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Dual innervation method using one-stage reconstruction with free latissimus dorsi 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☆

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Summary *Background:* One-stage microneurovascular free muscle transfer is a common surgical procedure for re-animation of established facial paralysis. However, innervation of the transferred muscle by the contralateral facial nerve prevents smile and other facial expressions on one side, and reinnervation requires about 7 months. To overcome these drawbacks, we report a dual innervation method using one-stage reconstruction with free latissimus dorsi muscle transfer.
Methods: Three patients were treated with the dual innervation method, which is based on the one-stage method with some modifications: the soft tissue present over the ipsilateral masseter muscle and the hilum where the thoracodorsal nerve proceeds into the muscle segment is removed; the muscle is harvested to locate the hilum in the cranial one-third of the segment; and the muscle is transferred to the malar pocket of the paralysed face such that the hilum contacts the masseter muscle.

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Results: On average, muscle movement was recognised on voluntary biting at 3.4 months and on spontaneous smiling at 5.9 months after surgery. A dual innervation sign was recorded on electromyographs 6.4 months after surgery. The patients developed a spontaneous symmetrical smile and facial expressions on one side with minimum synkinesis after postoperative mirror rehabilitation.
Conclusions: The advantages of the dual innervation method include faster reinnervation of the transferred muscle compared to one-stage options; achievement of spontaneous smile and voluntary smile on each side; augmentation of neural signals to the muscle for more symmetrical smiling; minimum synkinesis of the transferred muscle on biting for eyelid closure and emotional facial re-animation through a learning program to enhance cerebral cortical re-organisation.

One-stage microneurovascular free muscle transfer for established facial paralysis is the standard reconstruction method that enables spontaneous synchronous smiling on the healthy side.[1] However, we occasionally encounter cases in which resolution of the following problems is necessary to reconstruct an expressive smile. First, patients may not be able to smile on each side or make subtle expressions, although a synchronous bilateral smile is possible, which may be due to reinnervation of the transferred muscle depending only on the healthy facial nerve. Second, contraction of the transferred muscle may be insufficient.[2] A lack of muscle volume due to muscular atrophy during the deinnervated period (usually more than 7 months) before reinnervation of the transferred muscle and a lack of a regenerated nerve in the transferred muscle are probable causes.[3]

To address these problems, we developed a dual innervation method (Figure 1) and investigated its potential to improve the quality of smile and facial expression. The new method allows reconstruction of spontaneous synchronous smile on the healthy side and smile on each side by simultaneous reinnervation of a microneurovascular free latissimus dorsi muscle graft with two different cranial nerves: the buccal branch of the facial nerve (cranial nerve V) on the healthy side and the masseter motor nerve (cranial nerve VII) on the paralysed side.

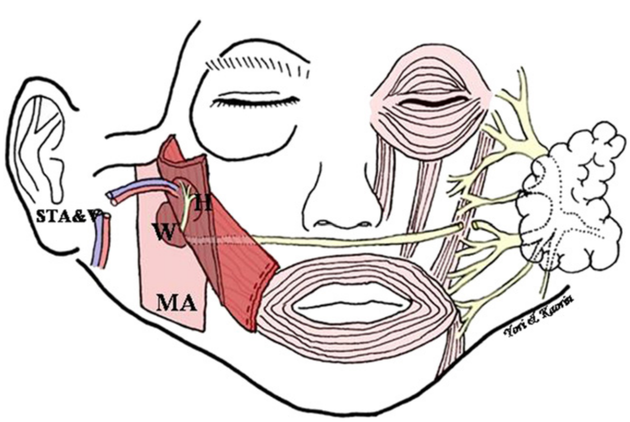

Figure 1 Schema of the dual innervation method. STA & V, Superficial temporal artery and vein; MA, Masseter muscle; H, Hilum of the muscle graft; W, Window of the masseter muscle.

Patients and methods

The subjects were three patients with established facial paralysis (two men and one woman; average age, 47 years) who were treated between March and November, 2006. To reconstruct lid-closure function, temporal muscle transfer for eyelid closure was performed simultaneously. The cause of the facial palsy was the resection of acoustic neuroma in all three patients. The procedure was performed 16—70 months (mean, 37.6 months) after onset of facial palsy (Table 1).

