Outcomes of Direct Muscle Neurotization in Pediatric Patients with Facial Paralysis

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Background: Multistage reconstructive procedures are often required to try to restore the emotional potential of human expression in cases of facial paralysis. In this study, the senior author's (J.K.T.) experience with the technique of direct nerve to muscle neurotization as a part of multistage facial reanimation procedures is presented. Age, denervation time, etiology of the lesion, previous reconstructive procedures, and types of muscles responsible for animation were analyzed to make evidence-based recommendations on the indications of the technique as well as its role and effectiveness in facial reanimation.

Methods: Retrospective review of 37 pediatric patients who underwent direct muscle neurotization took place. The patients were divided into three groups, depending on the region that direct neurotization was aiming to augment. Group A involved 28 patients for eye closure and blink, group B included 15 patients for smile, and group C included 19 patients for depressor augmentation.

Results: Twenty patients were female and 17 male. Patient age ranged from 1 to 16 years, with a mean age (±SD) of 9 ± 2.8 years. Denervation time ranged from 3 months to 15.25 years, and the mean denervation time was 6.72 years. Electromyographic scoring of the neurotized muscles showed an overall mean improvement of 36 percent for eye closure, 34.25 percent for blink, 37 percent for smile augmentation, and 30 percent for depressor function restoration.

Conclusion: Direct muscle neurotization has a valid role in pediatric facial reanimation procedures, as it augments and promotes expressivity. (*Plast. Reconstr. Surg.* 124: 1486, 2009.)

Restoration of emotional and voluntary expression comprises the aim of facial reanimation in patients with facial paralysis. When the palsy involves children, the problem acquires additional dimensions. Depression, isolation, withdrawal, problematic development of their sense of self and body image, and communicational, educational, psychological, and socialization problems are some of the sequelae.

The role of the reconstructive surgeon is fundamentally linked with restoration of facial expression in these patients who are in their most vulnerable age. This study presents the experience of a single surgeon (J.K.T.) in using the direct muscle neurotization procedure in facial paralysis in the pediatric population. The procedure has been used to augment the function of the eye sphincter, to improve the smile, and to strengthen the depressor muscle, as part of multistaged facial reanimation surgery. The aim is to offer evidence-based evaluation of the technique and definition of its effectiveness after systematic review of the experience in our center.

HISTORICAL REVIEW

The surgical technique of directly implanting motor nerves into paralyzed muscle was first described by Heineke[1] in 1914. He hypothesized that terminal ramification of the axis cylinder is involved down to the delicate endplates and bulbs. Steindler[2] and Erlacher[3] in 1915 independently reported successful direct muscle neurotization in their animal model studies.

Implantation of peripheral nerves in normally innervated muscles was attempted in a dog experimental model by Steindler[4] and in a rabbit model by

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Elsberg.[5] Both stated, however, that "no functional connections were established between the implanted nerves and the muscles."

Later, in the middle of the twentieth century, Gutmann and Young[6] published their seminal study in a rabbit model, on the effect of reinnervation on various periods of muscle atrophy. Detailed histological and morphological changes of the process were also described. Aitken[7] described a method of implanting nerves in muscle with minimal injury to the muscle. He observed that nerves regenerating into a denervated muscle formed functioning motor end plates in more than one location around the implantation site.

Sorbie and Porter[8] in a dog model made force measurements of directly neurotized muscles, with results ranging from 44 to 95 percent of the original muscle force. Histology showed that newly formed end plates were concentrated around the implanted nerve stump.

Sakelarides et al.[9] in a dog model divided the implanted nerve into several fascicles, which resulted in a consistent 60 to 75 percent of normal muscle functional recovery and a macroscopic appearance quite similar to the normal muscle.

Brunelli and Brunelli[10] showed in a rabbit model that motor function recovered and new motor end plates were formed in the "aneural" zone of the lateral head of the gastrocnemius muscle 4 weeks after direct muscle neurotization with the motor branch of the peroneal nerve. Good results were also demonstrated in eight clinical cases of severely damaged muscles with avulsion of the supplying nerve and direct muscle neurotization with a nerve graft.

Payne and Brushart[11] also described the location and distribution of the newly formed end plates in the rat soleus in relation to the distance from the implanted nerve. They further confirmed that new end plates can form in the previously "aneural" part of the muscle.

Nerve-Muscle Junction Formation

The implanted nerve influences the development of ectopic nerve–muscle junctions by inducing local alteration of the muscle fiber surface, making it a preferred site for the subsequent appearance of acetylcholinesterase. In addition, it induces muscle activity,[12,13] which is an important factor for the initial formation, the subsequent maintenance, distribution, and further metabolism of acetylcholinesterase in the neuromuscular junction.[14–18]

Recent studies[19,20] have described this morphological and functional differentiation in molecular terms. The role of neuregulins, which are cholesterol-like neuronal adhesion proteins, has been shown to be primarily important. They control the up-regulation of the acetylcholine receptor activity at the neuromuscular junction, mediating the formation of new end plates. In animal studies,[21,22] the consequences of altering the genetic expression of these proteins have been reported to be detrimental to neurons and their interaction on a cellular level with adjacent tissues.

