Results of end-to-side nerve coaptation in severe obstetric brachial plexus lesions and a review of the literature

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**Objective**  Options for nerve repair are limited in brachial plexus lesions with multiple root avulsions because an insufficient number of proximal nerve stumps are available to serve as lead-out for nerve grafts. End-to-side nerve repair might be an alternative surgical technique for repair of such severe lesions. In this technique, an epineurial window is created in a healthy nerve and the distal stump of the injured nerve is coapted to this site. Inconsistent results of end-to-side nerve repairs in traumatic nerve lesions in adults have been reported in small series. This article evaluates the results of end-to-side nerve repair in obstetric brachial plexus lesions and reviews the literature.

**Methods**  A retrospective analysis was performed of 20 end-to-side repairs in 12 infants. Evaluation of functional recovery of the target muscle was performed after at least 2 years of follow-up (mean, 33 mo).

**Results**  Five repairs failed (25%). Seven times (35%) good function (MRC at least 3) of the target muscle occurred in addition to eight partial recoveries (40%). In the majority of patients, however, the observed recovery cannot be exclusively attributed to the end-to-side repair. The reinnervation may be based on axonal outgrowth through grafted or neurolyzed adjacent nerves. It seems likely that recovery was solely based on the end-to-side repair in only two patients. No deficits occurred in donor nerve function.

**Conclusion**  This study does not convincingly show that the end-to-side nerve repair in infants with an obstetric brachial plexus lesion is effective. Its use cannot be recommended as standard therapy.
Obstetric brachial plexus lesions are the result of traction to the brachial plexus during delivery.\textsuperscript{1,2} Prognosis for the majority of patients is good; however, approximately 20\% to 30\% of these patients will not show complete spontaneous recovery.\textsuperscript{3} It is generally agreed that nerve repair can greatly improve the functional outcome in selected patients.\textsuperscript{4-7}

The goal of the surgical procedure is to restore nerve continuity to the target organ. In the case of neurotmesis, intraplexal nerve grafting is the most beneficial surgical procedure.\textsuperscript{5-8} In the case of root avulsions, however, proximal nerve stumps are not available to serve as an outlet. In these instances alternative repair techniques are required. Nerve transfer consists of a technique in which a healthy extra- or intraplexal “donor” nerve is transected and connected to the distal stump of an otherwise irreparable “recipient” nerve. The major disadvantage of nerve transfer is the sacrifice of donor nerve function and the limited number of potential donor nerves.

To further ameliorate functional results, investigation of alternative surgical approaches remains of paramount importance. In the literature, two techniques have been discussed in the past to improve functional results in adults. First, partial nerve transfer has been promoted by some authors in recent years.\textsuperscript{9-12} This technique consists of transection of a single fascicle of an intact donor nerve and coaptation to the distal stump of the injured recipient nerve. Functional deficits of the donor nerve were reported absent, transient, or minor.

Alternatively, end-to-side nerve repair consists of a technique in which the distal stump of the recipient nerve is attached to the side of an intact donor nerve, usually after an epineurial window has been created in the donor nerve. It is hypothesized that the attached denervated recipient nerve stimulates collateral sprouting of the axons of the intact donor nerve. From the axons of the intact donor nerve, a supplementary branch will grow into the recipient nerve, which leads to functional recovery of its function without a negative effect on the function of the donor nerve.

End-to-side repair regained attention subsequent to laboratory experiments by Viterbo et al.,\textsuperscript{13} and, thus far, clinical results were reported only in a limited number of adult patients.\textsuperscript{14-17}

This report presents the results of a pilot study in which end-to-side nerve coaptations were applied in severe cases of obstetric brachial plexus lesions.

**Patients and methods**

Operative records from the Institut de la Main, Paris, were retrospectively studied to identify all patients in whom end-to-side nerve coaptations were applied in the reconstruction of obstetric brachial plexus lesions.

We retrieved the records of 12 patients in which end-to-side nerve coaptations were used with a minimum of 2 years of follow-up evaluation. Surgery was performed at a mean age of 5 months (range 3-9 mo). One patient (Patient 11) demonstrated a bilateral paresis, which occurred after breech delivery. Because both sides were operated on with the technique under study, a total of 13 plexus repairs were evaluated.
Preoperative assessment demonstrated paralysis of the shoulder and biceps in 11 arms. One patient had slight shoulder movements (Patient 11 L). In one patient, proximal function had recovered spontaneously, but paralysis of extension of the arm, wrist, and fingers remained (Patient 12). Hand function was considered normal only in three patients.

