing IR transposition (IRT) in cases of undercorrection and vertical deviation after SRT might rebalance the vertical and horizontal alignment.<sup>12,61</sup> Moreover, a series of three cases with undercorrection after SRT combined with MR recession, managed with IR belly transposition without tenotomy (modified Nishida procedure, mentioned later in the text), has been reported.<sup>71</sup>

### **Inferior rectus transposition**

Compared to SRT procedure, there is only one small case series about IRT.<sup>62</sup> According to this report, IRT can be considered in cases of preexisting intorsion, where SRT cannot be suggested.

In addition, in patients with undercorrection or vertical deviation induced following SRT, IRT may be advised as a second procedure.<sup>12,61</sup>

### **Vertical rectus transposition without tenotomy**

#### **Muscle union procedure**

In muscle union procedure (Jensen procedure),<sup>72</sup> after splitting of SR, IR, and LR, the temporal halves of vertical muscles are looped and attached to the upper and lower half of the

**Table 3: Effects of partial-tendon vertical rectus transposition (Hummelsheim procedure) with or without various augmentations on deviation, single binocular field, and abduction**

Study	Number of patients	Preoperative deviation (PD/mean±SD)	Duration of deviation (months/mean±SD)	Transposition	Adjunctive procedure	Follow-up (months/mean±SD)	Outcome (EC, BSV, DC)
Neugebauer <i>et al.</i> , 2001 <sup>50</sup>	12	45±13	-	Partial-tendon VRT	None	1.5	EC 45 DC 4.17
Neugebauer <i>et al.</i> , 2001 <sup>50</sup>	17	51±12	-	Self-adjusting partial-tendon VRT	None	1.5	EC 49 DC 4.12
Britt <i>et al.</i> , 2003 <sup>54</sup>	5	45.2±23.9	-	Partial-tendon VRT	Foster augmentation All had previous MR recession	2.3±1.7	EC 50 BSV 17 DC 1.5
Ejzenbaum <i>et al.</i> , 2007 <sup>49</sup>	23	56.8±24	28.4±40	Adjustable partial-tendon VRT	MR recession	14±17.9	EC 55
Couser <i>et al.</i> , 2012 <sup>32</sup>	10	43±5	-	Partial-tendon VRT	Resection augmentation MR recession	7	EC 37 DC 1
Kinori <i>et al.</i> , 2015 <sup>58</sup>	9	70.5±30	-	Partial-tendon VRT	Foster augmentation MR weakening LR plication	7	EC 83 if primary ET >95 DC 3.1
Singh <i>et al.</i> , 2016 <sup>34</sup>	15	58.3±10.8	>6	Partial-tendon VRT	Resection augmentation plus intermuscular augmentation MR recession	11.35	EC 51 DC 2 BSV 65
Farid, 2019 <sup>31</sup>	14	35.7±11.41	>6	Partial-tendon VRT	Foster augmentation plus intermuscular augmentation MR recession if FDT is positive	7.2±1.6	EC 31.3 DC 2.7
Bagheri <i>et al.</i> , 2020 <sup>60</sup>	22	45.8±22	>12	Partial-tendon VRT (along LR)	MR recession in all	39.2±30.4	EC 45 DC 1.6

PD: Prism diopter, SD: Standard deviation, EC: Esotropia correction (PD), BSV: Binocular single vision field improvement (°), DC: Duction correction, VRT: Vertical rectus transposition, MR: Medial rectus, FDT: Forced duction test, LR: Lateral rectus

**Table 4: Effects of single muscle transposition with or without various augmentations on deviation, single binocular field, and abduction**