Morphologic Changes

When direct muscle neurotization takes place, the new motor nerve supply leads to rearrangement in the enzyme[23] and histochemical patterns[24] of the affected muscle fibers. The process of fiber-type changes occurs with some delay after establishment of functional neuromuscular connections by regenerating axons.[25] Reorganization of the normal motor unit architecture is reflected in the occurrence of local groups of histochemically similar fibers in reinnervated muscle, a phenomenon known as "fiber-type grouping." The clustering of muscle fibers innervated by one motor axon is due mainly to intramuscular sprouting of regenerating motor axons taking over adjacent denervated muscle fibers that previously belonged to different motor units.

Therefore, the number and the distribution of the fiber clusters depend on the number and location of the intramuscular axonal sprouts. A higher number of widely distributed axonal sprouts results in a more organized arrangement of fiber groups.[26,27]

Surgical Technique

Direct muscle neurotization is performed by implanting the interposition nerve graft directly into the substance of the muscle. The proximal end of the nerve graft is connected to the motor donor nerve. The distal end, which is destined to neurotize the muscle, is split into two to three fascicles, and each fascicle is implanted through a separate incision in the epimysium. After that, the epimysium is sutured over the implanted fascicle or fascicular group using 9-0 nylon by taking small bites of the epineurium so as to secure the distal nerve ending in position.[28]

In orbicularis oculi direct muscle neurotization, the distal end of the interposition graft is usually divided into two segments, which are further divided into two to three fascicles. One segment is for the upper and the other for the lower orbicularis oculi muscle.[29] Motor donors are usually the selectively neurectomized branches of the

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contralateral unaffected facial nerve[28,29] or, in cases of bilateral palsy, an ipsilateral unaffected motor donor.

Levator anguli oris muscle can similarly be neurotized by the corresponding contralateral zygomatic branch and the depressor anguli oris by the contralateral mandibular branch, both via cross-facial nerve grafts. In cases of bilateral facial paralysis (Moebius syndrome), contralateral motor donors are usually unavailable, and thus ipsilateral motor donors are used, such as the XII, V, and XI cranial nerves or motor fibers from the ipsilateral cervical or brachial plexus (C7 root).

PATIENTS AND METHODS

Data collection took place by reviewing retrospectively the charts of 102 patients who underwent direct muscle neurotization at some point of their multistaged facial reanimation procedures between January of 1981 and January of 2007. This study considered only the pediatric population, which consisted of 37 patients. Inclusion criteria included complete obstetric, medical, and surgical history; detailed preoperative evaluation, including physical, neurological, and electrophysiological examination; detailed examination of the facial musculature; and a follow-up period of 18 months or longer. Demographics are shown in Table 1 and the etiology of facial paralysis in Figure 1.

Table 1. Patient Demographics

	Value
Total no. of patients	37
Male, *n*	17
Female, *n*	20
Mean age	9 ± 2.8 yr
Mean denervation time	6.72 yr
Mean denervation time in cases in which ipsilateral motor donors were used	55 mo
Mean denervation time in cases in which contralateral motor donors were used	97 mo
Left-sided facial paralysis	11
Right-sided facial paralysis	15
Bilateral facial paralysis	11

Preoperative Evaluation

Preoperative evaluation included detailed medical and surgical history, specifics surrounding the onset and the etiology of the paralysis, obstetric history, any previous treatments, and examination of all cranial nerves. Needle electromyography, nerve conduction studies, and documentation of facial movements with standardized photographs and video protocol were performed. In developmental facial paralysis, computed tomography of the facial canal and temporal bone bilaterally or magnetic resonance imaging was performed.

Concerning eye closure and involuntary blinking, each patient was videotaped in a seated position, with a custom-made head restrainer for stabilization of the head and avoidance of lateral movements. The patients were then asked to look straight at the camera and to perform a specific series of functions, including closing their eyes lightly and then tightly several times. Each patient was then asked not to blink deliberately or close the eyes for 4 minutes, so as to record involuntary blinking. For smile documentation, the patients were asked to demonstrate a slight smile and a full denture smile, and to depress their lower lips without smiling, to record the depressor complex function. For additional assessment of the emotional-involuntary facial movements,