Preparation of the recipient site

The paralysed cheek was widely undermined under the superficial musculoaponeurotic system via a preauricular incision to prepare a recipient site. Since the superficial temporal artery and vein are preferred for anastomosis based on the position of muscle-graft fixation, these blood vessels were detached and secured. It is also possible to obtain a thoracodorsal artery and vein of the muscle graft of about 8 cm in length for anastomosis with the facial artery and vein. Detachment of the malar subcutaneous tissue was advanced to a site 1—2 cm oral to the nasolabial groove to be prepared, and the cross-region of the atrophied orbicularis oris muscle and greater zygomatic muscle was exposed. Centering on this region, four to five sutures were defined for muscle-graft fixation. By pulling on these sutures, formation of a nasolabial groove at a site symmetrical to the healthy side on smiling could be confirmed, and the direction of fixation of the transferred muscle could also be determined. Soft tissues such as fat and fascia on the side of the anterior margin of the recipient masseter were removed in as minimum an extent possible to allow the hilum of the transferred muscle to contact the anterior region of the masseter, and the anterior region of the masseter was partially exposed, that is, a window was prepared. When this window is created, careful attention should be paid to prevent unnecessary adhesion, which may disturb the final excursion of the transferred muscle, between the masseter and the transferred muscle.

Moreover, the position of this window was set to minimise the thoracodorsal nerve length attached to the

Table 1 Patient summary.

Case	Age (years)	Sex	Cause	Duration of paralysis (months)
1	37	Male	AN	16
2	44	Male	AN	70
3	60	Female	AN	27
Average	47	—	—	37.6

AN, Acoustic neuroma.

transferred muscle (Figure 1). An incision of about 1.5 cm was made in the malar region in the anterior margin of the parotid gland on the healthy side and the buccal branch of the facial nerve involved only in smile was identified using a nerve stimulator. This branch was detached and secured up to a maximum periphery.

Preparation of the donor muscle

An incision was made along the anterior margin of the latissimus dorsi muscle located at the posterior axillary line to prepare the thoracodorsal artery, vein and nerve. The thoracodorsal nerve was detached and the detachment was advanced as far as possible into the posterior cord of the brachial plexus on the proximal side and the latissimus dorsi muscle on the distal side to prepare a muscle graft with a nerve of about 15 cm in length. Soft tissue covering the hilum was removed to expose the hilum, via which the thoracodorsal nerve entered the latissimus dorsi muscle, and both ends of the muscle graft were cut using a disposable stapler to position the hilum about one-third to the cranial side of the length of the muscle graft.[4] The graft was thinned and trimmed to an appropriate volume while retaining blood flow, and then the thoracodorsal artery, vein and nerve were cut (Figure 2a—d).

Setting of the transferred muscle

The muscle was set so as to place the hilum on the cranial side of the masseter and to allow it to contact the window on the masseter. The thoracodorsal artery and vein are appropriate for anastomosis with the superficial temporal artery and vein based on the setting position, but the facial artery and vein may be selected for anastomosis when a subcutaneous tunnel advancing to the lower jaw is prepared. The thoracodorsal nerve was passed through a subcutaneous tunnel in the upper lip region, which was prepared to be as short as possible, and sutured with the epineurium of the buccal branch of the facial nerve on the healthy side prepared beforehand using 10/0 nylon (Figure 2e—f).

Postoperative rehabilitation

Rehabilitation was initiated about 2 months after surgery and involved mirror training of smile using visual feedback as frequently as possible on a daily basis, even if for a short duration.[5] Generally, the transferred muscle started to contract on biting about 3 months after surgery, and the muscle gradually came to contract on spontaneous smiling about 6 months after surgery. After these contractions were established, greater emphasis was placed on smiling on each side. Smile on the paralysed side was initially possible only by voluntary biting, but the patients continued to practice and became able to smile spontaneously without intention to bite. For smile on the healthy side, the patients practised smile at an intensity at which contraction of the transferred muscle was not noticeable. Temporal muscle transfer for eyelid closure is performed concomitantly in many cases of complete, established facial paralysis, and patients practice lid closure by contracting the temporal muscle by biting, but contraction of the transferred muscle is unavoidable due to synkinesis. However, there is a subtle difference between the intensities of biting required to close the eyelid and to smile on the paralysed side. Patients continued to practise to separate these synkinetic movements.

