ARTICLE IN PRESS
JID: PRAS [m6+;April 11, 2021;4:40]
Journal of Plastic, Reconstructive & Aesthetic Surgery xxx (xxxx) xxx

Long-term outcomes of dual innervation in functional muscle transfers for facial palsy

Kallirroi Tzafetta[a,*], Fawaz Al-Hassani[a], Rui Pinto-Lopes[a], Ryckie G. Wade[b], Zeeshan Ahmad[a]

[a] St Andrews' Centre of Plastic and Reconstructive Surgery, Broomfield Hospital, Chelmsford, CM1 7ET, United Kingdom
[b] The University of Leeds, Leeds, United Kingdom

Received 11 September 2020; accepted 13 March 2021
Available online xxx

KEYWORDS
Unilateral facial palsy;
Free functional muscle transfer;
Cross facial nerve graft;
Dual innervation

Summary *Background:* This study describes a different approach with a 2-stage facial reanimation in patients with long-standing unilateral facial paralysis using free gracilis muscle transfer, innervated by both cross-facial nerve graft and masseteric nerve. The authors present their rationale, surgical technique, and long-term outcomes.
Methods: Between August 2012 and March 2016, 11 patients (6 female and 5 male patients) underwent a 2-staged dually innervated gracilis muscle transfer. Patients were evaluated with physical examination and needle electromyography. A standardized assessment of preoperative and postoperative photographs and videos was performed using Terzis' smile functional grading system at 48 months following surgery and the Emotrics software to assess improvement in symmetry over a 36-month postoperative period.
Results: Voluntary contraction of the gracilis muscle was observed in all patients at a mean of 4 months and 4 days following muscle transfer. A spontaneous smile produced without teeth clenching was developed in all patients by 18 months postoperatively. Six patients achieved excellent and 5 good results. The difference between the averaged pre- and postoperative scores was statistically significant. With Emotrics, there were significant improvements in the smile angle, upper lip elevation, commissural excursion, and commissural height, with continuous improvement over 36 months. The postoperative electromyography (EMG) confirmed dual

Presentations This work has been presented at the following meetings of learned societies: 1) Winter BAPRAS meeting, Dublin, Ireland, November 2013 2) 12th Quadrennial ESPRAS meeting, Edinburgh, United Kingdom, 6-11 July 2014 3) The Meeting, ASPS, Chicago, USA, 10-14 October 2014 4) 8th Congress of WSRM, Mumbai, India, 19-22 March 2015 5) 10th International Caucasian Congress of Plastic Surgery, Tbilisi, Georgia, 8-9 July 2016 6) Advanced Courses in Plastic Surgery: Head and Neck, Manchester, United Kingdom, 24-25th April 2017 7) 13th International Facial Nerve Symposium, Los Angeles, USA, 3-6 August 2017 8) 12th Pan-Hellenic meeting, Athens, Greece, 18-21 October 2017 9) 17th Shanghai International Plastic and Aesthetic Surgery Congress, Shanghai, China, 23-25 March 2018 10) 14th Congress of the European Federation of Societies for Microsurgery, Belgrade, Serbia, 5-8 May 2018
Level of evidence: Therapeutic; IV

* Corresponding author.
E-mail address: kallirroi.tzafetta@meht.nhs.uk (K. Tzafetta).

https://doi.org/10.1016/j.bjps.2021.03.007
1748-6815/

Please cite this article as: K. Tzafetta, F. Al-Hassani, R. Pinto-Lopes et al., Long-term outcomes of dual innervation in functional muscle transfers for facial palsy, Journal of Plastic, Reconstructive & Aesthetic Surgery, https://doi.org/10.1016/j.bjps.2021.03.007

innervation of the gracilis muscle by the facial and masseteric donor motor neural sources. We present our results at minimum 48 months postoperatively.
Conclusions: Dual innervated two-stage gracilis transfer is an effective method for reanimation in long-standing unilateral facial paralysis, providing both rapid reinnervation of the transferred muscle, together with a powerful, synchronous smile.

Background

The main objectives of facial reanimation in patients with unilateral facial palsy include the restoration of facial symmetry together with spontaneity of smile. A two-stage reconstruction with cross facial nerve graft (CFNG) followed by free functional muscle transfer (FFMT) is regarded as the gold-standard treatment for long-standing unilateral facial paralysis. The contralateral healthy donor facial nerve is preferable as it provides spontaneity and emotional reactivation.[1-3]

The potential limitations of CFNG to animate an FFMT include the lack of predictability and inadequate muscle excursion that results from insufficient neural input to the transferred free muscle.[4] This may relate to the variable number of axons from donor nerve and that they reach the target muscle by crossing two coaptations, therefore potentially decreasing the axonal load and the recruitment of potential motor units.[5,6] This could affect the outcome following the correction of facial asymmetry, particularly in patients who have a "heavy face" with excess fat and deep nasolabial folds.

The masseteric nerve (MN) is a donor motor nerve that has several advantages, which include consistent and reliable anatomy,[7-9] minimal donor-site morbidity, and high number of neural axons with reliable recovery of facial motion.[10,11] Although there have been reports of restoration of spontaneous smile due to cortical plasticity, it is difficult to achieve the coordinated and spontaneous smile that the contralateral facial nerve can provide.[7,12]

The senior author (KT) was inspired by the babysitter concept.[13,14] This provides dual innervation (DI) to the paralyzed side of the face with the use of a donor motor nerve (hypoglossal or masseteric) together with CFNGs. We extrapolated the principle of DI of an FFMT. The authors hypothesize that by using both MN and CFNG to innervate the FFMT, the reliable restoration of resting tone with physiological and spontaneous mimetic recovery could be achieved from the facial neural source together with a powerful movement fuelled from the masseteric neural input.