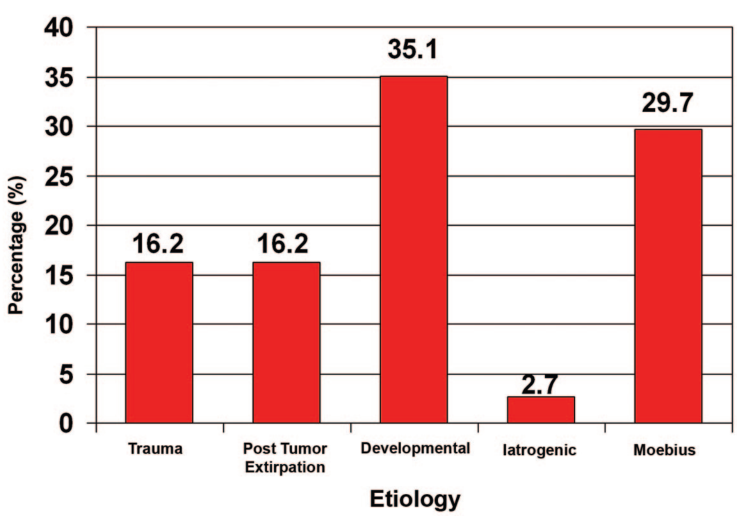

Fig. 1. Etiology of facial paralysis in the pediatric population.

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patients were also asked to talk and watch a funny video while their expressions were being continuously recorded.

Postoperative Evaluation

At all subsequent follow-up visits, detailed physical examination, electrophysiological studies, and the same standardized video recording with thorough documentation of facial movements were performed under the same conditions and always using the same established protocol. Three independent investigators reviewed the preoperative and postoperative videotapes of all the patients separately and rated the preoperative degree of functional impairment and the postoperative functional return using the grading systems shown in Tables 2 through 4. The senior author (J.K.T.) did not take part in the scoring process.

The intraclass correlation coefficient was 0.76, signifying a substantial degree of agreement among the investigators. The video material was the same, and the scoring took place under almost identical conditions.

Table 2. Aesthetic and Functional Grading System Used for Smile*

Group	Grading	Result	Description
I	1	Poor	Deformity, no contraction
II	2	Fair	No symmetry, bulk, minimal contraction
III	3	Moderate	Moderate symmetry and contraction, mass movement
IV	4	Good	Symmetry, nearly full contraction
V	5	Excellent	Symmetrical smile with teeth showing, full contraction

*From Terzis JK, Noah ME. Analysis of 100 cases of free-muscle transplantation for facial paralysis. *Plast Reconstr Surg.* 1997;99:1905–1921.

Table 3. Aesthetic and Functional Grading System Used for the Depressor Muscle*

Grade		
Scale	Designation	Description
0	Poor	Total paralysis
0.5	Fair	Trace contraction with no movement
1	Moderate	Observable movement but inadequate excursion and without symmetry
1.5	Good	Almost complete excursion of lower lip with depression and full denture smile
2	Excellent	Normal symmetric movement of lower lip

*From Terzis JK, Kalantarian B. Microsurgical strategies in 74 patients for restoration of dynamic depressor muscle mechanism: A neglected target in facial reanimation. *Plast Reconstr Surg.* 2000;105:1917–1931.

Statistical Evaluation

Preoperative and postoperative scores comparisons were evaluated by using Wilcoxon signed rank test (in every case that the ordinal data of

Table 4. Scoring System for Eye Closure and Blink*

Group	Grade	Designation	Description
Grading of Eye Closure			
I	1	Poor	No eye closure (no contraction); maximal scleral show
II	2	Fair	Poor eye closure (minimal contraction); 2/3 scleral show
III	3	Moderate	Incomplete eye closure; 1/3 scleral show
IV	4	Good	Nearly complete eye closure; minimal scleral show
V	5	Excellent	Complete eye closure; no scleral show
Grading of Blink			
I	1	Poor	No blink
II	2	Fair	Minimal blink (contraction)
III	3	Moderate	Initiation of blink present but only 1/3 amplitude
IV	4	Good	Some coordinated blink but only 2/3 amplitude
V	5	Excellent	Synchronous and complete blink present

*From Terzis JK, Bruno W. Outcomes with eye reanimation microsurgery. *Facial Plast Surg.* 2002;18:101–112.

Table 5. Scores of the Specific Facial Functions before and after the Procedure of Direct Muscle Neurotization*

Function	Preoperative Score	Postoperative Score	Normal Scores
Eye closure	2 (range: 1)	4 (range: 1)	5
Blink	2 (range: 1)	3 (range: 1)	5
Smile reanimation	1 (range: 1)	4 (range: 1)	5
Depressor	0.5 (range: 0.5)	1.75 (range: 0.25)	2

*The values are the median scores obtained by the three independent investigators. The last column shows the normal scores as used in the grading systems shown in Tables 2 through 4.
Range corresponds to maximum value minus minimum value.