Results

Initial contraction of the transferred muscle on biting and smiling occurred at an average of 3.4 and 5.9 months after surgery, respectively. For electromyography, needle electrodes were inserted into the three muscles (the transferred muscle, the masseter muscle on the paralysed side and the greater zygomatic muscle on the healthy side) and muscle contraction was measured simultaneously. Signs of dual innervation of the transferred muscle were found at an average of 6.4 months after surgery (Figure 4). The duration of follow-up after surgery was 15—20 months, with a mean of 17.3 months. The function of the transferred muscle was rated excellent (Grade 5) in all patients based on the criteria of Harii et al.[1] Patient satisfaction with the outcome was also very high, because they were able to smile and make facial expressions on each side, in addition to a bilateral spontaneous smile (Table 2). Movement of the transferred muscle was not noticeable during eating and speaking. Temporal muscle transfer also enabled eyelid closure on the affected side by voluntary biting, and contraction of the transferred muscle during closing of the eye, that is, abnormal synkinetic movement, was not noticeable.

The course of treatment by the dual innervation method is presented for Case 1 as a representative case. The patient was a 37-year-old man who developed complete left facial palsy after resection of left acoustic neuroma, with paralysis persisting for 16 months after surgery (Figure 3a—c). The dual innervation method and temporal muscle transfer for eyelid closure were performed simultaneously. The postoperative course was smooth and the patient started mirror rehabilitation for smile 2 months after surgery.[5]

The transferred muscle started to contract on biting 3.3 months after surgery, contracted well on biting at 4 months (Figure 3d—f) and started to contract with spontaneous smile at 5.9 months after surgery. Measurement of the transferred muscle, the masseter on the paralysed side and the greater zygomatic muscle on the healthy side by simultaneous three-channel needle electromyography 7