We report our experience in the treatment of 11 consecutive patients with long-standing unilateral facial paralysis, using this two-stage facial reanimation technique, and a minimum follow up of 48 months.

Methods

This technique is one in the array of different reanimation techniques used in our unit. Inclusion criteria were as follows: patients aged between 18 and 55 years old, with long-standing unilateral facial palsy (more than 3 years), and/or who had failed surgery elsewhere; patients with "heavy faces" i.e., excess adipose tissue around the nasolabial folds; and a subset of patients with House-Brackmann (HB) Grade IV–V[15] who had extremely high expectations for motor recovery. The study was registered and approved as service evaluation in our department.

Surgical Technique

The first stage involves harvest of the sural nerve through small step incisions along its course, to be used as CFNG. The reversed nerve graft is coapted end-to-end to a selected facial buccal branch on the unaffected side and tunnelled subcutaneously to the pre-tragal area on the affected side, through the superior part of the upper lip.

The second stage takes place at an average of 13 months (range: 8–15 months). Tinel's sign was elicited in all cases. The previously banked CFNG is identified through a modified facelift incision and mobilized all the way medially to the nasolabial fold, which further creates a pocket to accommodate the FFMT. The free end of the CFNG is serially incised with a diamond knife until healthy fascicles are seen under the microscope.

The MN is then identified at an average distance of 1 cm below the zygomatic arch and 3 cm anterior to the tragus within the deep substance of the masseter muscle.[8] In cases of HB IV-V, special attention is paid to carefully preserve the buccal and zygomatic branches of the facial nerve during the location of the MN.

The descending branch is preferentially divided at its most distal point, leaving the more proximal branch(es) intact. The divided distal end is transposed superficially for nerve coaptation.

Simultaneously, a segment of gracilis muscle is harvested as previously described,[14,16] debulked, and transferred to the face. The tendinous part of the gracilis muscle is split into 4 strips. The first suture is placed and secured at the commissure with 3/0 PDS®. The second and third sutures are placed along a line between the philtrum and the commissure, one-third and two-thirds, respectively. They are transdermal bolster sutures, 3/0 Ethilon™ on a straight needle that are brought out through the skin at 1 mm below the vermillion border, to be removed at 3 weeks postoperatively. The final strip is inset at the lower lip at 2 cm from the commissure with 3/0 Ethilon™ bolster suture also on a straight needle brought out 1 mm above the vermillion border (Figure 1). The muscle is then secured laterally at the deep temporal fascia and along the preauricular area with 3/0 PDS®. The facial artery and vein were used in all but

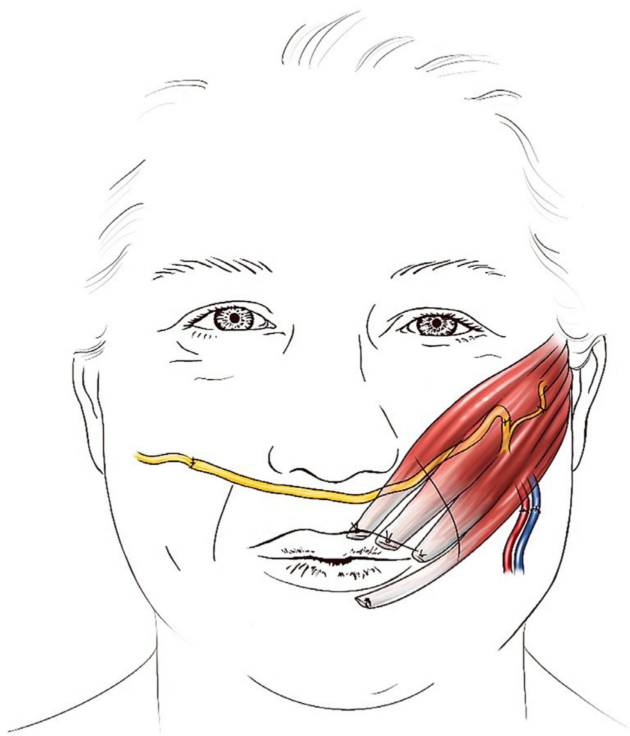

Figure 1 Drawing demonstrates the muscle insertion on the left side of the face. It also depicts the donor buccal branch of the contralateral facial nerve, the CFNG, the masseteric nerve, and the obturator nerve that is split longitudinally.

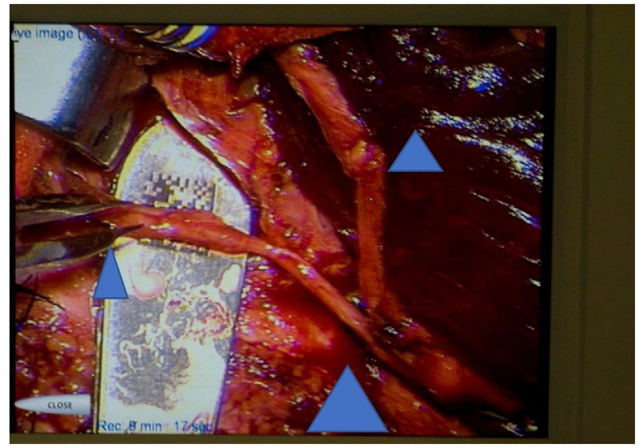

Figure 2 Photo taken with the microscope camera after the nerve coaptations, showing the longitudinally divided obturator nerve (large triangle), the end-to-end coaptation with the CFNG (medium triangle), and the end-to-end coaptation just distally to the tip of the microsurgery forceps (small triangle).

one case where the superficial temporal vessels were the vessels of choice on a patient who had a failed free flap elsewhere.