Surgical exploration of 13 brachial plexus lesions showed avulsion or partial avulsion of a single nerve root (n=2), of two roots (n=8) or of three roots (n=3). These 27 root avulsions were accompanied by partial or complete neurotmesis of other brachial plexus elements. (Table 1)

The recipients in end-to-side repairs were C5 (n=4), C6 (n=7), superior trunk (n=2), C7 (n=6), and C8 (n=1). The donor nerves used were C5 (n=1), C7 (n=3), C8 (n=11), and T1 (n=5). Additional surgical therapy was performed using nerve grafts (n=4), or extra- to intraplexal nerve transfer (n=1). (Table 1)

Results were scored at regular intervals during visits to the outpatient clinic. The clinical result of the end-to-side repair was evaluated as follows: for C5, abduction and external rotation; for C6, the biceps muscle; for C7, the triceps together with extension of wrist and fingers. The clinical results were assessed before any secondary surgery (muscle transfer or correction osteotomy) was performed. The Medical Research Council (MRC) scale was adapted in that the maximum score of volitional muscle power was scored as M3 in infants younger than 5 years of age. Abduction was noted in degrees of active motion from the sagittal plane. External rotation was assessed with the arm in abduction and expressed with MRC classification as M3 when external rotation against gravity occurred or as M0 when it was absent. Recovery was defined as volitional muscle force M3 or more of the reinnervated muscle. A partial recovery was defined as recovery of the muscle to force M1 or M2.

Additionally, the overall surgical procedure was analyzed to assess whether pathways other than through the end-to-side repair may have partially or completely contributed to the recovery of the evaluated target muscles. If, for instance, C5 was grafted to the superior trunk, and end-to-side repair of C6 had been performed by coaptation to the spinal nerve C7, recovery of the biceps muscle was not exclusively attributed to the end-to-side nerve repair. (Figure 1) After all, the biceps muscle is innervated by both C5 and C6. Likewise, recovery of wrist extension was not exclusively attributed to end-to-side repair of C7 when C8 was uninjured.

**Surgical Technique**

All patients underwent operation by the senior author (AG). The brachial plexus was explored as was outlined in previous reports. The severity of the nerve lesion was assessed by intra-operative morphological findings, combined with results of selective monopolar stimulation. In the case of root avulsion combined with rupture of adjacent nerves, preferably severed spinal nerves were repaired with nerve grafts using the ruptured nerve stumps as lead-out. When proximal stumps were either not available, or looked poor on visual inspection or the number of proximal outlet was limited, end-to-side nerve coaptations were applied.
### Table 1: Patient-characteristics and outcome