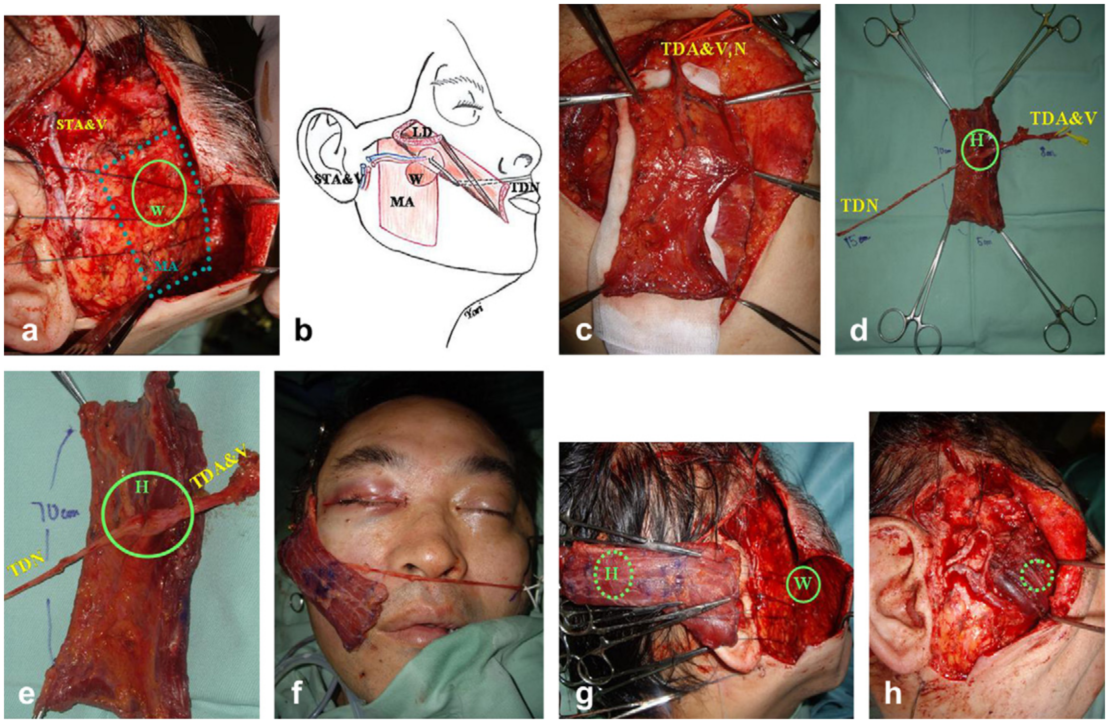

Figure 2 (a,b). Preparation of the recipient site: (a, left) Recipient site: soft tissues such as fat and fascia on the side of the anterior margin of the masseter were removed to partially expose the anterior region of the masseter as a window. (b, right) Schema showing the positional relationship between the recipient site and the transferred muscle. STA & V, Superficial temporal artery and vein; MA, Masseter muscle; W, Window; TDN, Thoracodorsal nerve; LD, Latissimus dorsi muscle. (c,d). Preparation of the muscle graft: (c, left) Soft tissues covering the hilum, via which the thoracodorsal nerve and vessels enter the latissimus dorsi muscle, was removed to expose the hilum, and the muscle graft to be transferred was excised. (d, right) The thoracodorsal nerve was bluntly dissected and detached from the muscle and brachial plexus as much as possible, and a muscle graft with a nerve of about 15 cm in length was prepared. H, Hilum; TDN, Thoracodorsal nerve; TDA & V, Thoracodorsal artery and vein. (e,f). (e, left) Close-up of the hilum: this region was in contact with the window on the masseter. (f, right) The muscle graft was placed at the recipient site and the shortest subcutaneous tunnel to the buccal branch of the facial nerve on the healthy side was designed in the upper lip region, and the thoracodorsal nerve was passed through the tunnel. The green circle represents the hilum. H, Hilum; TDN, Thoracodorsal nerve; TDA & V, Thoracodorsal artery and vein. (g,h). (g, left and h, right) The transferred muscle was fixed to place the hilum (green, dotted circle) on the cranial masseter side and allow it to contact the window (green, solid circle) on the masseter. The thoracodorsal artery and vein are appropriate for anastomosis with the superficial temporal artery and vein based on the fixation position.

months after surgery detected active potentials only in the transferred muscle and masseter on the paralysed side on biting. With normal and large smiles, an action potential was detected in the transferred muscle and greater zygomatic muscle on the healthy side at a level corresponding to the transferred muscle contraction intensity (Figure 4). These findings confirm that the transferred muscle received dual innervation by the masseter motor nerve on the paralysed side and the facial nerve on the healthy side.

The patient was able to smile on each side without thinking about it and biting at 12 months after surgery (Figure 5a, b). Abnormal synkinesis was not noticeable during eating or talking. At 14 months, he was able to close the eye and smile on the paralysed side alone, and he also

Table 2 Results of the procedure.

Case	First movement on biting (month)	First movement on smiling (month)	First dual Innervative sign by EMG (month)	Follow-up (month)	Evaluation Criteria[1,a]	Preliminary results
1	3.3	5.9	7.0	20	5	Excellent
2	2.6	5.8	4.5	17	5	Good
3	4.2	6.1	7.7	15	5	Excellent
Average	3.4	5.9	6.4	17.3	5	–

[a] Harii's evaluation criteria.[1]

Figure 3 Case 1: A 37-year-old man with established facial palsy after left acoustic neurotomy.(Above) pre-operative views: (a, above left) resting state, (b, above center) eyelid closure, (c, above right) smiling. (Below) 4 months after surgery: (d, below left) resting state. (e, below center) Smile was noted only on the right healthy side on smiling. (f, below right) Smile was noted only on the left paralysed side on biting due to contraction of the transferred muscle.

had a spontaneous symmetric smile (Figure 5c, d). However, the transferred muscle contraction was insufficient for a large smile, leading to slight lateral imbalance. The patient increased the contraction intensity of the transferred muscle to widen his smile on the paralysed side by slight voluntary biting, and acquired lateral balance (Figure 5e–g). Currently, the patient is continuing rehabilitation to achieve a balanced large smile and facial expressions on each side without voluntary biting.