The obturator nerve (ON) from the gracilis muscle is split longitudinally under the microscope into two halves 4 cm from the hilum. This nerve commonly has 3–4 fascicles. One large fascicle that supplies the anterior portion of the gracilis muscle and the remaining fascicles that supply the rest of the muscle.[17,18] The half that contains the large fascicle is then shortened to 1 cm from the hilum and end-to-end epineural coaptation is performed with the CFNG using 9/0 Ethilon™ suture. The remaining half, 4 cm from the hilum is coapted to the previously divided descending branch of the MN with 9/0 Ethilon™ suture in end-to-end fashion (Figure 2).

A thermoplastic custom-made splint is placed at the corner of the mouth for 10 days to prevent muscle avulsion from its attachments.[16]

Outcome Assessment

All patients received complete evaluation, including clinical examination, standardized photographs, and videos preoperatively and at 3, 6, and 12 months and every 6 months thereafter following FFMT. The patients were asked to contact the surgical team for an immediate examination when the first voluntary movement of the commissure was noted, or when a relative or friend observed the spontaneous activation of the transferred muscle during smiling. EMG studies were also performed postoperatively at 6-month intervals.

Three independent trainee plastic surgeons, blinded to demographics and date of video recording, rated each video according to the Functional and Aesthetic Grading System described by Terzis and Noah.[19] Similarly, photographs were analysed using the Emotrics software,[20] which automatically identifies facial landmarks and computes differences in position. All measurements and assessments with Emotrics and Terzis' Grading System were performed during a natural smile.

Statistical Analysis

Data were analysed using Stata/MP v15. Continuous variables that approximate the normal distribution are summarized by the mean and standard deviation (SD). Change in Emotrics facial measurements over time were skewed; therefore, they are summarized by the geometric mean (and 95% confidence interval, CI). Wilcoxon signed-rank test was used for repeated Emotrics facial measurements and Terzis' Grading System outcomes. To estimate the change in facial measurements over time, mixed-effects generalized linear regression was used (using the gamma family function), with the fixed effect being time (in years) and the patient forming the random coefficient.

Results

Between October 2011 and March 2016, 11 adults (6 females and 5 males) with long-standing unilateral facial paralysis underwent two-stage facial reanimation using DI of FFMT. At the time of the first surgery, the mean age of patients was 32 (SD 8) and the mean weight was 78 Kg (SD 14). Five patients were scored as House-Brackman VI, 4 were V and 2 were IV. Details of individual patients are given in Table 1.

Table 1 Patient Demographics.

	Sex	Age	Weight (kg)	Pathology	Denervation Time (months)	HB score	Date of FFMT	Laterality
1	M	46	74.9	Bell's Palsy	52	VI	Aug-12	Right
2	F	33	64	Acoustic neuroma	36	VI	Jul-13	Left
3	F	47	94	V. Schwannoma	48	VI	Sep-13	Right
4	F	30	79.3	Astrocytoma	42	VI	Oct-13	Right
5	F	31	85	Parotidectomy	39	V	Oct-13	Left
6	F	32	55	Bell's in Pregnancy	49	V	Mar-14	Left
7	F	38	95	Bell's Palsy	59	V	Mar-14	Left
8	M	24	100	Bell's Palsy	39	V	Apr-15	Right
9	M	22	76	Bell's Palsy	46	IV	Nov-14	Right
10	M	21	66	Neurofibromatosis	120	VI	Jul-14	Left
11	M	32	82	Skull base fracture	55	IV	Dec-15	Right

Clinical outcomes

The median delay between the first and second stage surgery was 13 months (range: 8-15 months). Intraoperatively, the mean time to dissect the MN was 18 min (SD 2). Clinical examination and surface Doppler provided no evidence of total flap loss in any patient. The average duration of hospitalization was 1.6 days following CFNG (range: 0-3 days) and 5.1 days following second stage FFMT (range: 4-10 days).

Postoperatively, one patient developed flap venous congestion, which was salvaged by the revision of the venous anastomosis. Two further patients underwent surgical debulking of the gracilis at 26 and 29 months post-transfer. Both were young athletic males who had bulky gracilis muscles that were already sculpted during muscle harvest. Resting facial tone returned at an average of 2.7 months after FFMT (range: 2-3.25 months). Voluntary contractions were noted at a mean of 4 months and 4 days following FFMT (range: from 3 months 8 days to 4 months 21 days). At 6 months postsurgery, all patients recovered some voluntary smiling. A spontaneous smile produced without teeth clenching, developed in all patients by 18 months postoperatively. No weakness in the healthy side or impaired masticatory function were noted although very mild involuntary movement of the transferred gracilis muscle was observed with chewing.

Facial Measurements

With Emotrics the change in facial measurements over 36 months period after the second stage are summarized in Table 2. There were significant improvements in the smile angle, upper lip elevation, commissural excursion, and commissural height. Most of the improvements in facial symmetry were made within the first postoperative year and gains thereafter were smaller. The values represent differences between right and left side of the face; thus, a value of (0) implies perfect symmetry.

