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Outcomes of direct muscle neurotisation in adult facial paralysis

Julia K. Terzis*, Dimitrios Karypidis

Department of Surgery, Division of Plastic and Reconstructive Surgery, Microsurgery Program, Eastern Virginia Medical School, 700 Olney Road, LH 2055, Norfolk, VA 23501, USA

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Summary Fifty-seven adult patients with facial paralysis, who underwent direct muscle neurotisation, were reviewed and divided into three categories depending on the function that direct neurotisation was aiming to augment. Group 1 included 30 patients who underwent direct neurotisation for eye closure and blink, group 2 consisted of 23 patients for smile augmentation, and group 3 comprised 31 patients for depressor.

The age of the patients ranged from 21 to 74 years. Denervation time (Dt) ranged from 8 months to 42 years. Eight patients had partial facial paralysis, and 49 patients had complete facial paralysis. The results were based on the functional and electromyography (EMG) scoring of the neurotised muscles showing an overall EMG mean improvement of 26.56% in eye closure, 34.47% in smile restoration and 32.67% in depressor function by the procedure. Median improvement in all facial functions was one grade (25%) in theTerzis grading systems regarding the respective facial functions. The prerequisites are Dt less than 6 months and a functional contralateral facial nerve. In cases where Dt is more than 27 months and preoperative EMG's are silent, a free or pedicled muscle should be used to substitute the denervated native facial muscle. Promoting expressivity and augmenting facial muscle function using direct muscle neurotisation are important components in facial reanimation.

Direct muscle neurotisation (DMN) has been used by the senior author during the past 30 years to augment the function of the eye sphincter, of smiling and of the depressor complex (DC), as part of multi-staged facial reanimation procedures.

DMN was described more than a century ago by Hacker,[1] who reported a clinical case in which the central end of the spinal accessory nerve was successfully implanted into a paralysed trapezius muscle. However, Heineke[2] performed the first experimental study of reinnervation implanting the original or a foreign nerve in the muscle tissue. Other studies explained the underlying mechanism of nerve regeneration in DMN, and distinguished this technique from muscular neurotisation.[2,3]

* Corresponding author. Tel.: +1 757 446 5272; fax: +1 757 446 5109.
E-mail address: mrc@jkterzis.com (J.K. Terzis).

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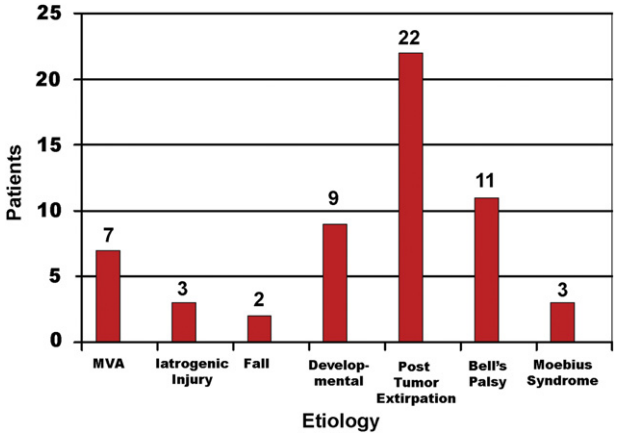

Figure 1 Aetiology of facial paralysis in the adult population.

The early work of Steindler and Elsberg[3,4] indicated that nerve implantation into denervated muscles forms connections that lead to muscle reinnervation. More specifically, Steindler[3] implanted the proximal end of the anterior tibial nerve into the denervated vastus externus muscle, in a dog-and- cat model showing that successful nerve—motor connection and 'reappearance of the normal contours of the muscle fibres and of normal striations' was possible in 8—10 weeks following implantation. Histological studies[4–6] supported this finding by demonstrating the formation of new end-plates with a central one containing acetyl-cholinesterase induced by the arrival of a healthy terminal axon at the newly formed neuro-muscular junction, and being primarily functional.[4,6]

However, the formation of neuromuscular junctions following nerve implantation remained unclear. That led Gutmann and Young[6] to publish their study on the effect of muscle atrophy on various reinnervation methods, and describe the associated histological changes based on a rabbit model. Six years later, Aitken[7] described the formation of new neuromuscular junctions in multiple sites around the implanted medial gastrocnemius nerve into the lateral head of the gastrocnemius in a rabbit model. A minimally traumatic successful method of DMN using round-bodied needles to create a pathway between the muscle bundles and using human fibrinogen instead of suturing the nerve into the muscle was also described.