Discussion

In 1976, Harii et al. first reported microneurovascular free gracilis muscle transplantation with motor nerve anastomosis to the branch of the ipsilateral deep temporal nerve for re-animation of established facial paralysis, and subsequently the procedure has progressed with marked improvement of outcomes.[6] The early method reported by Harii et al. enabled only smile on voluntary biting, but no spontaneous smile, and resulted in abnormal synkinesis (involuntary contraction of the transferred muscle on biting).[6] Later, O'Brien et al.[7] (1980) reported a two-stage method combined with cross-face nerve grafting to acquire communication between the gracilis muscle and the contralateral facial nerve, and this became the common method for enabling spontaneous smile.[8,9]

The method of O'Brien et al. is limited in that it requires about 2 years for acquiring contraction of the transferred muscle, as well as two-stage surgery. To solve these disadvantages, Koshima et al. (1994) reported a one-stage method using transfer of the neurovascularised rectus femoris muscle with a sufficiently long motor nerve.[10] Subsequently, one-stage reconstructions with transfer of several muscles, including the gracilis muscle,[11] abductor hallucis muscle,[12] rectus abdominis muscle,[13] latissimus dorsi muscle[1] and short head of the biceps femoris muscle[14] have been reported. In 1998, Harii et al. reported 24 cases of transfer of the latissimus dorsi muscle, and since then one-stage microneurovascular free muscle transfer has been established as the standard reconstruction method that enables synchronous spontaneous smile on the healthy side.[1] Generally, contraction of the transferred muscle is gradually acquired at an average of about 7 months after surgery with the one-stage methods, about 1/3 of the time

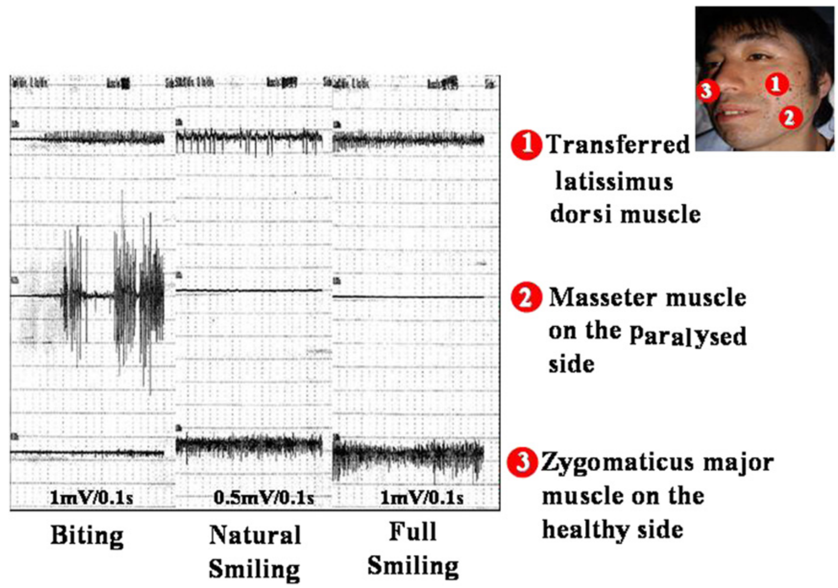

Figure 4 Simultaneous three-channel needle electromyographs (EMG) of the transferred latissimus dorsi muscle, masseter on the paralysed side and greater zygomatic muscle on the healthy side 7 months after surgery. (Left) Action potentials were detected on biting only in the transferred latissimus dorsi muscle and masseter on the paralysed side. The first 1s showed the EMG of these three muscles at rest. (Center and right): Action potentials were detected on smiling only in the transferred latissimus dorsi muscle and greater zygomatic muscle on the healthy side. These findings confirm the dual innervation of the transferred latissimus dorsi muscle by the masseter motor nerve on the paralysed side and the facial nerve on the healthy side.

required in the two-stage method, and patients acquire spontaneous smile at an earlier time.