There were statistically absolute improvements in the commissural excursion (mean increase of 6.66 mm [95% CI 0 mm and 1.36 mm]) and upper lip elevation (mean increase 1.78 mm [95% CI 0.88 mm and 3.59 mm]) in the Hollywood expression (Figure 3).

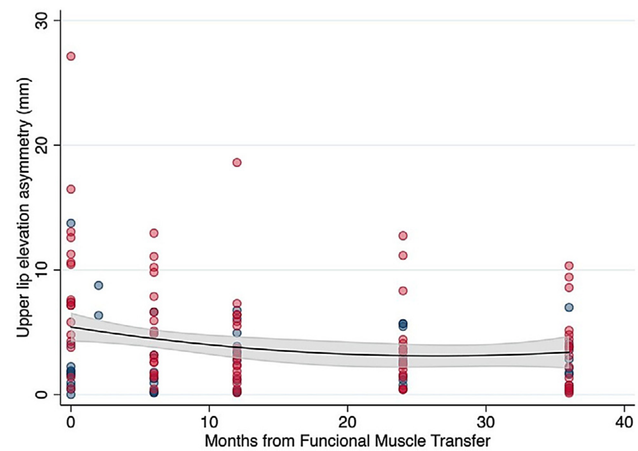

Figure 3 Emotrics measurements of upper lip elevation changes over a period of 36 months after surgery. The scatter plot (with the line of fit and 95% CI) shows that upper lip elevation was highly asymmetrical at baseline but following DI of FFMT, the difference falls significantly, and patients attain more symmetrical elevation of the upper lip. HB VI = red and HB IV-*V* = blue.

According to Terzis' Classification,[19] 6 patients had excellent outcomes (symmetrical smile with teeth showing full contraction) and 5 patients had good outcomes (symmetry, nearly full contraction) at 48 months after the second stage of surgery (Table 3). There was a statistically significant improvement between the mean preoperative and postoperative scores (mean 1.60 (SD 0.39) to mean 4.30 (SD 0.43), $p < 0.05$, and Wilcoxon signed-rank test). Figures 4-7; Video, SDC 1 depict patient clinical results.

Electromyography

Simultaneous three-channel needle EMG was used to investigate the innervation of the transferred gracilis muscle. Needle electrodes were inserted into the following 3 muscles: transferred gracilis, masseter muscle on the paralyzed side, and the zygomatic major muscle on the healthy side. The muscle contraction was measured simultaneously. Signs of DI of the transferred muscle were found at an average

Table 2 The absolute Emotrics scores over time according to the facial expression. Values that decrease from baseline to follow are desirable as they imply less asymmetry.

	Expression	Geometric mean (95% CI) of facial asymmetry			
		Baseline	Final follow-up	Improvement	p-value
Commissural excursion (mm)	Repose	2.60 (0.97, 7.01)	4.58 (2.28, 9.20)	3.63 (1.60, 8.27)	0.789
	Hollywood	7.53 (3.23, 18)	2.69 (1.18, 6.17)	2.61 (0.39, 179)	0.051
	Mona Lisa	5.02 (2.21, 11)	4.09 (1.42, 11.7)	5.07 (0.49, 52)	0.767
Commissural height (mm)	Repose	1.98 (1.36, 6.42)	2.11 (1.05, 4.21)	0.94 (0.06, 14)	0.612
	Hollywood	6.09 (3.10, 11.9)	1.63 (0.73, 3.67)	1.38 (0.06, 14.5)	0.013
	Mona Lisa	5.32 (3.32, 8.52)	1.30 (0.42, 4.08)	2.98 (0.50, 178)	0.013
Smile angle (°)	Repose	4.80 (2.12, 10.9)	4.70 (2.69, 8.18)	1.72 (1.81, 2.83)	1.0
	Hollywood	6.90 (4.82, 9.86)	2.36 (0.91, 6.11)	2.26 (1.81, 2.82)	0.131
	Mona Lisa	9.66 (6.33, 14.7)	4.66 (2.79, 7.77)	−6.0 (−10.8, −1.4)	0.001
Upper lip height (mm)	Repose	3.25 (1.66, 6.38)	1.59 (0.57, 4.46)	3.24 (−3.62, 0.16)	0.028
	Hollywood	5.49 (4.76, 11.9)	2.01 (0.56, 4.68)	1.42 (0.39, 5.18)	0.021
	Mona Lisa	2.30 (0.47, 11.3)	3.26 (1.81, 5.87)	4.34 (2.11, 8.91)	0.767
Dental show (mm)	Repose	0.15 (0.02, 0.99)	0.09 (0.01, 1.69)	0.77 (0.08, 7.70)	0.893
	Hollywood	3.41 (1.47, 7.88)	3.06 (1.35, 6.94)	1.16 (0.10, 13)	0.155
	Mona Lisa	0.03 (0.01, 0.19)	0.06 (0.02, 0.24)	0.04 (0.01, 0.24)	0.314

Table 3 Averaged Scores of Outcomes for Smile (Terzis' Functional Grading System).