Study	Number of patients	Preoperative deviation (PD/mean±SD)	Duration of deviation (months/mean±SD)	Transposition	Adjunctive procedure	Follow-up (months/mean±SD)	Outcome (EC, BSV, DC)
Mehendale <i>et al.</i> , 2012 <sup>12</sup>	7	53.5	-	SRT	With or without intermuscular augmentation Adjustable MR recession	10	EC 36.7 DC 1.8
Velez <i>et al.</i> , 2014 <sup>63</sup>	7	47.42±24.8	-	SRT	Intermuscular augmentation Adjustable MR recession	>2	EC 38.7
Patil-Chhablani <i>et al.</i> , 2016 <sup>64</sup>	13	55.4±24	>6	SRT	Foster augmentation plus intermuscular augmentation MR recession	5.2	EC 45.5 DC 1.9
Lee and Lambert, 2017 <sup>27</sup>	8	41.9±14.6	44.6±53	SRT	Foster augmentation MR recession	6.2	EC 36.4 DC 1.6
Agarwal <i>et al.</i> , 2018 <sup>65</sup>	10	51.5±18.8	-	SRT	Foster augmentation if >40 PD Adjustable MR recession	>6	EC 45.4 DC 1.8
Akbari <i>et al.</i> , 2018 <sup>66</sup>	11	28±8.5	>6	SRT	Foster augmentation	4	EC 20 DC 1
Velez <i>et al.</i> , 2017 <sup>62</sup>	5	39±17	-	Primary IRT	Intermuscular augmentation Adjustable MR recession	>3	EC 27 DC 1
Liu <i>et al.</i> , 2019 <sup>61</sup>	13	82	>6	SRT	Foster augmentation MR recession if FDT positive	9.5	EC 51.4 DC 1.5
Liu <i>et al.</i> , 2019 <sup>61</sup>	5	40	>6	Secondary IRT	Intermuscular augmentation	9.5	EC 32

PD: Prism diopter, SD: Standard deviation, EC: Esotropia correction (PD), BSV: Binocular single vision field improvement (°), DC: Duction correction, SRT: Superior rectus transposition, MR: Medial rectus, IRT: Inferior rectus transposition, FDT: Forced duction test

LR muscle using nonabsorbable sutures. This procedure was designed primarily to save ciliary arteries.<sup>72</sup> However, three rectus muscles are involved, and cases of ASI have been reported, probably secondary to strangulation of ciliary arteries in sutures.<sup>73,74</sup> Jensen procedure has not been very popular due to the difficulty of muscle revision during reoperation and also lack of long-term stability.<sup>73</sup> After a while, floppy paralyzed LR will be dragged away and vertical muscles will come back to their original site eventually.<sup>75</sup>

In a modified form of muscle union procedure, half to one-third muscle width of SR and IR are sutured to LR, 6–8 mm posterior to insertion, without LR splitting.<sup>76</sup> The vertical muscles can also be united together without attaching to LR, using direct nonabsorbable suture or silicone band, with or without LR plication.<sup>77,78</sup> The results of different muscle union procedures are available in Table 5.

**Transposition without tenotomy or splitting (modified Nishida procedure)**

In the modified Nishida procedure, about one-third of each vertical muscle width at the temporal side is grasped with a nonabsorbable suture, 8–10 mm posterior to muscle insertion, without splitting (although, in the original Nishida procedure,

vertical rectus muscles had been split into two parts before transposition).<sup>75</sup> The sutures can be tied there to avoid muscle breakage. Then, the temporal border of the muscles will be sutured to the sclera in superotemporal and inferotemporal quadrant 10 or 12 mm from limbus, midway between LR insertion and vertical muscle insertion [Figure 3].<sup>80</sup>