Re-animation of established facial paralysis has progressed over the last 30 years and outcomes have improved markedly, but the dual innervation method reported here has several new characteristics compared to current reconstruction methods, and may be widely applicable in the field of reconstruction using neurovascularised muscle transfer. In our patients, the latissimus dorsi muscle transferred by the dual innervation method started to contract at an average of 3.4 months after surgery, thereby decreasing the duration of deinnervation of the muscle graft to half of that after surgery by the one-stage method. Contact between the hilum of the transferred latissimus dorsi muscle and the window of the masseter may have promoted rapid reinnervation of the transferred muscle by the masseter motor nerve on the paralysed side.[15] According to Manktelow et al., the transferred gracilis muscle starts to contract about 3 months after surgery when the motor nerve of the gracilis muscle is coaptated to the masseter motor nerve on the affected side, and more stable muscle contraction is obtained early after surgery.[16] This timing is consistent with that seen in our patients. Contraction of the transferred latissimus dorsi muscle on spontaneous smile started at an average of 5.9 months after surgery, earlier than that obtained in the current one-stage method.

Spontaneous recovery of movement of the lips, cheeks and lower eyelids is well known following reconstruction of facial palsy by masseter muscle transfer and removal of the masseter fascia.[15,17,18] Collateral budding/muscular neurotisation have been suggested to account for these results, with the motor nerve of the masseter muscle thought to contact and reinnervate the deinnervated, pre-atrophied muscles of facial expression.[19,20] Conley reported that reinnervation of the muscles for facial expression by the masseter motor nerve was not stable, but played an important role in rehabilitation after facial palsy.[21,22] Using this principle, our method is aimed at stable reinnervation of the latissimus dorsi muscle by the masseter motor nerve by allowing the hilum of the latissimus dorsi muscle graft to contact the masseter window (collateral budding/muscular neurotisation).

Contraction of the transferred muscle obtained by the current one-stage reconstruction method is insufficient in some cases, making it difficult to acquire symmetrical balance, and no muscle contraction is obtained in others.[1,2,23] A lack of muscle due to atrophy during deinnervation of the transferred muscle before reinnervation (usually, more than 7 months) and an insufficient amount of regenerated nerve innervating the transferred muscle are considered to be possible causes. Our method may provide a simultaneous solution for these two problems, since reinnervation of the transferred muscle by the masseter motor nerve occurred about 3 months before that by the facial nerve on the healthy side, which minimises deinnervation atrophy of the transferred muscle (Table 2). This is a modified 'baby-sitter' procedure, which is partially consistent with the 'baby-sitter' concept proposed by Terzis.[24] This is because the reinnervation by the masseter motor nerve as a 'baby-sitter', is not removed prior to cross-facial innervation by the facial nerve on the healthy side, but is preserved to produce a smile on each side or make subtle expressions. It is also advantageous that an appropriately sized muscle can be grafted by one-stage surgery because the muscle volume should not decrease,