Patient	Preoperative Smile Average Score *	Preoperative Smile Grading	Postoperative Smile Average Score *	Postoperative Smile Grading
1	1.33	Poor	4.66	Excellent
2	1.33	Poor	4.66	Excellent
3	1.33	Poor	4.00	Good
4	1.33	Poor	4.66	Excellent
5	1.67	Fair	4.00	Good
6	2.33	Moderate	4.66	Excellent
7	1.33	Poor	3.67	Good
8	1.67	Fair	3.67	Good
9	1.67	Fair	4.66	Excellent
10	1.33	Poor	4.00	Good
11	2.33	Moderate	4.66	Excellent
Mean (SD)	1.60 ± 0.39	NA	4.30 ± 0.43	NA

* $p < 0.05$ (Wilcoxon signed rank test).

of 12 months after surgery, with the following observations: on biting, action potentials were detected only in the transferred gracilis muscle, and masseter on the paralyzed side; with natural smiling, action potentials were detected in the transferred gracilis muscle and zygomatic major muscle on the healthy side. Voluntary motor units in the gracilis muscle were shown with the patient smiling or biting but were more evident with the patient smiling and biting at the same time: an electrophysiological sign of DI of the muscle. At 4 months postsurgery, the voluntary motor units in the gracilis muscle were present only when the patient was biting, and a very minimal trace was obtained during her/his natural smile.

Figure 8 shows EMG results on patient 4, at 24 months following the FFMT.

Discussion

Yamamoto et al [21] reported their experience with neural supercharging, where a second source of axonal input was supplied together with facial nerve stimulus. They used the hypoglossal nerve input together with facial nerve stimulus in patients with recent facial paralysis to achieve adequate contraction while maintaining spontaneity. They utilized interpositional nerve grafts between the hypoglossal and facial nerve trunk or branches. Watanabe et al [22] initially reported the use of single-stage latissimus dorsi (LD) flap dually innervated both by the contralateral facial nerve and by positioning the hilum of the flap in contact with a part of the denuded masseter on the paralyzed side. Recently, Watanabe et al [23] published a modification of their previous technique with harvesting in addition to LD, a small portion of the serratous anterior muscle with its nerve been coapted end to end with the thinner branch of the MN. The other branch of the MN was used for direct intramuscular neurotization of the cranial side of the LD muscle, while the nerve of the LD muscle was coapted to contralateral buccal branches.

Biglioli et al [24] described a single-stage dually innervated gracilis FFMT with an end-to-end masseteric to ON coaptation and an end-to-side coaptation of the CFNG to the ON.

Figure 4 Pre- (A) and postoperative (B and C) pictures at 50 months following the gracilis muscle transfer on patient 9. During the first operation with the CFNG, he also had tarsal strip advancement of the right lower eyelid. Four months prior to the postoperative picture presented (C), he had a platinum chain to the upper eyelid to correct scleral show and paralytic lagophthalmos.

Cardenas-Mejia et al [25] reported their experience with a 2-stage DI of FFMT with the use of CFNG and the MN. The second stage took place 3–4 months later, with the CFNG being the main motor donor nerve as it was coapted in end-to-end fashion with the ON, while the masseteric was coapted end-to-side with an epineural window to the ON at 1 cm from the muscle hilum to act as a babysitter. Although the authors have referred to their results from the EMG analysis and found a 68.3% increase in motor unit recruitment at 1 year postsurgery, they have not clearly demonstrated electrophysiologically the dual nature of innervation, in terms of how much each motor donor nerve has contributed. Uehara and Shimizu[26] used the intramuscular motor branch of the ON to coapt with the MN to double-power the gracilis muscle in 6 patients. All was done in a single stage, with a CFNG which has been coapted end-to-end with the ON of the muscle. Okazaki et al [27] reported four cases of one-stage transfer of the LD muscle that was split in two segments both based on the thoracodorsal vessels. The larger segment had the thoracodorsal nerve that was coapted end to end to a branch from contralateral facial nerve and the smaller segment was originally innervated by the short branch of the thoracodorsal nerve that was cut off the main trunk and was coapted to the ipsilateral masseteric nerve.

In contrast to most previous publications, our technique is a two-staged procedure. The DI of gracilis muscle was achieved through an end-to-end coaptation between the distal stump of the CFNG and one half of the longitudinally

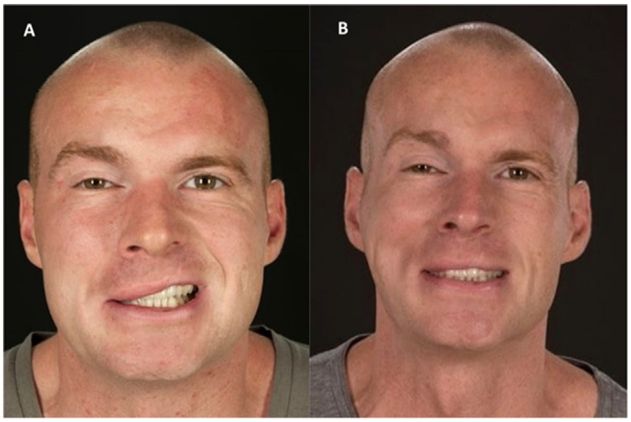

Figure 5 Pre- (A) and postoperative (B) pictures at 36 months for patient 11. During the first stage with the CFNG, he also had an insertion of a platinum chain to the right upper lid for 3 mm paralytic lagophthalmos and negative Bell's phenomenon.

Figure 6 Preoperative (A) and 38 months postoperative (B) pictures smiling showing teeth, of patient 7 who had a "heavy face" and "high expectations".