Table 6. Direct Neurotization of Facial Muscles*

Facial Muscle	No. of Times Directly Neurotized
Orbicularis oculi	30 (25 patients)†
Depressor anguli oris	13
Levator anguli oris	1
Orbicularis oris	1
Total	45 procedures in 37 pediatric patients

*The number of the procedures is shown. It is also noted that several patients underwent direct neurotization of the same type of target muscle more than once or/and of multiple target muscles.
†Five patients had both right and left orbicularis oculi muscle directly neurotized.

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Tables 2 through 4 were used). In addition, results are presented in the form of median values, and variation is indicated by ranges. Mean values plus/minus standard deviation were also used where appropriate (interval and ratio data), as mentioned throughout the text. Spearman's rank correlation coefficient (ρ_s) was used when testing for an association between two variables in data with matched pairs based on alpha = 0.05 and the corresponding number of patients in the investigated group.

Table 7. Direct Neurotization of Muscles That Have Been Used for Specific Facial Muscle Substitution*

Target Muscle	No. of Times Directly Neurotized
Temporalis for eye	2
Digastric for depressor	6 (5 patients)†
Anterior sternocleidomastoid for depressor	1
Free platysma for eye sphincter	1
Free gracilis for smile	7
Free pectoralis minor for smile	7
Total	24 procedures in 37 pediatric patients

*The number of the procedures is shown. It is also noted that several patients underwent direct neurotization of the same type of target muscle more than once or/and of multiple target muscles.
†One patient underwent direct neurotization of both of the transferred anterior digastric bellies for depressor function.

Table 8. Direct Neurotization of Facial Muscles and Improvement in Corresponding Function*

	Before Direct Neurotization	After Direct Neurotization	Improvement (%)
Orbicularis oculi	1.5	3.5	50
Depressor anguli oris	0.5	1.5	50
Levator anguli oris	1	2	25
Orbicularis oris	1	2	25

*The improvement comprises the percentage conversion of the difference between preoperative and postoperative median scores in the function that each muscle is responsible for. Please note that scores are not mere numeric values but correspond to specific increments in the grading systems mentioned in the text. Thus, the percentages reflect the improvement based on these increments.

RESULTS

Direct muscle neurotization concerned three types of muscle: native facial muscles, local pedicled muscles that were transferred to substitute or augment a specific function, and free transplanted muscles. Several patients had more than one directly neurotized target muscle.

The population was divided into three groups, depending on the function that was being aug-

Table 10. Number of Neurotization Procedures Performed in Each Stage

Neurotizations	No.
1st stage	18
2nd stage	29
3rd stage	18
4th stage	2
5th stage	2
Total	69

Table 11. Preoperative and Postoperative Electromyographic Findings of Facial Muscles (Motor Unit Potentials)*

Facial Muscle	Preoperative Electromyography	Postoperative Electromyography
Orbicularis oculi	1.12	2.31
Depressor anguli oris	1.14	2.76
Levator anguli oris	1	2
Orbicularis oris	1	2
Blink reflex†	34.25%	

*Motor unit potentials range from 0 to 3, and the shown values comprise the mean number of motor unit potentials in each muscle category before and after direct neurotization of that muscle.
†The percentage in blink reflex represents the mean improvement in the electromyographic response latency after electrical stimulation of the R1, and ipsilateral and contralateral R2 components. The initial measurements were in milliseconds, and the difference of the mean scores was converted into a percentage.

Table 9. Direct Neurotization of Muscles That Have Been Used for Specific Facial Muscle Substitution and Improvement in Corresponding Function*

	Functional Substitution of	Before Direct Neurotization	After Direct Neurotization	Improvement (%)
Mini-temporalis	Orbicularis oculi	2.5	3.5	25
Free platysma	Orbicularis oculi	3	4	25
Free gracilis	Levator anguli oris	2	3	25
Free pectoralis minor	Levator anguli oris	2	3	25
Digastric	Depressor	0.5	1.75	62.50
Anterior sternocleidomastoid	Depressor	2	2	0.00

*The improvement comprises the percentage conversion of the difference between preoperative and postoperative median scores in the function that each muscle is responsible for. Please note that scores are not mere numeric values but correspond to specific increments in the grading systems mentioned in the text. Thus, the percentages reflect the improvement based on these increments.

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mented or restored. Each group was further divided into two subgroups as follows:

Group A consisted of patients undergoing procedures for eye closure and blink restoration. Subgroup 1a consisted of patients undergoing direct muscle neurotization of the orbicularis oculi muscle, while subgroup 2a included patients undergoing direct muscle neurotization of muscle targets that have been used to substitute the orbicularis oculi muscle.