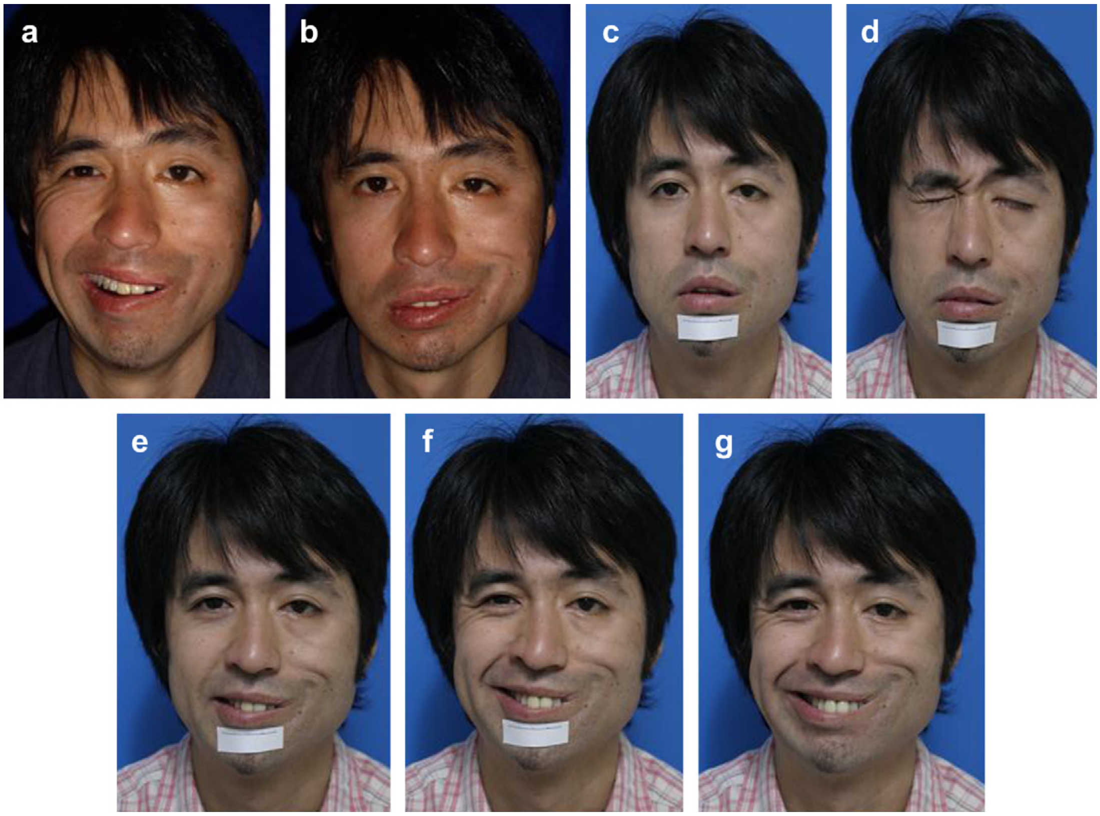

Figure 5 (a,b). Twelve months after surgery, the patient was able to smile on each side (the healthy (a, right) and affected (b, left) sides) without thinking about it and biting after mirror rehabilitation. (c,d). Fourteen months after surgery. (c, left) Resting state. (d, right) The patient was able to close the left eyelid with temporal muscle transfer by biting, but the synkinesis of the transferred muscle was not outstanding. After rehabilitation, the patient was able to separate smiling from closing of the eye on the affected (left) side. (e,f,g). Changes in the quality of smile and facial expressions. (e, left) The patient developed a spontaneous symmetric smile in normal smiling. (f,center and g, right) Contraction of the transferred muscle was slightly insufficient to allow a large smile, with slight loss of symmetric balance, but the patient was able to contract the transferred muscle by voluntary small biting and achieved symmetrical balance.

which avoids a post-operative bulky appearance of the paralysed malar region and makes it easier to achieve aesthetic facial symmetrical balance. Regarding insufficient contraction of the transferred muscle due to insufficient reinnervation, our method induces additional reinnervation of the muscle with the masseter motor nerve, which amplifies nerve stimulation and assists contraction, and finally induces sufficient contractile potential of the transferred muscle. This is also consistent with the Signal Augmentation/Neural Supercharge concept proposed by Yamamoto et al.[25]

Eyelid-closure function is concomitantly impaired in many cases of complete, established facial paralysis, and reconstruction of smile with the muscle graft and reanimation of eyelid closure by temporal muscle transfer are often performed simultaneously. Accordingly, biting causes eyelid closure after these reconstruction procedures. When end-to-end epineural suture of the motor nerve of the transferred muscle with the masseter motor nerve is performed, the eye on the affected side closes due to abnormal synkinesis every time the patient bites in eating and bites to smile. In contrast, our method induces reinnervation of the transferred muscle by the masseter motor nerve via direct contact between the hilum of the graft and the window of the anterior masseter without impairing reinnervation by the facial nerve on the healthy side or injuring the masseter motor nerve. Therefore, patients are able to move the transferred muscle for closing the eyelid separately by learning to differentiate between the strength required for moving the transferred muscle for biting and closing the eyelid in mirror rehabilitation, as shown for Case 1. But we are concerned about that the risk of synkinesis is inevitable in many cases, when using the trigeminal nerve to power the smile concurrently with use of the temporal muscle to improve eyelid closure.