Despite the relatively abundant primarily histological descriptions, there were not many detailed functional reports. Nineteen years later, the first force and macroscopic measurements of directly neurotised muscles in a dog model showed a wide range (44—95%) of original muscle recovery.[8] In a similar study in a dog model,[9] where the implanted nerve was previously divided into several fascicles, force measurements demonstrated 60—75% original muscle force recovery.

Millesi[10] described DMN using nerve grafts that were implanted in denervated muscles. He reported a series of six patients with long-standing unilateral orbicularis oris muscle (OOM) paralysis who underwent DMN from the innervated OOM to the denervated side. Histological findings revealed myelinated axons in the graft, and he suggested that the nerve grafts were neurotiszed from the innervated OOM muscle.

In a rabbit model, Brunelli et al.[11] reported motor function recovery and new motor-endplates formation in the 'aneural' zone of gastrocnemius lateral head, one

Table 1 Patients Demographics in the adult population

Demographics	
Total patients	57
Male	12
Female	45
Age range/mean age	38 ± 16.07 y.o
Mean denervation time	12 years
Left sided facial paralysis	26
Right sided facial paralysis	28
Bilateral facial paralysis	3

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 and Noah ME. Analysis of 100 cases of free muscle transplantation for facial paralysis.Plast Reconstr Surg. 1997 Jun;99(7):1905-21.

Table 3 Aesthetic and functional grading system used for the depressor muscle

Grade		Description
Scale	Designation	
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. and Kalantarian B. Microsurgical strategies in 74 patients for restoration of dynamic depressor muscle mechanism: a neglected target in facial reanimation. Plast Reconstr Surg. 2000 May; 105(6):1917-31.

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 (min.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. and Bruno W., Outcomes with Eye Reanimation Microsurgery Facial Plast Surg. 2002 May;18(2):101-12.

month after DMN with the motor branch of the peroneal nerve. Their findings also included that an implanted nerve could only be accepted by a denervated muscle target, which is sensitive to acetylcholine throughout its fibres through an 'adoption phenomenon'. Adoption phenomenon was also described as the formation of new functional motor units due to new axonal branches sprouting from the implanted nerve to the denervated muscle fibres, 'adopting' the latter by increasing their sensitivity to acetylcholine and enabling the formation of new endplates. In confirmation of the functional restoration of denervated muscle observed by Brunnelli,[11] Zhang et al.[12] reported no significant difference in the weight between directly neurotised and reinnervated with grafts muscles, in a rat model.

Morphological studies[13–16] showed that the previously mentioned ectopic nerve—muscle junctions' development includes an early synaptogenesis stage in which the nerve induces a persistent local alteration of the muscle fibre surface, which makes it a preferred site for the subsequent appearance of acetyl-cholinesterase.

Subsequently, the nerve induces muscle activity, which leads to the formation of acetyl-cholinesterase and of the corresponding binding sites in the basal lamina of the future endplate.[13–15] Junctional folds form where the axon is 'making contact' with the muscle cell[16,17] augmenting the surface area within the synaptic cleft of the muscle cell.

Our understanding of the muscle response to direct neurotisation has increased. The aim of this article is to evaluate the procedure and its role in the surgical reconstruction of facial expression by reviewing the experience in our Centre.

Material and methods

A retrospective review of 102 patient charts, who underwent DMN at some stage of their facial reanimation procedures, between January 1981 and January 2007 was done. Seventy-five adult patients (≥17 years) were included. This study conforms to the World Medical Association Declaration of Helsinki and subsequent amendments.

Detailed medical and surgical history, facial paralysis (FP) aetiology, patient demographics (Figure 1, Table 1) and complete cranial nerves examination were preoperatively documented. Nerve-conduction studies and needle electromyography (EMG) were always included. Computed tomography (CT) or magnetic resonance imaging (MRI) of the facial canal and temporal bone bilaterally was performed in developmental FP. A follow-up period of 18 months or longer was also required for inclusion. No patients with immediate post-trauma or post-tumour extirpation DMN or with ongoing radiation therapy were included.

Video documentation of eye closure and involuntary blinking required each patient to be in a seated position with the head stabilised. Each patient was then asked to close their eyes lightly and then tightly several times, and then not to blink deliberately for 4 min looking straight at the camera.

Video documentation of a smile required patients to demonstrate first a slight smile, and then a full smile several times. DC function was recorded after asking each patient to depress the lower lip without smiling. Emotional-involuntary facial movements were videotaped for further evaluation while patients were talking and watching a funny video.