Figure 7 Preoperative (A) and 36 months postoperative (B) pictures smiling showing teeth, of patient 10 who had a complete paralysis due to neurofibromatosis. In addition to dual innervation, he also had the correction of the lower lip with anterior belly of digastric muscle transfer at 15 months after the gracilis muscle transfer.

split anterior ON approximately 1 cm from the hilum, and a second end-to-end coaptation between a branch of the MN and the remaining half of the longitudinally split ON 4 cm from the hilum. As the MN is a powerful nerve with over 2700 myelinated motor axons,[8] we elected to use only a branch of the MN to avoid overpowering of the muscle. This selectivity also prevented paralysis and atrophy of the masseter muscle. It is known that the MN is a strong motor driver when compared with the CFNG, which produces a weaker motor action. We purposely chose to perform the coaptation closer toward the hilum of the CFNG to allow for faster remyelination as opposed to the 4 cm site of coaptation for the MN. This therefore optimizes the role of each motor driver in the neurological contribution to facial movement and power. Although this technique involves 2 procedures, we believe the results are more predictable, giving time for the CFNG axons to myelinate after the first stage and gain some advantage over the MN, for better facial balance, spontaneity, and emotional expression.

Voluntary contraction of the dually innervated gracilis muscle was observed at an average of 4.15 months following transfer, which is significantly faster as compared to the standard free gracilis transfer innervated by CFNG alone.[19] This was due to the rapid reinnervation of the transferred muscle by the MN. Indeed, previous studies reported that the transferred gracilis muscle starts to contract at approximately 3–4 months[7,28] following the coaptation of the ON to MN. The shorter duration of muscle denervation in our technique could also minimize potential muscle atrophy while waiting for the CFNG to innervate the muscle. By splitting the ON in two longitudinal segments, we hypothesized that each neural source innervated different territories within the gracilis muscle. The EMG studies demonstrated the dual nature of innervation of the FFMT after 12 months from the muscle transfer and was more evident at 24 months.

In our study, the patients were followed up for a minimum of 48 months. They were able to produce a spontaneous, natural smile without biting or clenching of the teeth, although the muscle excursion was further enhanced by clenching while smiling. All of them achieved excellent or good outcomes on the natural smile according to Terzis' smile functional grading system.[19] Although cortical adaptation and spontaneous activation of the trigeminal nerve nuclei has been postulated as a potential mechanism for the restoration of a spontaneous smile after FFMT innervated by MN,[7] we believe that the emotional smile we achieved in our patients was related to the presence of the CFNG, which was evidenced by the postoperative EMG studies. Schaverian et al [29] showed the contraction of the masseter muscle during a natural smile in 40% of their study subjects who had no facial palsy, hypothesizing that this could potentially explain the spontaneity of the smile when the MN is used to innervate the transferred muscle as smiling could trigger MN activation.

One potential drawback of innervating FFMT with the MN is a possibility of involuntary smiling movement during mastication. In our series with the dual innervation, such mild movement was observed in all patients, but was remarked by us rather than them. This is consistent with previously reported experience where synkinesis is noted but overall represented minimal hindrance.[7,30]