Table 12. Preoperative and Postoperative Electromyographic Findings of Other Muscle Targets (Motor Unit Potentials)*

Muscle Target	Preoperative Electromyography	Postoperative Electromyography
Mini-temporalis for eye	0.5	2.25
Digastric for depressor	1.95	2.79
Anterior sternocleidomastoid for depressor	1	2
Free platysma for eye	2.7	3
Free gracilis for smile	1.77	2.75
Pectoralis minor for smile	1.25	2.58

*Motor unit potentials range from 0 to 3 and the shown values comprise the mean number of motor unit potentials in each muscle category before and after direct neurotization of that muscle (0 corresponds to complete denervation, and 3 signifies complete electrogenesis).

Group B included patients who underwent procedures for smile augmentation. Subgroup 1b included one procedure of direct muscle neurotization of the levator anguli oris, and subgroup 2b consisted of patients who underwent direct muscle neurotization of other muscles that had been used for smile augmentation.

Group C consisted of patients who underwent direct muscle neurotization procedures for depressor reanimation or augmentation. Subgroup 1c consisted of patients who underwent direct muscle neurotization of the depressor complex, and subgroup 2c included patients who underwent direct muscle neurotization of other muscles that had been used for depressor substitution.

The median preoperative and postoperative scores for each group are shown in Table 5. The included procedures and the functional improvement in each group and subgroup are shown in Tables 6 through 9.

The number of direct muscle neurotization procedures per stage in the population is shown in Table 10. Motor unit potentials (needle electromyographic findings) before and after direct muscle neurotization of facial muscles are shown in Table 11, and motor unit potentials of other muscles are shown in Table 12.

The improvement regarding the evoked motor unit potentials after direct muscle neurotization of facial muscles and the improvement of the other muscle targets are presented in Figures 2

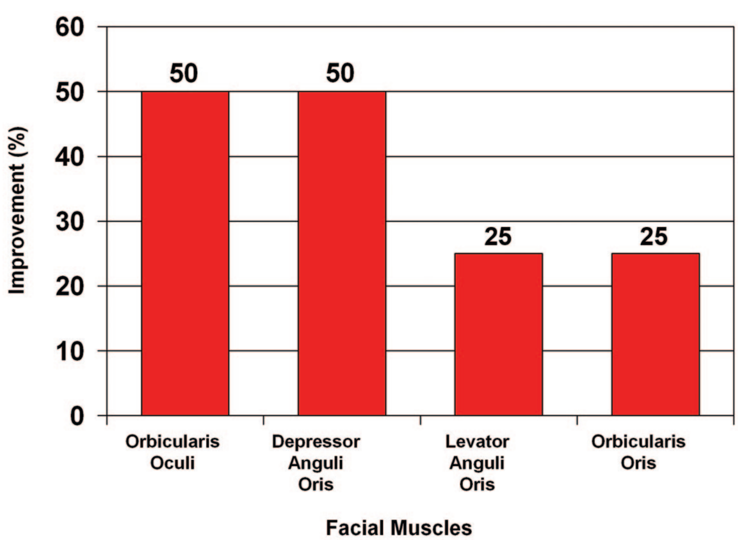

Fig. 2. Improvement in the electromyographic scores of the facial muscles after being directly neurotized. The percentages represent gain in the 0 to 3 scale of measurement during the electromyographic study [with 0 for no evoked potentials and 3 for the maximum number of active motor units (full electrogenesis)].

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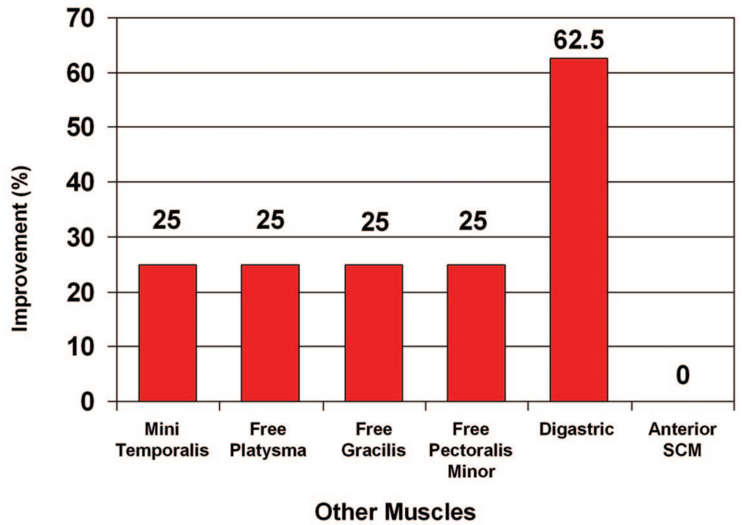

Fig. 3. Improvement in the electromyographic score of the other muscle targets after being directly neurotized. The percentages represent gain in the 0 to 3 scale of measurement during the electromyographic study [with 0 for no evoked potentials and 3 for the maximum number of active motor units (full electrogenesis)]. SCM, sternocleidomastoid muscle.