Table 5 Scores of the specific facial functions before and after the procedure of direct muscle neurotization in the adult population. The values are the median scores obtained by the 3 independent investigators. The last column shows the normal scores as used in the grading systems shown in Tables 2,3 and 4. Range = maximum value - minimum value. Statistically significant results for $p < 0.05$

Function	Preoperative score	Postoperative score	Normal Scores	p
Eye closure	2 (range: 1)	3 (range: 1)	5	.02
Blink	2 (range: 1)	3 (range: 1)	5	.02
Smile reanimation	2 (range: 1)	3 (range: 1)	5	.03
Depressor	0.5 (range: 0.5)	1.5 (range: 0.5)	2	.02

Table 6 Direct neurotization of facial muscles and the improvement in corresponding function in the adult population. The number of the procedures is shown. Several patients underwent direct neurotization of the same type of target muscle more than once or/and of multiple target muscles

Facial Muscle	Number of times directly neurotized	Pre Direct Neurotization	Post Direct Neurotization	Normal Scores	Improvement	p
OOM	27(26 patients) [a]	2 (range:1)	3(range:1)	5	25%	.03
LAO	2	1(range:0)	2(range:0)	5	25%	NS
DAO	13	0.5(range:0.5)	1(range:0.5)	2	25%	.02
Total:	42 procedures					

OOM: Orbicularis Oculi Muscle, LAO: Levator Anguli Oris, DAO: Depressor Anguli Oris
The improvement comprises the percentage conversion of the difference between pre- and postoperative median scores in the function that each muscle is responsible for. Note: 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 as shown in Tables 2, 3 and 4. Range = maximum value - minimum value, NS: not statistically significant (Statistically significant results for $p < 0.05$).
[a] 1 patient had both right and left Orbicularis Oculi muscle directly neurotized.

Three types of muscles underwent DMN: native facial muscle (FM), local pedicled muscles that were transferred to substitute or augment a specific target and free muscles, forming three groups:

Group 1: patients who underwent procedures for eye closure. Subgroup 1a and 1b: patients undergoing DMN of the OOM or muscle targets that were used to substitute the OOM, respectively.

Group 2: patients undergoing procedures for smile augmentation. Subgroup 2a and 2b: patients who underwent DMN of the levators or of transferred muscles that were used for smile augmentation, respectively.

Group 3: patients who underwent DMN for DC reanimation or augmentation. Subgroup 3a and 3b: patients who underwent DMN of the DC or of other muscles used for DC substitution, respectively.

In OOM neurotisation, the proximal end of a nerve graft is connected to the donor nerve, while the distal end is divided into two segments, which are then dissected into 2–3 fascicles using a 45° single-edge diamond knife. The fascicles of one segment are implanted into the upper while the fascicles of the other are implanted into the lower OOM through the epimysium, through a separate incision. Using 9/0 nylon, the epimysium is sutured over the nerve end and the nerve position is then secured by taking small bites of the epineurium. Selectively neurectomised OOM branches of the contralateral un-involved facial nerve (FN) comprise the motor donors.[18–20] Zygomatic and marginal mandibular branches of the contralateral FN can be used as motor donors in levator and DC neurotisation, respectively, via cross facial nerve grafts. When FP is bilateral (Moebius syndrome), FN branches are unavailable, thus foreign ipsilateral motor donors are used such as the XII, V, XI cranial nerves, or small segments of the ipsilateral C7 root.[21–26]

The same series of detailed examinations and standardised video recording took place at the preoperative and all the follow-up visits for each patient. All videotapes of each patient were reviewed separately by three independent investigators who rated the degree of the preoperative impairment and the postoperative functional return. Tables

Table 7 Direct neurotization of muscles that have been used for specific facial muscle substitution in the adult population and the improvement in corresponding function. The number of the procedures is shown. Note: several patients underwent direct neurotization of the same type of target muscle more than once or/and of multiple target muscles

Target Muscle	Number of times directly neurotized	Functional substitution of	Pre DMN	Post DMN	Improvement	p
Frontalis	2	OOM	1	1	0%	NS
Free Platysma	2	OOM	1	3	50%	NS
Minitemporalis	8	levator	2	3	25%	.03
Masseter [a]	1[a]	levator	1	3	50%	NS
Free Gracilis	13	levator	1	2	25%	.025
Adductor Longus	1	levator	2	3	25%	NS
Digastric	11	depressor	0.5	1.5	50%	.03
Platysma	6	depressor	0	1	50%	.05
Total:	44 procedures					

[a] A 25-years-old patient with complete left and partial right developmental facial paralysis who underwent left segmental masseteric transfer to the left commissure of the mouth for smile restoration. Direct neurotization of the left masseteric segment was performed. (See also Figure 7). The improvement comprises the percentage conversion of the difference between pre- 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 as shown in Tables 2, 3 and 4. OOM: Orbicularis oculi muscle, DMN: Direct muscle neurotization, NS: not statistically significant (Statistically significant results for $p < 0.05$).