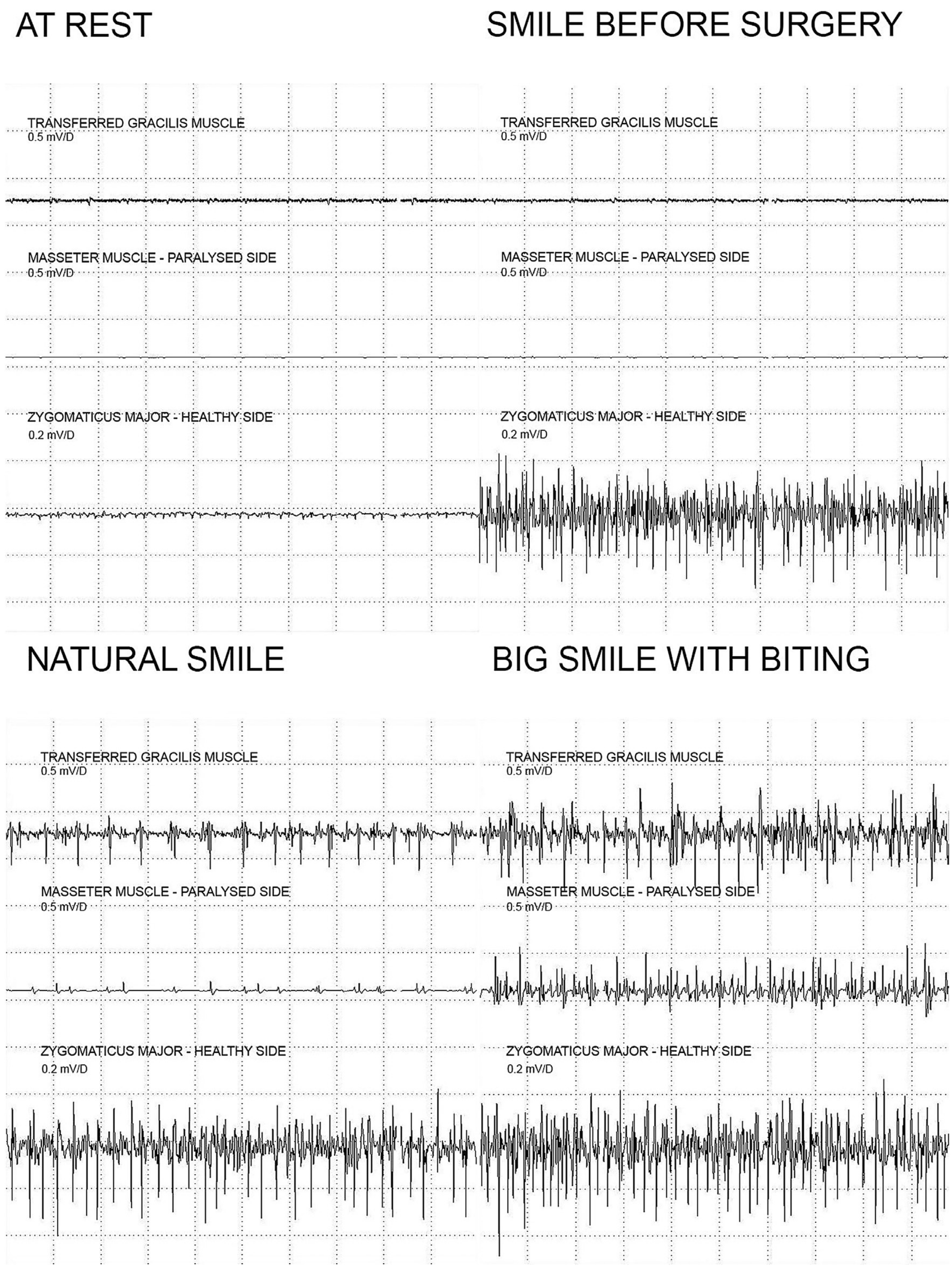

Figure 8 Three-channel synchronous EMG study on patient 4 at 24 months following the muscle transfer with the needle electrodes has been inserted at the gracilis and masseteric muscle on the affected side and at the zygomaticus major on the contralateral side. No activity is noted at rest that serves as baseline measurement. There is activity only on the zygomaticus major at the healthy side during smile before surgery. During a natural smile, voluntary motor units are noted at the gracilis and contralateral zygomaticus major with much smaller activity at the ipsilateral masseteric muscle, but the voluntary motor units are exaggerated during smile while biting (clenching of teeth) at the gracilis, ipsilateral masseter muscle, and contralateral zygomaticus major.

Conclusion

Dually innervated two-staged FFMT with the ON being coapted end to end with CFNG and a branch of the MN provides a reliable and symmetrical smile restoration in long-standing unilateral facial paralysis. It ensures powerful muscle excursion, along with the ability to smile spontaneously and without biting down or clenching. We believe that this technique offers an innovation in the surgical treatment of long-standing unilateral facial palsy on selected patients with "heavy" faces, previously failed reconstructions, and those with a high expectation of recovery from facial weakness of HB IV-VI.[15]

Declaration of Competing Interest

No author reports conflicts of interest.

Acknowledgments

The authors would like to acknowledge

1. Dr J Deeb, Consultant Neuro-electrophysiologist, who performed the nerve conduction and electromyographic testing for our patients.
2. Miss Jenny Goodenough and Miss Thet Su Win both trainees at St Andrews Centre of Plastic and Reconstructive Surgery for presenting and drafting some preliminary work.
3. Department of Medical Photography, St Andrews Centre of Plastic and Reconstructive Surgery. Without the dedication and efforts of this department, the static and dynamic evidence of preoperative and postoperative outcomes for our own assessment, for our patients understanding and appreciation, and for publication would not have been possible.
4. Miss Julia Ruston senior trainee in plastic surgery for her drawing on Figure 1.

Ethical Approval

Not required.

Financial Disclosures

None of the authors have a financial interest or any commercial association related to the information presented in this article. There are no conflicts of interest. Ryckie Wade is a Doctoral Research Fellow funded by the National Institute for Health Research (NIHR, DRF-2018-11-ST2-028). The views expressed are those of the author(s) and not necessarily those of the United Kingdom's National Health Service, NIHR, or Department of Health.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.bjps.2021.03.007.