Table 13. Number of Patients per Group That Achieved a Moderate or Better* Postoperative Result

Group	Subgroup	No. of Patients	No. of Patients with Moderate or Better Postoperative Result (%)
A	1a	25	23 (92)
	2a	3	3 (100)
B	1b	1	1 (100)
	2b	14	12 (86)
C	1c	13	12 (92)
	2c	6	5 (83)

*Moderate or better result has a score of ≥3 in the grading systems used for smile and eye closure and a score ≥ 1 in the grading systems used for the depressor.

Group A, patients who underwent procedures for eye closure and blink restoration; subgroup 1a, patients of group A with direct neurotization of the orbicularis oculi muscle; subgroup 2a, patients of group A with direct neurotization of other muscles, used for eye sphincter substitution; group B, patients who underwent procedures for smile restoration; subgroup 1b, patients of group B with levator anguli oris muscle direct neurotization; subgroup 2b, patients with direct neurotization of other muscles used for smile restoration; group C, patients who underwent procedures for depressor reanimation; subgroup 1c, patients with direct neurotization of the depressor muscle; and subgroup 2c, patients with direct neurotization of other muscles used for depressor substitution.

and 3, respectively. All patients in all groups experienced improvement in the postoperative function of the muscle being neurotized. The number of patients per group who achieved a moderate or better postoperative outcome is shown in Table 13.

The most commonly used motor donor was the contralateral orbicularis oculi muscle branch. The use of the various motor donors is shown in Table 14.

Age was negatively correlated to the functional result after direct muscle neurotization at a statistically significant level. The majority of the most favorable functional improvement of facial muscles after direct muscle neurotization (moderate or better postoperative score) was observed in patients younger than 13 years old (Table 15). Conversely, age was not a statistically significant factor in patients who underwent direct muscle neurotization of transferred muscles.

Direct muscle neurotization of facial muscles resulted in a more favorable electromyographic improvement when the preoperative electromyographic score was greater than 2+ ($p < 0.05$). There was no statistically significant difference in improvement related to previous surgical history, gender, or etiology. In this study, denervation time had a statistically significant negative correlation to the functional as well as to electromyographic improvement (-0.31; $p < 0.05$) of directly neurotized facial muscles only. There was no statistically significant correlation between denervation time and postoperative outcome in cases of other muscle transfers.

No complications relevant to the procedures of direct muscle neurotization were observed. Representative cases are shown in Figures 4 through 7.

DISCUSSION

The key factors that determine success with the direct muscle neurotization procedure are the clinical presentation and the age of the patient as well as the findings from electromyography.

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Table 14. Main Motor Donors with the Respective Muscle Targets, Number of Times Used, and Improvement in Corresponding Function*

Motor Donor	Muscle Target	Times Used	Before Direct Neurotization	After Direct Neurotization	Improvement (%)
Orbicularis oculi muscle branch	Orbicularis oculi muscle	13	2	4	50
	Temporalis for eye substitution	2	3	4	25
	Free platysma for eye	1	3	4	25
Zygomatic branch	Orbicularis oculi muscle	2	2	4	50
	Depressor complex	1	1	2	50
	Free pectoralis minor	2	1.5	3	37.5
	Free gracilis	4	2	3	25
Buccal branch	Depressor complex	3	1	2	50
	Free pectoralis minor	2	1.5	3	37.5
	Free gracilis	3	2	3	25
Mandibular branch	Depressor complex	2	0.5	1.5	25
	Digastric for depressor	3	0	1	50
	Anterior sternocleidomastoid	1	2	2	0
	Free pectoralis minor	3	2	3	25
CN V	Orbicularis oculi	1	2	3	25
CN XI	Orbicularis oculi	2	2	3	25
	Digastric for depressor	1	0.5	1.5	50
CN XII	Orbicularis oculi	3	2	3	25
	Levator	1	1	2	25
	Depressor complex	5	1	2	50
	Digastric for depressor	2	1	2	50
C4	Orbicularis oculi	2	1.5	2.5	25
C7	Orbicularis oculi	5	2	3	25
	Depressor complex	2	0.5	1	25
	Orbicularis oris	1	1	2	25
C8†	Orbicularis oculi	1	1	2	25
T1†	Orbicularis oculi	1	1	2	25

*The improvement comprises the percentage conversion of the difference between preoperative and postoperative median scores in the function that each muscle is responsible for. Please note that scores are not mere numeric values but correspond to specific increments in the grading systems mentioned in the text. Thus, the percentages reflect the improvement based on these increments.
†Case of Moebius syndrome with congenital amputation of right upper extremity at the level of the humeral neck. Motor fibers were harvested from C8, T1 to neurotize two grafts for direct neurotization of upper and lower eye sphincter.