Table 8 Number of neurotization procedures performed in each stage, in the adult population

Neurotisations	Number
1st stage	7
2nd stage	39
3rd stage	29
4th stage	11
5th stage	2
Total	86

2–4 show the grading systems that were used. The authors did not participate in the reviewing. The intra-class correlation coefficient (ICC) for eye sphincter, smile and DC function grading was 0.75, 0.70 and 0.71, respectively, suggesting a considerable level of agreement among the investigators who reviewed and scored separately the same video material under almost identical conditions.[27]

Statistical analysis

Results are presented in the form of medians and ranges when function-grading scores in Tables 2, 3 and 4 were used. The Wilcoxon signed rank test was used in comparison between preoperative and postoperative scores. When testing correlations between two variables with matched pairs, Spearman's rank correlation coefficient (ρ_s) was used taking into account the number of patients in each group and for $p = 0.05$. Mean values and $\pm$ SD were also used for interval and ratio data. Fisher's exact tests were performed when comparing improvement between subgroups or among groups.

Results

Statistically significant functional improvement following DMN was 25% for the OOM ($p = 0.03$)and DC ($p = 0.02$), 25% for the minitemporalis ($p = 0.03$) and free gracilis muscles ($p = 0.025$) used for smile restoration, and 50% for the digastric ($p = 0.03$) and platysma ($p = 0.05$) muscles used

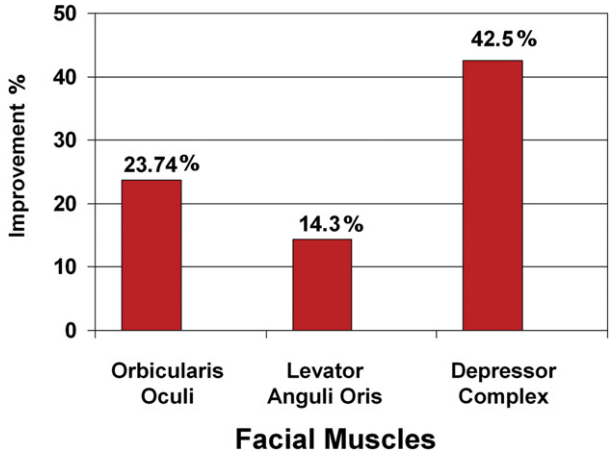

Figure 2 Improvement in the EMG scores of the facial muscles after being directly neurotized in the adult population. The percentages represent gain in the 0 to 3 scale of measurement during the electromyographic study [with 0 for no evoked potentials and 3 for the maximum number of active motor units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

for DC reanimation (Tables 5–7). Several patients underwent DMN of the same type of target muscle more than once and/or of multiple target muscles (Tables 6 and 7). Consequently, some patients are in more than one group since there are 74 treatments on 57 adult patients. Each function has been scored separately, the results are both function- and muscle- specific, and DMN of one target muscle does not have a measurable effect on another. Table 8 shows the number of DMN in each stage.

Similarly, statistically significant EMG improvement following DMN was 73.5% for OOM ($p = 0.027$) and 59.8% for DC ($p = 0.022$), 59.6% for minitemporalis ($p = 0.032$) and 54.8% for free gracilis ($p = 0.025$), 17.6% for digastric ($p = 0.031$) and 171% for platysma ($p = 0.05$), (Table 9, Figs. 2 and 3).

Non-statistically significant results concerned free platysma and masseter DMN, which yielded 50% improvement

Table 9 Preoperative and postoperative Electromyographic findings of facial and other muscles in the adult population (motor unit potentials)

	Muscle Target	Preoperative EMG	Postoperative EMG	p
Facial Muscle	Orbicularis Oculi	1.21	2.1	.02
	Levator Anguli oris	1	2	NS
	Depressor Anguli Oris	1.32	2.11	.015
Other muscle	Frontalis eye sphincter	1	2	NS
	Free Platysma for eye sphincter	2.5	3	NS
	Minitemporalis for smile	1.66	2.65	.02
	Masseter for buccinator	1.25	2.58	NS
	Free Gracilis for smile	1.55	2.4	.02
	Adductor Longus	2	3	NS
	Digastric for depressor	1.93	2.27	.02
	Platysma for depressor	1	2.71	.04

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), EMG: Electromyographic findings, NS: not statistically significant (Statistically significant results for $p < 0.05$).