To reconstruct spontaneous smile, it is optimal to select the facial nerve on the healthy side as the neural source of the transferred muscle, but the masseter motor nerve on the affected side is inevitably selected in patients with bilateral facial palsy and children in whom a long motor nerve cannot be harvested with the muscle graft.[26] Manktelow et al. recently reported that spontaneous smile could be reconstructed in 59% of cases regardless of age when the gracilis muscle motor nerve was connected with the ipsilateral masseter motor nerve because of plasticity of the cerebral cortex induced by effective rehabilitation.[16]

Our method enables patients to reconstruct a spontaneous smile without specific rehabilitation, but effective post-operative rehabilitation is essential to achieve smiles on the left and right side and other facial expressions. Recent cerebral physiological studies using functional magnetic resonance imaging (fMRI) have shown that post-operative rehabilitation induces formation of a new neural pathway between different cerebral motor centers, and in this respect our method is advantageous because the transferred muscle starts to contract only 3 months after surgery, strongly motivating patients to rehabilitate from an early post-operative stage.[27,28] As Lifchez et al. and Manktelow et al. have reported, our method may also promote formation of a new horizontal cortical pathway between the center of the facial nerve (cranial nerve VII) on the paralysed side and that of the masseter motor nerve (cranial nerve V).[29,16] As shown in Case 1, a spontaneous symmetrical smile and a smile on each side without voluntary biting can be achieved by mirror rehabilitation. Furthermore, the patient became able to separate eyelid closure from smile on the affected side (Figure 5). The efficacy of the method and effective rehabilitation approaches require further investigation through accumulation of cases (Figure 6).

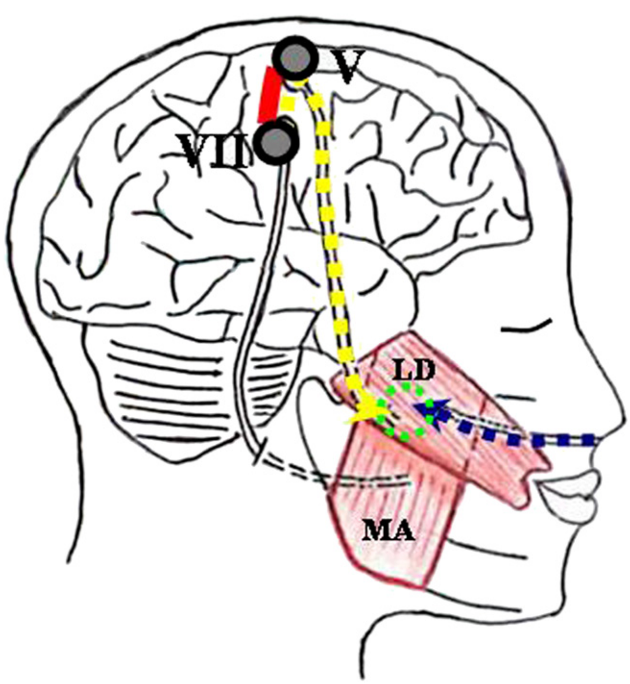

Figure 6 Schema of the horizontal cortical pathway. The red line represents a new horizontal cortical pathway formed between the V and VII cranial nerve motor centers.[20] Mirror rehabilitation that promotes cerebral cortical reorganisation may reconstruct the ability to make spontaneous facial expressions and smile on the affected side alone. The transferred latissimus dorsi muscle receives combined innervation from the masseter motor nerve (branch of cranial nerve V) and facial nerve (cranial nerve VII) on the affected side (yellow dotted line), and from the facial nerve (cranial nerve VII) on the healthy side (blue dotted line). The dual innervation method is based on this neural signal system.

The advantages of the dual innervation method are as follows: (1) reinnervation to the transferred muscle through the hilum occurs twice as early as in one-stage options using collateral budding/muscular neurotisation from the ipsilateral masseter motor nerve, which serves as a baby-sitter to minimise deinnervation atrophy; (2) both spontaneous and voluntary smile and various facial expressions can be achieved on one side; (3) the masseter motor nerve augments neural signaling to the transferred muscle for more symmetrical smiling with or without voluntary biting after rehabilitation; (4) synkinesis of the transferred muscle with biting for eyelid closure is not outstanding and (5) emotional facial re-animation without biting may occur through a learning program to enhance cerebral cortical reorganisation. These advantages indicate that the dual innervation method improves the quality of smile and facial expression.

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