<table>
<thead>
<tr>
<th>Pt</th>
<th>Diagnosis</th>
<th>Operative findings</th>
<th>Followup</th>
<th>Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>C5 partial neurotmesis</td>
<td>neurolysis C5 ES C6 on C8 ES C7 on C8</td>
<td>50</td>
<td>complete abd, ext rot M3 flex/ext elbow M3 ext wri/fing M3</td>
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<tr>
<td>2</td>
<td>C5 avulsion</td>
<td>grafting C6-C6 ES C5 on C7</td>
<td>48</td>
<td>no abd, ext rot M0 biceps M0 ext wri/fing M3</td>
</tr>
<tr>
<td>3</td>
<td>C5 neuroma</td>
<td>grafting C5-C5 grafting C5-C7 ES C6 on C8</td>
<td>26</td>
<td>abd 90°, ext rot</td>
</tr>
<tr>
<td>4</td>
<td>C5-C7 avulsion C8/T1 normal</td>
<td></td>
<td>32</td>
<td>no abd, ext rot M0 no elbow flex, triceps M3 co-contractions biceps-triceps ext wri M0, ext fing M2 flex wri/fing M3</td>
</tr>
<tr>
<td>5</td>
<td>C5 neuroma C6 avulsion C7-T1 normal</td>
<td>grafting C5-C5 ES C6 on C7</td>
<td>40</td>
<td>complete abd ext rot M3 biceps M3</td>
</tr>
<tr>
<td>6</td>
<td>C5-C7 avulsion C8/T1 normal</td>
<td>neurotisation C4-C5/C6 ES C7 on C8</td>
<td>33</td>
<td>no abd, ext rot M0 biceps M0, no elbow flex triceps M2, flex/ext wri M2</td>
</tr>
<tr>
<td>7</td>
<td>C5/C6 avulsion C6 partial neurotmesis C7-T1 normal</td>
<td>ES sup trunk on C8 neurolysis C7</td>
<td>54</td>
<td>no abd, ext rot M0 biceps M0</td>
</tr>
<tr>
<td>8</td>
<td>C5/C6 avulsion C7 partial avulsion C8/T1 normal</td>
<td>neurolysis C7 ES C5/C6 on C8/T1</td>
<td>24</td>
<td>abd 120°, ext rot M3 biceps M3 ext wri M3, ext fing M3</td>
</tr>
<tr>
<td>9</td>
<td>C5/C6 avulsion C7 partial neurotmesis C8/T1 normal</td>
<td>neurolysis C7 ES C5 on C7 ES C6 on C8</td>
<td>30</td>
<td>no abd, ext rot M0 biceps M3 ext wri M3, ext fing M2 flex wri/fing M3</td>
</tr>
<tr>
<td>10</td>
<td>C5 neuroma C6-C8 avulsion T1 normal</td>
<td>grafting C5-ST ES C7 on C8 on T1</td>
<td>24</td>
<td>no abd, ext rot M0 biceps M2 ext wri/fing M0, flex wri/fing M5</td>
</tr>
<tr>
<td>11R</td>
<td>C5/C6 partial avulsion stim</td>
<td>ES PDST on C8</td>
<td>25</td>
<td>no abd, ext rot M0 biceps M0 triceps M3, ext wri/fing M2</td>
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<tr>
<td>11L</td>
<td>C5/C7 avulsion some response on stim C5/C8/T1</td>
<td>ES C6/ C6 on C5 ES C7 on C8</td>
<td>24</td>
<td>abd 90°, ext rot M0 biceps M3 flex wri/fing M3 ext wri M0</td>
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<tr>
<td>12</td>
<td>conducting neuroma of the sup trunk C7 avulsion</td>
<td>ES C7 on C8</td>
<td>24</td>
<td>abd 130°, ext rot M3 biceps M3 triceps M3, ext wri/fing M3</td>
</tr>
</tbody>
</table>

Pt – patient no.; 11R – patient 11 Right side; L – Left side; ES – end-to-side coaptation; ST – superior trunk; PDST – posterior division of superior trunk; stim – selective perioperative stimulation; n/a – not applicable; FU – follow-up (in months); Examination, muscle power in adapted MRC-scale (maximum M3) or degrees of movement; abd – abduction; ext rot – external rotation; flex – flexion; ext – extension; wri – wrist; fing – fingers; Nerve, recipient nerve evaluated for recovery; Recovery: part – partial; Excl – recovery exclusively attributed to the end-to-side repair Yes/ No; Alt – alternative pathway repaired or left intact, which could explain the observed recovery.
In all patients but one (Patient 1) the epineurial sleeve of the donor nerve was opened. If present, the spinal ganglion was resected from the avulsed recipient nerve. Biological glue was applied to secure the coaptation; in one patient (Patient 2), microsurgical sutures were used as well. A post-operative restraint was used for 3 weeks.

**Results**

Twelve patients were evaluated after a mean follow-up period of 33 months (range 24-54 mo), 20 end-to-side coaptations were analyzed in 13 plexus repairs. (Table 2)

The different recipient nerves are summarized in Table 2. The C6 root was the recipient nerve seven times. In five patients good recovery of the biceps muscle took place (Patients 1,5,8,9, and 11 L); one partial recovery (Patient 3) and one failure (Patient 4) occurred. In only two patients (Patients 8 and 9) the recovery of the biceps could be exclusively attributed to the end-to-side repair because alternative pathways through adjacent nerves were absent. In one of these patients (Patient 8), shoulder function recovered as well, which can most likely be attributed to the end-to-side repair.

Functional deficits of the donor nerve innervated functions could not be detected; extension of the arm, wrist, and fingers was powerful after using C7 as donor and no impairment of hand function could be demonstrated after using C8 and/or T1.