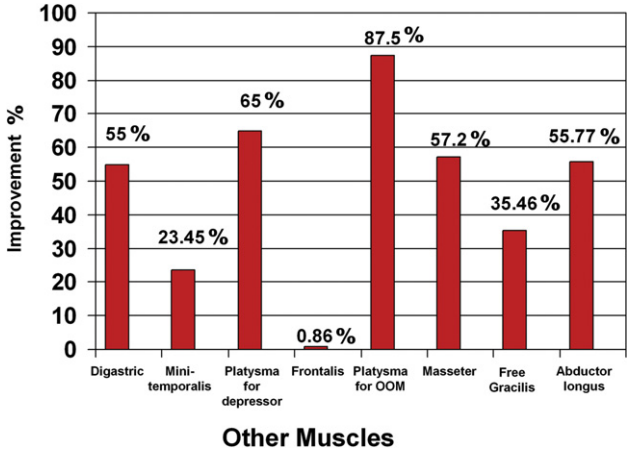

Figure 3 Improvement in the EMG score of the other muscle targets after being directly neurotized in the adult population. The percentages represent gain in the 0 to 3 scale of measurement during the electromyographic study [with 0 for no evoked potentials and 3 for the maximum number of active motor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

in their function, levator and adductor longus DMN, which resulted in 25% functional improvement and frontalis DMN, which yielded no improvement. Table 10 shows the number of patients per group that achieved a moderate or better postoperative outcome, with better results being observed in groups of direct neurotisation of other muscles used for smile restoration (91%) and for depressor substitution (94%). In Table 11, the motor donors that were used are presented. No statistically significant correlation was found between age and the functional result after DMN of both facial and other muscles. Preoperative EMG score greater than 2+ ($p < 0.05$) was associated with a more favourable postoperative EMG improvement in FM neurotisation.

No statistically significant difference in improvement related to previous surgical history, gender and aetiology was noted. Denervation time (Dt) had a statistically significant negative correlation to the functional as well as EMG improvement (−0.36, $p < 0.025$) of directly neurotised FM only (decreasing ratio of EMG improvement following DMN after a Dt of 10–11 months). Denervation time of 10–11 months represents the cutoff point (maximum observed time), after which EMG improvement ratio began to decrease. However, Dt of 6 months represents the mean observed time in which EMG increase ratio is at its peak.

Table 11 The main motor donors in the adult population and the number of times used

Motor Donor	Times used
OOM branch[a]	31
Zygomatic branch	16
Buccal branch	5
Mandibular branch	24
CN XII[b]	7
CN XI[c]	1
C4[d]	2

[a] OOM – orbicularis oculi motor branch.
[b] Cranial nerve XII (hypoglossal nerve).
[c] Cranial nerve XI (accessory nerve).
[d] 4th cervical root.

FM neurotisation demonstrated more favourable electromyographic improvement when the preoperative EMG was greater than 2+ ($p < 0.05$). No complication relevant to the procedures of DMN was noted. Figures 4–7 show four exemplary cases.

Fisher's exact tests were performed between subgroups within each group, to identify statistically significant differences regarding the number of patients that achieved a moderate or better postoperative result (Table 10). Fisher's exact probability p for group 1 was 0.64, for group 2 was 0.09 and for group 3 was 0.39, reflecting the lack of statistically significant ($p < 0.05$) difference between FM and other muscle targets neurotisation outcome, in all groups.

Similarly, the Freeman–Halton [28] extension of the Fisher exact probability test showed P-value = 0.99 (two-tailed

Table 10 The number of patients per group that achieved a moderate or better [a]postoperative result

Group	Subgroup	Number of patients	Patients with moderate or better postoperative result
Group 1	Subgroup 1a	26	23(88.5%)
	Subgroup 1b	4	4(100%)
Group 2	Subgroup 2a	2	2(100%)
	Subgroup 2b	23	21(91%)
Group 3	Subgroup 3a	13	11(85%)
	Subgroup 3b	17	16 (94%)

Group 1: patients who underwent procedures for Eye closure and Blink restoration, Subgroup 1a: patients of Group 1 with direct neurotization of the orbicularis oculi muscle, Subgroup 1b: patients of Group 1 with direct neurotization of other muscles, used for Eye sphincter substitution.
Group 2: patients who underwent procedures for Smile restoration, Subgroup 2a: patients of Group 2 with levator anguli oris muscle direct neurotization, Subgroup 2b: patients with direct neurotization of other muscles used for smile restoration.
Group 3: patients who underwent procedures for depressor reanimation, Subgroup 3a: patients with direct neurotization of the depressor muscle, Subgroup 3b: patients with direct neurotization of other muscles used for depressor substitution.
Note: several patients underwent direct neurotization of multiple target muscles.
[a] 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.