Table 15. Direct Neurotization of Facial Muscles and Improvement in Corresponding Function in Children Older and Younger than 13 Years*

	Younger than 13 Years		Older than 13 Years		
	Preoperative	Postoperative	Preoperative	Postoperative	Normal Scores
Eye closure	2 (range, 1)	4 (range, 1)	3 (range, 1)	4 (range, 1)	5
Smile	1 (range, 1)	4 (range, 1)	2 (range, 1)	4 (range, 1)	5
Depressor	0.5 (range, 0.5)	1.75 (range, 0.25)	0.75 (range, 0.5)	1.75 (range, 0.25)	2

*The values are the median scores obtained by the three independent investigators. The last column shows the normal scores as used in the grading systems shown in Tables 2 through 4.

If there is facial movement, even if inadequate, this comprises an indication for the muscle neurotization procedure. If the findings on needle electromyography are indicative of partial innervation, implantation of a motor nerve from a powerful ipsilateral donor can enhance muscular recovery.

Factors that determine the decision to perform direct muscle neurotization are:

Etiology of Paralysis

Depending on the etiology, the paralysis can be central or peripheral, partial or complete, bilateral or unilateral. Other associated injuries (fractures, vascular injuries) may also be present in posttraumatic facial paralysis. In developmental paralysis, there could be mononeural agenesis or multicranial nerve involvement. The etiology may also influence the availability, accessibility, and integrity of other neighboring nerves as motor donors for nerve transfer procedures.

Denervation Time

The length of muscle denervation and residual motor activity affect the choice of motor donor. Use of ipsilateral motor donors do not restore coordinated animation with the contralateral side

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Fig. 4. A 5-year-old patient with incomplete Moebius syndrome, presenting with complete left and partial right facial paralysis, complete bilateral VI cranial nerve involvement, and partial involvement of V, IX, X, XI, and XII cranial nerves. First-stage reconstruction included two cross-facial nerve grafts. Nine months later, left pectoralis minor free transfer was performed to the left face for smile reanimation. Cross-facial nerve grafting from the contralateral zygomatic branch was used to innervate the pectoralis minor. Twelve months later, a gold weight implant was used for the left upper eyelid, and palmaris longus transfer to the left lower eyelid was performed 12 months later. Left eye closure was addressed 14 months later by direct orbicularis oculi muscle neurotization using ipsilateral C4 motor root and cranial nerve XI (sternocleidomastoid branch) as motor donors. Preoperative electromyography showed 10 percent motor unit activity for the left orbicularis oculi muscle. The postoperative result in eye closure is excellent and electromyography showed 70 percent orbicularis oculi muscle motor unit activity. Left digastric muscle transfer for depressor complex substitution was performed 24 months later and was directly neurotized from the contralateral cranial nerve XI. (*Above*) Preoperative photograph of patient attempting eye closure. (*Below*) Postoperative photograph of patient during last follow-up visit 16 years after the direct muscle neurotization procedure.

Fig. 5. A 13-year-old girl presented with right developmental facial paralysis. First-stage reconstruction included three cross-facial nerve grafts. Mini-hypoglossal procedure[35] with direct neurotization of the right depressor via interposition nerve graft from the ipsilateral hypoglossal nerve was performed. Preoperative electromyography showed 10 percent motor unit activity for depressor. Restoration of depressor function postoperatively is presented, with the patient having a nearly symmetrical depression of the right lower lip. Postoperative electromyography revealed almost full motor unit activity 1 year later. Ten months later, free gracilis was transferred to the right hemiface for smile reanimation. A cross-facial nerve graft from the contralateral main zygomatic branch innervated the gracilis, while a cross-facial nerve graft from the contralateral buccal branch directly neurotized it. Six years later, right mini-temporalis transfer for smile augmentation was performed.[46] (*Above*) Preoperative view of patient. Note paresis of the right lower lip. (*Below*) Patient displayed nearly symmetrical depression of the lower lip 9 years after the direct muscle neurotization procedure.

in adults (e.g., in the eye, the reinnervated sphincter can augment only eye closure and not the blink reflex), but with motor reeducation, substantial coordinated animation can be achieved in children because of increased brain plasticity.[30,31]

In our study, functional and electromyographic improvement was negatively correlated with denervation time only in directly neurotized facial muscles. This can be explained by the fact that transferred muscles either retain their native

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Fig. 6. Six-year-old female patient with right developmental facial paralysis. First-stage reconstruction included three cross-facial nerve grafts. Twelve months later, nerve conduction studies confirmed complete axon regeneration through the cross-facial nerve graft, and the depressor complex was directly neurotized using cross-facial nerve grafting from the mandibular branch of the contralateral facial nerve. Preoperative electromyography showed 20 percent motor unit activity for the depressor, while postoperative electromyography showed nearly full electrogenesis. Left palmaris longus tendon was transferred for left lower eyelid reconstruction.[47] After 22 months, the left free gracilis was transferred to the right hemiface for smile reanimation. A cross-facial nerve graft from the contralateral main zygomatic branch innervated the gracilis. After 22 months, revisional secondary surgery took place. (*Above*) Patient is seen here preoperatively attempting to depress the lower lip. Note weakness on the right side. (*Below*) At 9 years postoperatively, the patient is capable of nearly full lower lip depression.