**Discussion**

It is still not fully clear which techniques should be applied in the treatment of OBPLs in infants with multiple root avulsions. Both extra-intraplexal and intraplexal nerve transfers have been proposed. This article describes the results of 20 end-to-side repairs in 12 patients. Good recovery of the target muscle was found seven times; there were five partial recoveries and eight failures. In the majority of patients, however, the observed recovery could not be exclusively attributed to the end-to-side nerve repair. The recovery could have also been based on other neighboring neural pathways, which were surgically treated by means of nerve grafting or neurolysis, or remained

**Table 2: Outcomes**

<table>
<thead>
<tr>
<th>Recipient</th>
<th>No recovery</th>
<th>Partial recovery</th>
<th>Recovery</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>alt</td>
<td>alt excl</td>
<td>alt excl</td>
<td></td>
</tr>
<tr>
<td>C5</td>
<td>3</td>
<td>-</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>C6</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>sup trunk</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>C7</td>
<td>2</td>
<td>3</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>C8</td>
<td>-</td>
<td>1</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>Total</td>
<td>8</td>
<td>5</td>
<td>3</td>
<td>20</td>
</tr>
</tbody>
</table>

Summary of recovery, grouped by recipient nerve
sup trunk – superior trunk; alt – alternative pathway present than end-to-side repair; excl – exclusively attributed to the end-to-side repair
intact. Because most of the target muscles are multisegmentally innervated, the contribution of the end-to-side repair is difficult to evaluate.

In this study, restoration of biceps function after end-to-side repair of C6 was exclusively attributed to the end-to-side repair only when a contribution from recovery through the C5 root could be excluded. Full recovery of the biceps muscle through the spinal nerve C7 was considered highly unlikely (Patients 8 and 9). Some C7 contribution to biceps function, however, cannot be completely ruled out.

Reinnervation of the target muscles occurred in only two patients (Patients 8 and 9) in the present series, whereas reinnervation through alternative pathways was considered highly unlikely. (Figure 2) In both patients, elbow flexion recovered; in one patient, shoulder motion recovered as well.

The end-to-side technique did not affect the donor nerve function in this series, and can, therefore, be considered a safe procedure.

Based on the present results, the clinical use of end-to-side repair was discontinued. When a proximal stump is available, nerve grafting is indisputably preferred. In the case of root avulsion, nerve transfer is a generally accepted technique, although

**Figure 1:** Example of C6-C7 end-to-side nerve coaptation

Note the presence of alternative pathways for reinnervation (case 5). Root C5 was ruptured and C6 was found avulsed. A grafting C5-C5 was performed together with end-to-side repair of C6 on C7. Recovery of the biceps could either have resulted from the nerve grafting procedure (intersected line) or from the end-to-side repair (dotted line)

**Figure 2:** Example of double end-to-side nerve coaptation

In this case recovery of shoulder function and biceps through adjacent pathways was considered very unlikely (case 8). Roots C5 and C6 were found avulsed, and were attached end-to-side to C8 and T1, respectively. Root C7 was partially avulsed, and was left untouched.
the loss of function of the donor nerve has not been studied systematically. Donor nerves that have been used for nerve transfer in infants are: the intercostal nerves, the accessory nerve, the pectoral nerves, the phrenic nerve, the contralateral spinal nerve C7 and the hypoglossal nerve. More recently, partial nerve transfer using a single fascicle from the ulnar nerve was advocated for biceps reanimation.9,11

**End-to-side coaptation – a critical review**

Interest in end-to-side nerve coaptations was renewed by Viterbo et al. in an experimental rat study. The technique has frequently been evaluated in the rat sciatic nerve, in which the peroneal nerve is cut and the distal stump is attached in an end-to-side fashion to the tibial nerve. In most studies, the epineurium of the donor nerve was resected to create an epineurial window to facilitate axonal sprouting. In these studies, reinnervation was evaluated by histological examination of the recipient nerve, histological examination of the target muscles, muscle weight, titanic force after electrical stimulation, nerve conduction studies, and functional results.

From these experiments, it is concluded that functional reinnervation based on end-to-side coaptation can occur. However, the results are inferior to “classic” end-to-end repair. Restoration of sensory function seems to be more successful than restoration of motor recovery.

The hypothesis that is commonly put forward to explain the observed recovery of the target nerve is that of collateral sprouting of axons into the donor nerve. Collateral sprouting involves axonal branching of the donor nerve at the coaptation site. A supplementary branch splits off the donor nerve axon and subsequently grows in the attached recipient nerve, which eventually results in functional reinnervation of the target muscle. The motor neuron in the spinal cord is also thought to have a connection to the “original” muscle innervated by the donor nerve to the target muscle. This is elucidated in double-labeling studies, in which neurons in the spinal cord were found that contained a retrograde tracer from both the donor nerve and the recipient nerve.