Figure 4 This is a 24-years—old patient with post tumour extirpation (acoustic neuroma) left facial paralysis. When she was 22 years old she underwent first stage reconstruction with cross facial nerve grafting and partial left hypoglossal nerve transfer to left facial nerve with end-to-end coaptation (Babysitter procedure). One year later free gracilis transfer to left hemi-face was performed for smile restoration. Third stage restoration included left digastric muscle transfer for depressor complex substitution, revision procedures and direct orbicularis oculi neurotization using the cross facial nerve graft coapted to the contralateral orbicularis oculi branches for eye sphincter function. Preoperative electrodiagnostic studies showed 40-50% motor unit activity. One year after the direct orbicularis oculi neurotization motor unit activity increased to 70-80%. 4(a-c) Preoperative photographs of the patient in repose and attempting eye closure. 4(d-f) Postoperative photographs of patient. Excellent postoperative restoration of eye closure is apparent.

probability) indicating a not statistically significant difference in achieving better or moderate results among the three groups.

Discussion

Our findings showed that OOM neurotisation yielded the best postoperative functional outcome, and resulted in similar improvement with DC neurotiszation. In the group of muscles used for specific FM substitution, neurotisation of the digastric and the platysma yielded the highest functional improvement. Neurotisation of the free platysma muscle (used for OOM substitution) had the best postoperative functional outcome as well as the highest improvement, while neurotisation of the frontalis (used for OOM substitution) showed no improvement. However, due to the small number of cases, results regarding free platysma and frontalis neurotisation were not statistically significant.

The decision to perform DMN depends on muscle target condition, FP aetiology, Dt, regeneration distance and on the available motor donors.[29]

The aetiology of FP determines the location (intracranial, intratemporal and extratemporal), the mechanism and the extent of FN lesion. Axial and coronal CT scan views of the temporal bone in most cases excluded unresolved trauma and revealed variable degrees of (developmental) stenoses of the facial canal. Associated anomalies of the inner, middle, external ear and mandibles were also present in a minority of cases supporting the diagnosis of developmental paralysis. MRI studies were mainly performed when better definition of suspected nerve hypoplasia or aplasia, was required. In the majority of the cases, MRI demonstrated