References

1. O'Brien BM, Pederson WC, Khazanchi RK, Morrison WA, MacLeod AM, Kumar V. Results of management of facial palsy with microvascular free-muscle transfer. *Plast Reconstr Surg* 1990;**86**(1):12–22 discussion 23-14.
2. Terzis JK, Olivares FS. Long-term outcomes of free-muscle transfer for smile restoration in adults. *Plast Reconstr Surg* 2009;**123**(3):877–88.
3. Gousheh J, Arasteh E. Treatment of facial paralysis: dynamic reanimation of spontaneous facial expression-apropos of 655 patients. *Plast Reconstr Surg* 2011;**128**(6):693–703.
4. Faria JC, Scopel GP, Busnardo FF, Ferreira MC. Nerve sources for facial reanimation with muscle transplant in patients with unilateral facial palsy: clinical analysis of 3 techniques. *Ann Plast Surg* 2007;**59**(1):87–91.
5. Frey M, Happak W, Girsch W, Bittner RE, Gruber H. Histomorphometric studies in patients with facial palsy treated by functional muscle transplantation: new aspects for the surgical concept. *Ann Plast Surg* 1991;**26**(4):370–9.
6. Terzis JK, Wang W, Zhao Y. Effect of axonal load on the functional and aesthetic outcomes of the cross-facial nerve graft procedure for facial reanimation. *Plast Reconstr Surg* 2009;**124**(5):1499–512.
7. Manktelow RT, Tomat LR, Zuker RM, Chang M. Smile reconstruction in adults with free muscle transfer innervated by the masseter motor nerve: effectiveness and cerebral adaptation. *Plast Reconstr Surg* 2006;**118**(4):885–99.
8. Borschel GH, Kawamura DH, Kasukurthi R;, Hunter DA, Zuker RM, Woo AS. The motor nerve to the masseter muscle: an anatomic and histomorphometric study to facilitate its use in facial reanimation. *J Plast Reconstr Aesthet Surg* 2012;**65**(3):363–6.
9. Hwang K, Kim YJ, Chung IH, Song YB. Course of the masseteric nerve in masseter muscle. *J Craniofac Surg* 2005;**16**(2):197–200.
10. Hontanilla B, Marre D, Cabello A. Facial reanimation with gracilis muscle transfer neurotized to cross-facial nerve graft versus masseteric nerve: a comparative study using the FACIAL CLIMA evaluating system. *Plast Reconstr Surg* 2013;**131**(6):1241–52.
11. Henstrom DK. Masseteric nerve use in facial reanimation. *Curr Opin Otolaryngol Head Neck Surg* 2014;**22**(4):284–90.
12. Lifchez SD, Matloub HS, Gosain AK. Cortical adaptation to restoration of smiling after free muscle transfer innervated by the nerve to the masseter. *Plast Reconstr Surg* 2005;**115**(6):1472–9 discussion 1480-1472.
13. Terzis JK, Tzafetta K. The babysitter" procedure: minihypoglossal to facial nerve transfer and cross-facial nerve grafting. *Plast Reconstr Surg* 2009;**123**(3):865–76.
14. Terzis JK, Tzafetta K. Babysitter" procedure with concomitant muscle transfer in facial paralysis. *Plast Reconstr Surg* 2009;**124**(4):1142–56.
15. House JW, Brackmann DE. Facial nerve grading system. *Otolaryngol. Head Neck Surg* 1985;**93**:146–7.
16. Terzis JK, Tzafetta K. Facial Reanimation. In: *Plastic Surgery: Indications and Practice*, 1. Edinburgh: Saunders Elsevier; 2009. p. 907–26. Bahman Guyuron EE, John Persing, Kevin Chung, Joseph Disa, Arun Gosain, Brian Kinney, J Peter Rubin.
17. Morris SF, Yang D. Gracilis muscle: arterial and neural basis for subdivision. *Ann Plast Surg* 1999;**42**(6):630–3.
18. Fattah AY, Ravichandiran K, Zuker RM, Agur AM. A three-dimensional study of the musculotendinous and neurovascular architecture of the gracilis muscle: application to functional muscle transfer. *J Plast Reconstr Aesthet Surg* 2013;**66**(9):1230–7.
19. Terzis JK, Noah ME. Analysis of 100 cases of free-muscle transplantation for facial paralysis. *Plast Reconstr Surg* 1997;**99**(7):1905–21.

20. Guarin DL, Dusseldorp J, Hadlock TA, Jowett N. A machine learning approach for automated facial measurements in facial palsy. *Fac Plast Surg* 2018;**20**(4):335–7.
21. Yamamoto Y, Sekido M, Furukawa H, Oyama A, Tsutsumida A, Sasaki S. Surgical rehabilitation of reversible facial palsy: facial-hypoglossal network system based on neural signal augmentation/neural supercharge concept. *J Plast Reconstr Aesthet Surg* 2007;**60**(3):223–31.
22. Watanabe Y, Akizuki T, Ozawa T, Yoshimura K, Agawa K, Ota T. Dual innervation method using one-stage reconstruction with free LD muscle transfer for re-animation of established facial paralysis: simultaneous reinnervation of the ipsilateral masseter motor nerve and the contralateral facial nerve to improve the quality of smile and emotional facial expressions. *J Plast Reconstr Aesthet Surg* 2009;**62**(12):1589–97.
23. Watanabe Y;, Yamamoto T, Hirai R;, Sasaki R; Agawa K, Akizuki T. One-stage free transfer of latissimus dorsi-serratus anterior combined muscle flap with dual innervation for smile reanimation in established facial paralysis. *J Plast Reconstr Aesthet Surg* 2020 1-9 (in Press).
24. Biglioli F, Colombo V, Tarabbia F, et al. Double innervation in free-flap surgery for long-standing facial paralysis. *J Plast Reconstr Aesthet Surg* 2012;**65**(10):1343–9.
25. Cardenas-Mejia A; Covarrubias-Ramirez JV, Bello-Margolis A, Rozen S. Double innervated free functional muscle transfer for facial reanimation. *J Plast Surg & Hand Surg* 2015;**49**(3):183–8.
26. Uehara M, Shimizu F. The distal stump of the intramuscular motor branch of the obturator nerve is useful for the reconstruction of long-standing facial paralysis using a double-powered free gracilis muscle flap transfer. *J Craniofac Surg* 2018;**29**:476–81.
27. Okazaki M, Kentaro T, Noriko U, et al. One-stage dual latissimus dorsi muscle flap transfer with a pair of vascular anastomoses and double nerve suturing for long standing facial paralysis. *J Plast Reconstr Aesthet Surg* 2015;**68**:113–19.
28. Bianchi B, Copelli C, Ferrari S, Ferri A, Bailleul C, Sesenna E. Facial animation with free-muscle transfer innervated by the masseter motor nerve in unilateral facial paralysis. *J Oral Maxillofac Surg* 2010;**68**(7):1524–9.
29. Schaverien M;, Moran G;, Stewart K;, Addison P. Activation of the masseter muscle during normal smile production and the implications for dynamic reanimation surgery for facial paralysis. *J Plast Reconstr Aesthet Surg* 2011;**64**:1585–9.
30. Rozen S, Harrison B. Involuntary movement during mastication in patients with long-term facial paralysis reanimated with a partial gracilis free neuromuscular flap innervated by the masseteric nerve. *Plast Reconstr Surg* 2013;**132**(1):110e-1116.