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One-stage free transfer of latissimus dorsi-serratus anterior combined muscle flap with dual innervation for smile reanimation in established facial paralysis[☆]

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Summary Microneurovascular free muscle transfer is the gold-standard surgical procedure for the reanimation of established facial paralysis. However, the innervation of the transferred muscle by the contralateral facial nerve is usually insufficient to produce a stable smile. Besides, the corner of the mouth sometimes moves unnaturally as if it were being pulled up because of the single-direction movement. Thus, we propose one-stage facial reanimation using free latissimus dorsi (LD)-serratus anterior (SA) combined muscle flap transfer with dual innervation. The LD-SA combined muscle flap was harvested with the thoracodorsal artery and vein as common vessels to move the corner of the mouth bidirectionally for natural smiling. The LD muscle was located in the same direction as the zygomaticus major muscle and reinnervated by dual innervation. The contralateral facial nerve was coapted with the thoracodorsal nerve, and the ipsilateral masseter motor nerve was inserted into the LD muscle by intramuscular neurotization. The 6th or 7th SA muscle was located in the same direction as the risorius muscle and reinnervated by neurorrhaphy of the long thoracic nerve and the thin branch of the ipsilateral masseter motor nerve. Since 2015, seven patients have been treated with this method without complications. On average, SA muscle movement was detected in voluntary biting at 3.1 months, and spontaneous smiling occurred 7.7 months after surgery. All patients

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developed a spontaneous natural smile. This method for established facial paralysis has the potential to improve the quality of the reconstructed smile and the unstable results of conventional single-innervation-single-muscle transfer.

Introduction

For smile reanimation in facial paralysis, natural smiling through the spontaneous manifestation of emotion and the morphology of the mouth in a natural smile formed by the elevation of the corners of the mouth are essential elements in improving the quality of smile.[1,2] In the conventional procedure for natural smile reanimation for established facial paralysis using a single muscle (the latissimus dorsi [LD] or gracilis), the healthy-side facial nerve is the only motor neural source. This is regardless of the use of a one-stage or two-stage method requiring cross-face nerve graft (CFNG) accompanied by sural nerve grafting. Thus, the contraction of the grafted muscle depends on the reinnervation by the healthy-side buccal branch of the facial nerve alone to allow a natural smile.[1,3,4] However, a weak muscle flap contractile force is problematic because the motor neural source is dependent on nerve regeneration from the thin healthy-side buccal branch of the facial nerve alone.[5,6] Moreover, the facial skin and subcutaneous tissue are thick in Asians, unlike in Caucasians, and subcutaneous fat tends to increase after middle age. [7] Both of these result in a more unsatisfactory treatment outcome with muscle transfer.[6]

To address the insufficient muscle flap contractile force, a method for reconstructing the elevation of the corner of the mouth by stable muscle flap contraction was investigated. This method used the paralyzed-side masseter motor nerve as the motor neural source.[8-11] However, the achievement of natural smile is less likely with this method. While aiming at natural smile reanimation through reinnervation by the healthy-side buccal branch of the facial nerve to supplement the weakness of the motor neural source, we reported the dual innervation method in 2009 as a one-stage reanimation method, in which the LD muscle was grafted and reinnervated by the paralyzed-side masseter motor nerve in addition to the healthy-side buccal branch of the facial nerve.[12] Since that report, several new methods using reinnervation of a single muscle flap by two motor neural sources have been described.[13-17]

In addition, improvements to the morphology of the corner of the mouth obtained by conventional reconstruction methods[1,4,6,18-20] have been developed to reconstruct a more natural smile that corresponds to the morphological characteristics of a patient's smile. Multidirectional elevation of the corner of the mouth is performed by the transfer of two or three muscles.[21-25]

In this paper, we describe a new surgical procedure that addresses the various problems of conventional smile reconstruction through one-stage LD-serratus anterior (SA) combined muscle flap transfer with dual reinnervation by the healthy-side buccal branch of the facial nerve and the paralyzed-side masseter motor nerve (Figure 1).

Patients and Methods

A retrospective analysis of patient data was performed. The present study was approved by the institutional review board and complied with the Helsinki Declaration. Informed consent was obtained from all patients. The surgical procedure was indicated to a patient aged over 40 years old with complete, established unilateral facial paralysis (>18 months) and with relatively thick skin and subcutaneous tissue on the paralyzed side of the face. Patients with bilateral facial paralysis and previous facial reanimation surgery and those who were lost during follow-up were excluded from the study. The selection of the surgical procedure was determined on an individual basis. All procedures were performed by the senior author (Y.W.). In all patients, a complete evaluation, including facial examination and standard photograph and video taking, was conducted preoperatively and 3, 6, 9, 12, 15, 18, and 24 months after surgery. Simultaneous four-channel needle electromyography was performed 9 months after surgery to evaluate the dual innervation of the transferred muscle flap.

Harvesting of the LD-SA combined muscle flap

Surgery was performed under general anaesthesia in the supine position, including harvesting of the muscle flaps from the side ipsilateral to the paralysis (Supplement Figures 1 and 2). The LD-SA combined muscle flap was elevated with a 7–8-cm thoracodorsal artery and vein as common feeding blood vessels. A 13-cm or longer thoracodorsal nerve of the LD muscle was required for one-stage suturing with the healthy-side buccal branch of the facial nerve. A muscle flap 3-4 cm wide and 8–10 cm long was excised from the LD muscle to distribute the neurovascular bundle that comprised the thoracodorsal artery and vein and the thoracodorsal nerve at about 1 cm cranial to its branching in the LD muscle over the intramuscular central region. For the SA muscle flap, the muscle bundle distal to the intersecting region (crow's feet: white arrowhead in Supplement Figure 2) of the long thoracic nerve, the SA muscle branch of the thoracodorsal artery, and the vein feeding the SA muscle (i.e. the lower 6th or 7th muscle) could be excised with a long thoracic nerve of about 5 cm in length (Figure 2). The long thoracic nerve distributed in the 5th and upper muscles cranial to the crow's feet was conserved to prevent a winged scapula.[24-29] The harvested LD-SA muscle flaps were slightly trimmed prior to the transfer, but the size was adequate for grafting into the buccal pocket prepared on the paralyzed side.