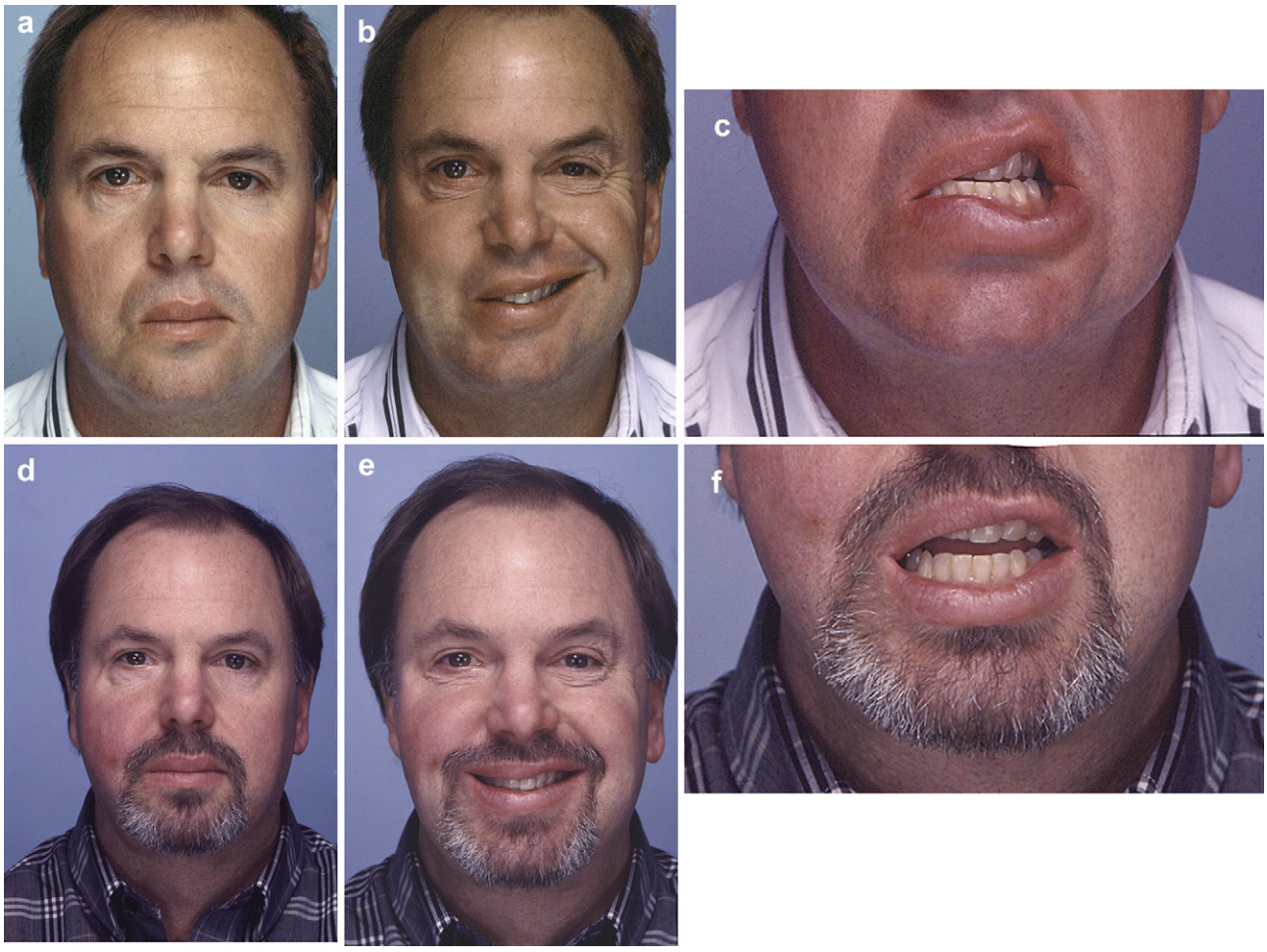

Figure 5 Forty nine years old patient with partial right facial paralysis due to facial neuroma extirpation who underwent direct depressor neurotization using a previously placed cross facial nerve graft from the contralateral mandibular branch. Preoperative electromyographic studies showed 30% motor unit activity for depressor. One year postoperatively, depressor motor unit activity was increased to 60-70%. 5(a-c) Preoperative photographs of the patient. 5(d-f) One year postoperatively, the functional outcome was excellent with the patient presenting almost full and symmetric lower lip depression.

filamentous degeneration of the last intracranial part of the FN, which was subsequently confirmed by mastoid and parotid area exploration.

MRI also aided towards the exclusion of central nervous system and soft tissue lesions secondary to trauma or tumour. Most of the cases of developmental paralysis presented as unilateral consolidated late partial FP. DMN was therefore used on partially denervated muscles with sub-optimal clinical function, but with electromyographic evidence of remaining activity to augment their function and/or restore their bulk. Muscle transfer procedures were used for fibrosed, clinically and electrically non-functional FM substitution.

Motor donor availability for DMN could be limited in cases that motor donors are involved in the lesion. [30] In our centre, the choice of motor donors includes contralateral FN branches as motor donors for the corresponding muscle targets after intra-operative microstimulation and mapping muscle targets, after meticulous selective neurectomies and via carry-through cross facial nerve grafts.[31] Prerequisites are Dt less than 6 months, and a functional contralateral FN.[19,31] In cases where Dt is more than 27 months and preoperative EMG's are silent, a free or pedicled muscle is used to substitute the denervated native FM. Contralateral motor donors can be used to coordinate the activity of these muscles. Motor neurons of the functional FN take over a function-specific role in restoring both the innervation and the synchronicity of contralateral movement. In that way, both action and timing are being disconnected from the nerve signals of the injured side and slaved to the ones of the homologous contralateral side.[32] Ipsilateral motor donors do not restore coordinated animation with the contralateral side (e.g., in the eye, the sphincter can augment only eye closure and not the blink reflex)

Denervation time had a statistically significant negative effect on FM neurotisation because they were partially denervated, but not totally fibrosed. However, as gradual fibrosis progresses, the quality of innervation by DMN is time dependent reflecting the negative correlation of Dt and functional improvement. Conversely, Dt had no effect on transferred muscles as they were fully functional and innervated preoperatively. Histochemistry and retrograde neuronal labelling showed that the increase in the length of nerve grafts interferes in behavioural recovery and increases motor fibres misdirection.[25,33] Girdley et al.[34] and

Figure 6 Twenty five years old female patient with right developmental facial paralysis. Preoperatively, the function of depressor was poor and electromyographic studies revealed 5-10% motor unit activity. Depressor function restoration was addressed by right digastric muscle transfer. The digastric was innervated by previously placed cross facial nerve graft from the contralateral marginal mandibular branch. However due to cross-sectional diameter discrepancy between the cross facial nerve graft and the digastric nerve, one fifth of the cross facial nerve graft was coapted to the nerve and the remaining was implanted in the digastric to directly neurotize it. Postoperative electromyography, one year later, showed full motor unit activity of the digastric. 6(a-c) The patient preoperatively 6(d-f) Postoperative photographs of the patient. Digastric direct neurotization significantly contributed to the excellent postoperative depressor function as shown.