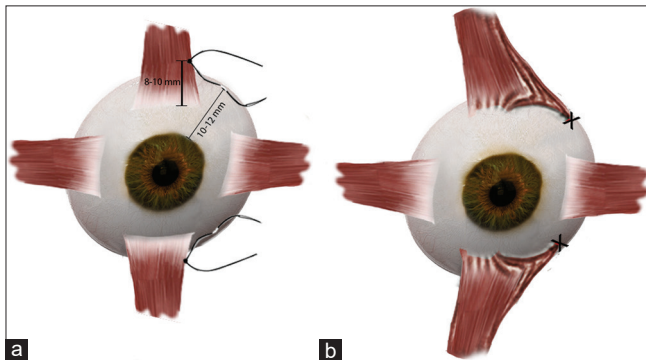
The surgical results of published studies are available in Table 6. Modified Nishida procedure itself can correct 24–36 PD of esotropia, but when accompanied by adjustable or nonadjustable MR recession, the effect for esotropia correction will be increased to 50–60 PD.<sup>80,81</sup> Therefore, in deviations <40 PD, modified Nishida procedure plus MR recession is not advised due to high risk of overcorrection.<sup>81</sup> No case of ASI has been reported yet. If sutures are placed carefully to preserve ciliary arteries, the procedure can be performed in cases with a history of previous unsuccessful horizontal surgery. Vertical ductions are not significantly reduced since the force vector of vertical muscles in the nasal portion is minimally affected.<sup>80,81</sup> This correction has remained stable in the long-term follow-up.<sup>83</sup>

**Surgical outcome**

Success rates for various transposition procedures have been reported from 50% to 80%.<sup>6,84</sup> It depends on the definition of a successful surgery and the amount of preoperative deviation in different studies. Residual LR function, duration of deviation, and degree of MR contracture have some effects on the outcome. For best results, the surgeon should consider all the effective factors before surgical planning.

**Undercorrection**

The rate of undercorrection after augmented VRT surgery has been reported at 0%–25%.<sup>20</sup> Recession of ipsilateral MR (if not performed before) and injection or reinjection of BTA are modalities that can complete the treatment. Recession of contralateral MR, with or without posterior fixation suture (Faden operation), is also available, mainly if a significant incomitance exists.<sup>20,85</sup> The transposition itself can also be revised: Partial transposition can be converted to full tendon, IRT can be added to SRT, and any type of the augmentations can be added.<sup>7</sup>



**Figure 3:** Modified Nishida procedure (transposition without tenotomy or muscle splitting) for abduction deficit, (a) Suture placement on muscle and sclera, (b) Final appearance of the transposed muscles

**Table 5: Effects of muscle union procedures on deviation, single binocular field, and abduction**

Study	Number of patients	Preoperative deviation (PD/mean ± SD)	Duration of deviation (months/mean ± SD)	Transposition	Adjunctive procedure	Follow-up (months/mean ± SD)	Outcome (EC, BSV, DC)
Frueh and Henderson, 1971 <sup>79</sup>	6	35±11.4	-	Jensen	MR recession	10.8±7.3	EC 32
Cline and Scott, 1988 <sup>73</sup>	-	-	-	Jensen	Adjustable MR recession	-	EC 51 BSV 41
Park <i>et al.</i> , 2015 <sup>76</sup>	17	53	-	Muscle union	None	12±9	EC 52
Inal <i>et al.</i> , 2020 <sup>77</sup>	36	47.7±18.4	46.3±84	Muscle union	LR plication Preoperative BTA in MR	15.2±9	EC 48.7 DC 2.4

PD: Prism diopter, SD: Standard deviation, EC: Esotropia correction (PD), BSV: Binocular single vision field improvement (°), DC: Duction correction, MR: Medial rectus, LR: Lateral rectus, BTA: Botulinum toxin A