This hypothesis is not undisputed, and a number of alternative explanations have been put forward.

First, axons traveling in the epineurium of the donor nerve were found, which was interpreted as “contamination”: outgrowing axons from the proximal part of the severed recipient nerve were guided to the distal stump by the epineural tissue of the donor nerve. It was shown that the epineurium of an intact nerve could serve as a conduit in the same way as a nerve graft. Some investigators tried to overcome contamination by burying the proximal stump in muscles, by redirecting the proximal stump, or by connecting the recipient nerve to a contralateral (thus more distant) donor nerve.
Second, and probably most important, the concept of collateral sprouting from an intact donor nerve is not accepted by most critics. From a neurobiologist’s view the thought that peripheral axons regenerate across an intact perineurium is generally rejected; it was suggested, therefore, that the integrity of the perineurium must have been damaged in end-to-side nerve repairs. In other words, it is hypothesized that subclinical damage to the donor nerve occurs at the time of end-to-side coaptation, after which severed axons sprout “accidentally” into the attached recipient nerve, instead of into the distal part of the donor nerve. Thus, reinnervation of the recipient nerve must be considered to result from unintentional partial nerve transfer instead of from true collateral sprouting.

This alternative explanation is supported by laboratory experiments in which mechanical trauma to the donor nerve was shown to enhance regeneration. Likewise, it was found that an increase of the epineurial window enhances the number of axons in the recipient nerve. Some authors conclude that recipient nerve function depends on the amount donor nerve axonotomy. This view corresponds with electromyographic findings of temporary denervation in target muscles of the donor-nerve, although functional evaluation could not detect a deficit.

The presence of double-labeled motor neurons in the spinal cord is not necessarily contradictory to the alternative hypothesis of unintentional damage to the donor nerve. In a recent quantitative study of end-to-side coaptation the number of double-labeled motor neurons proved to be low. Only 2.5% of motor neurons were double-labeled, compared with 16% of single-labeled motorneurons with retrograde tracing from the recipient nerve. After a crush lesion or graft repair, 2.5 to 6% double-labeled motor neurons can be found in the spinal cord. The presence of double-labeled motor neurons is, therefore, not definite proof of true collateral sprouting, but may be a normal finding in peripheral nerve regeneration.

True collateral sprouting would result in a double connection of the motor neuron to two different muscles, which, in theory, could lead to synchronous opposite movements. The concept of such a double projection is rejected by some critics. Rovak et al. separate functional and anatomic double connections; in their view anatomical double connections are accepted, but axons establishing functional neuromuscular connections through an end-to-side coaptation must relinquish functional connections to their original targets.

The results of end-to-side coaptations in humans were summarized by Al Qattan. It was concluded that clinically functional motor recovery is not predictable in the human patient. Most reports failed to demonstrate useful function after end-to-side coaptation. Especially successful outcomes after end-to-side repair at the level of the brachial plexus were not reported in adults.

The better results in the present series of infants, although still unsatisfactory, may be explained by the presumed superior nerve regeneration in infants as compared with adults. Clinically, hand function showed better recovery after surgical repair in obstetric brachial plexus injuries than was reported in adult traumatic injury. Laboratory reports suggested better regeneration capacities of nerves in young lambs.
as compared with adult sheep. Young rats showed better results after end-to-side nerve repair than older animals. Additionally, the plasticity of the spinal cord motor neurons was found to be superior in young animals as compared with adult ones. Such reprogramming of the spinal cord may play a role in infants with OBPLs adding to recovery through adjacent nerves.

**Conclusion**

In this report, results are presented of a pilot series of end-to-side nerve repair in severe obstetric brachial plexus lesions. This technique seems to be safe, in that the donor nerve does not decline in function. Our results show return of function in some of these patients, but the exact source of reinnervation could not be unequivocally contributed to the end-to-side repair. In the majority of patients, only limited or no function returned. On the basis of these results, there is no substantial support to use the end-to-side nerve repair technique in the reconstruction of severe obstetric brachial plexus lesions. The clinical use of end-to-side repair was discontinued.
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45 Al Qattan MM, al Thunyan A. Variables affecting axonal regeneration following end-