innervation or have short denervation periods, as they are reinnervated by new neural sources.[33]

Strength of Motor Donor

One parameter of motor donor "strength" is its neuronal pool. There are several studies investigating the number of myelinated axons of nerves used as motor donors in facial reanimation.[29,33,34] The senior author (J.K.T.) has systematically used quantitative morphometry from nerve biopsies of both the nerve grafts and the motor donors as a prerequisite for adequate augmentation of the desired muscle target. In 1984, the senior author (J.K.T.) introduced the babysitter procedure (mini-hypoglossal).[35]

Using the same principle, the mini-hypoglossal has been effectively used in the direct muscle neurotization of weak muscle targets. In this way, the hemitongue atrophy and the resulting complications in speech, mastication, and swallowing that other authors reported from the traditional hypoglossal to facial nerve transfer[36,37] have been avoided.

With the use of the accessory nerve as a motor donor, a certain degree of atrophy and downgrading of the trapezius muscle function was reported by several authors.[38–40] Conversely, the senior author (J.K.T.) has always used end-to-side coaptations to part of the nerve to the sternocleidomastoid and to the trapezius with interposition grafts, thus avoiding atrophy and downgrading of the donor muscle function.

Several authors have suggested the use of the masseteric nerve as a motor donor but reported masseter function downgrading as a major disadvantage of the method.[41–44] The masseteric nerve has always been used by the senior author (J.K.T.) in an end-to-side fashion so as to avoid downgrading the function of the masseter.

A second parameter of the final strength of the motor donor in cases in which a nerve graft is used (cross-facial or interposition) is its length, which comprises the distance that regenerating axons have to travel to reach the target. The length of the interposition or cross-facial nerve graft affects both the required time and the quality of neurotization.[45]

Although clinical studies that clearly quantitate the relationship between nerve graft length and functional outcome in facial paralysis are not available, there is a consensus on the following: (1) use of atraumatic tensionless coaptations is the first priority; (2) concerns about the length of the graft should not prevent the surgeon from choosing a strong, corresponding, contralateral facial nerve motor donor; (3) if a motor donor is intact and the distance to the target is short, this would result in enhanced augmentation of the function of the target than if the distance is much longer or if the motor donor is involved in the developmental lesion. (4) Choosing to directly neurotize a partially denervated muscle rather than performing a nerve-to-nerve coaptation of its supplying

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Fig. 7. Six-year seven-month-old female patient presented with partial right developmental facial paralysis. First-stage reconstruction involved three cross-facial nerve grafts. One year later, free pectoralis minor was transferred to the right hemiface for smile restoration, and a cross-facial nerve graft from the contralateral main zygomatic branch innervated its upper slip. Direct neurotization of the lower slip that was anchored to the right modiolus was performed using a second cross-facial nerve graft from the contralateral buccal branch. Postoperatively, an excellent smile was restored. Preoperative electromyographic studies of the levator muscle showed 20 percent activity. Postoperative electromyography showed full motor unit activity for the free pectoralis minor. (*Left*) Preoperative photograph of the patient displaying right facial deformity. (*Right*) Fourteen years later, the patient has full functional, aesthetic, and psychological recovery.

nerve depends on whether carrying out a nerve-to-nerve coaptation would further downgrade its function. If the muscle presents adequate motor unit potentials (≥2+) during intraoperative stimulation, it is wise not to disrupt the current innervation and to proceed with direct muscle neurotization of that muscle. This results in increased augmentation of function without downgrading the existing function.

Conclusively, our experience with direct muscle neurotization has shown that the indications are:

1. When reinnervation by direct nerve repair is not possible because of the lack of a distal nerve segment.
2. To augment the function of a muscle target without downgrading its existing innervation when it presents with adequate motor unit potentials (≥2+) but inadequate clinical function.
3. To substitute or augment the innervation of the muscle when there is a size discrepancy between the distal muscular branch and the graft/motor donor. In the second case, the nerve is divided into two segments. One is coapted in an end-to-end fashion with the nerve to the muscle, and the other is implanted into the muscle.
4. When there is the need to restore coordinated animation of partially denervated muscles and the need to retain the bulk and mass of a muscle.

CONCLUSIONS

This study has shown: (1) the major indication for direct muscle neurotization procedure is the augmentation of partially denervated muscles; and (2) in young, compliant patients with high expectations, it should comprise an integral part of procedures that can restore psychological, functional, and aesthetic improvement.

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