Stephanian et .al.,[35] report that there was no significant correlation of the length of the graft with clinical recovery in FP patients. However, in both studies, the sample was small when it comes to comparing outcomes for grafts more than 5 cm in length. Consequently, the statistical significance of outcomes among grafts of such a small range of variance is rather limited,[36] as it was also observed in this study.

The fibre types of the FM need to be considered as well because the nerve innervating a muscle determines the type of its fibres.[37–40] Rowlerson et.al.,[41] in their study of fibre-type differences in masseter muscle in various facial morphologies, suggested that neurotised FM should have motor donors that innervate muscles with fibres of the same type. Similar observation was made by Doi et.al.[42] regarding free muscle transplantation.

In subgroups 1a, 2a and 3a, muscle fibre type-nerve compatibility was maintained due to the use of the contralateral facial nerve as motor donor for partially denervated FM. In subgroups 1b, 2b and 3b, functional and physiologic findings of previous studies in our centre[43–48] regarding the suitability (fibre type, transferability and anatomic properties) of muscle targets established the basis for the choice of transferred muscles and of the motor donors used in neurotisation. Therefore, DMN yielded optimum effects in respect to muscle fibre type-nerve compatibility.

Based on experience in our centre, DMN in adults should be included in the establishment of a reconstructive strategy in facial reanimation in the following situations:

(1) When the neural portion of a muscle and the distal segment of the supplying nerve are not available for nerve repair due to traumatic reasons;
(2) When the muscle retains a degree of its native innervation and has electromyographic evidence of

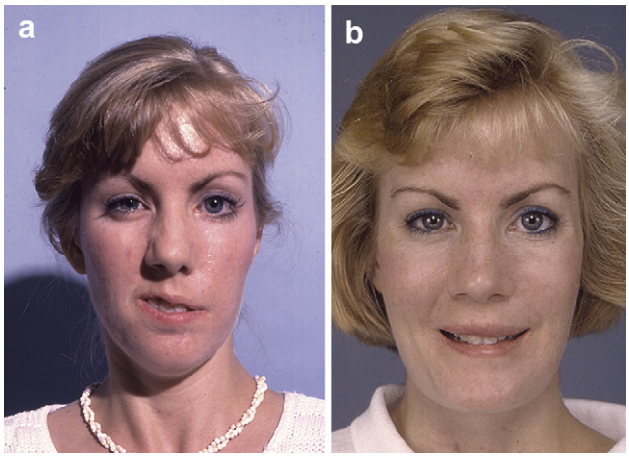

Figure 7 This is a 25-years-old patient with complete left and partial right developmental facial paralysis. She underwent left segmental masseteric transfer to the left commissure of the mouth for smile restoration. Direct neurotization of the left masseteric segment using the cross facial nerve graft from the contralateral zygomatic branch was performed. Preoperative electrodiagnostic studies showed decreased motor unit activity for the left levator. Postoperative treatment included extensive stimulation and motor re-education in using the masseter in order to dissociate the biting part from the smile. The postoperative electromyographic studies showed full pattern motor unit activity for the masseter. 7(a) The patient is seen preoperatively. 7(b) Postoperative photograph of the patient showing the very rewarding functional result in smile restoration.

remaining activity (motor unit potentials $\leq 2+$) but suboptimal clinical function;

(3) In case of discrepancy between the diameters of the motor donor and the nerve stump of the muscle target, the donor nerve is divided into two segments so that one is sized down to being appropriate for an end-to-end coaptation with the muscle nerve, while the other is used for DMN; and

(4) DMN can be used for the restoration of coordinated animation of partially denervated muscles and muscle bulk, when there is adequate clinical and electrophysiological confirmation that no further function is likely, and strengthening of the target is needed to enhance functional and aesthetic outcomes.

Conflict of interest statement

The authors have no financial and personal relationships with other people or organisations or any other conflict of interest that could inappropriately influence (bias) their work

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