**Table 6: Effects of Nishida procedure on deviation, single binocular field, and abduction**

Study	Number of patients	Preoperative deviation (PD/mean ± SD)	Duration of deviation (months/mean ± SD)	Transposition	Adjunctive procedure	Follow-up (months/mean ± SD)	Outcome (EC, BSV, DC)
Nishida <i>et al.</i> , 2005 <sup>80</sup>	3	58	-	Modified Nishida procedure	MR recession	-	EC 50
Muraki <i>et al.</i> , 2013 <sup>81</sup>	9	52.2±21	36±47.4	Modified Nishida procedure	With or without MR recession	14.3±28	EC 46.3
Sharma <i>et al.</i> , 2017 <sup>82</sup>	10	56±23.66	-	Modified Nishida procedure	Adjustable MR recession	6	EC 51
Sharma <i>et al.</i> , 2017 <sup>82</sup>	11	57.6±24.3	-	Modified Nishida procedure	Nonadjustable MR recession	6	EC 66
Sabermoghdam <i>et al.</i> , 2018 <sup>4</sup>	10	49.5±9	8-16	Modified Nishida procedure	MR recession	7±1.8	DC 2.1 EC 49

PD: Prism diopter, SD: Standard deviation, EC: Esotropia correction (PD), BSV: Binocular single vision field improvement (°), DC: Duction correction, MR: Medial rectus

### Overcorrection

Full-tendon VRT, with or without augmentation procedures, is proved to be a powerful procedure which can create a significant abduction force. Therefore, in esotropia <25–30 PD, especially when intervention on MR is indicated due to a positive forced duction test, one should be cautious about planning muscle transposition.<sup>16,19</sup> The patient might be able to control small amounts of overcorrection, with or without prism prescription.<sup>7</sup> However, significant overcorrections after transposition are better to be managed surgically including removal of the augmentation sutures,<sup>40,46,54</sup> recession of the transposed muscle,<sup>19,21</sup> ipsilateral MR resection or advancement,<sup>40</sup> and LR recession in the fellow eye.<sup>77</sup>

As mentioned before, performing transposition and MR recession on adjustable sutures may improve surgical outcomes and decrease the rate of over and undercorrections.<sup>12,30,48,50</sup>

### Bilateral sixth cranial nerve palsy

In bilateral cases, the amount of residual LR function may be different between two eyes. Therefore, surgeries should be planned accordingly. Bilateral cases usually need more than one intervention to correct esotropia, but in most cases, final alignment is acceptable.<sup>14,16,86</sup> Surgery on both eyes should not be performed at the same time, since the results may be unpredictable, and severe overcorrections may happen.<sup>26</sup>

## DISCUSSION

This review mainly includes different transposition procedures and their results for the management of strabismus caused by sixth cranial nerve palsy. Unfortunately, the published studies are not matched primarily for definition of complete sixth nerve palsy. Complete palsy of an extraocular muscle is documented mainly by forced generation test and saccadic velocity. However, these tests might not usually be applicable in the clinic, and the complete versus incomplete LR palsy is determined by the ability of the eye to pass midline. Therefore, the surgeon might not be able to detect residual LR function (probably due to MR contracture), and that would affect the

result of surgery, in terms of over or underestimation, and that causes the inaccuracy when comparing results of different studies. Moreover, patient selection is very divergent among the studies, and most of the studies are retrospective and included different etiologies, bilateral and unilateral cases, patients with previous surgeries, and those with other cranial nerve palsies in their analysis. In addition, the amount of primary deviation varies from 25 to more than 95 PD, even in one report. The duction grading criteria were not the same between studies, for example, limitation of abduction of –5 in one study was equal to –8 in another one. Some studies report multiple cases with or without MR weakening and even various augmentations in one series, but they finally have analyzed all cases together. Due to these existing limitations and the limited number of cases in each study, comparing different groups of patients is not possible. Furthermore, there is no randomized controlled trial in this topic to systematically compare different transposition procedures and their augmentations with each other.

Finally, there are two main pitfalls for management of sixth cranial nerve palsy: inability to distinguish between complete and partial LR paralysis that leads to LR ciliary artery disruption and failure to identify MR contracture, which causes undercorrection. Since there is no straightforward approach for surgical management of complete sixth cranial nerve palsy, we hereby provide information on effects and adverse effects of different transposition procedure and their modifications, so that the surgeon can decide for proper surgical approach considering each patient's unique situation.

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There are no conflicts of interest.

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