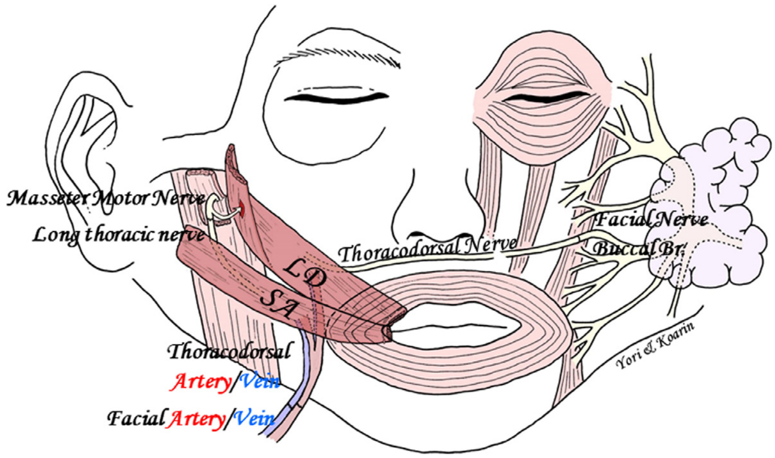

Figure 1 Schema of the surgical procedure of the LD-SA combined muscle flap with dual innervation.

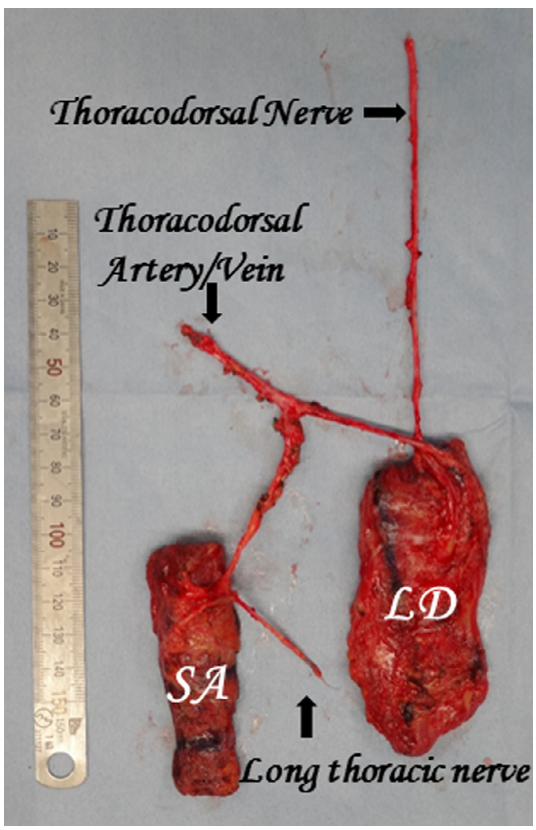

Figure 2 Harvested the LD-SA combined muscle flap.

Preparation of the recipient site

A muscle transfer space was prepared under the superficial musculoaponeurotic system (SMAS) through a facelift incision.[30] After dissection under the SMAS, the facial artery and vein were first identified and secured as recipient blood vessels at the intersecting level of the anterior margin of the masseter and the inferior margin of the mandible. This was followed by advancing a dissection of the same layer as that in these vessels toward the oral and cranial sides in the alar base region, with the preparation of a sufficient transfer space that extends beyond the nasolabial fold to the lips and around the corner of the mouth (Supplement Figures 3 and 4). In order to reduce cheek bulkiness after the operation, the subcutaneous fat tissues and buccal fat pad were removed to create a pocket.

The setting of the LD-SA combined muscle flap

The LD muscle was transplanted by reversing and placing the neurovascular pedicle entrance side to the oral side and roughly setting it in the position and direction of the zygomatic muscle. Similarly, the SA muscle was transplanted by reversing and placing the neurovascular pedicle entrance side to the oral side and setting it in the position and direction of the buccinator and risorius muscles. The LD and SA muscles were grafted at target angles to the Frankfort horizontal (FH) line of about 60° and 45°, respectively [24] (Figure 1 and Supplement Figure 3). In order to fix the muscle flap on the oral side, a 3-0 absorbable thread was used. Four stay sutures for the LD muscle and three stay sutures for the SA muscle were applied slightly to the mucosal side of the vermilion. The sutures for both muscles were pulled to elevate the corner of the mouth in two directions, and the reproduction of natural smile morphology was confirmed by the preoperative smile on the healthy side (Supplement Video 1). The thoracodorsal nerve of the LD muscle was guided through the subcutaneous upper lip-subnasal tunnel to the region of the suture with the buccal branch of the facial nerve prepared on the healthy side (Supplement Video 2). After fixation of the muscle flap on the oral side, feeding blood vessels common to the thoracodorsal artery and vein of the LD and SA muscles were anastomosed with the facial artery and vein (Supplement Video 3 and Supplement Figure 4).

Neural input to muscle flaps by dual innervation

The masseter motor nerve on the paralyzed side was identified and secured in the muscle, targeting a position 3 cm

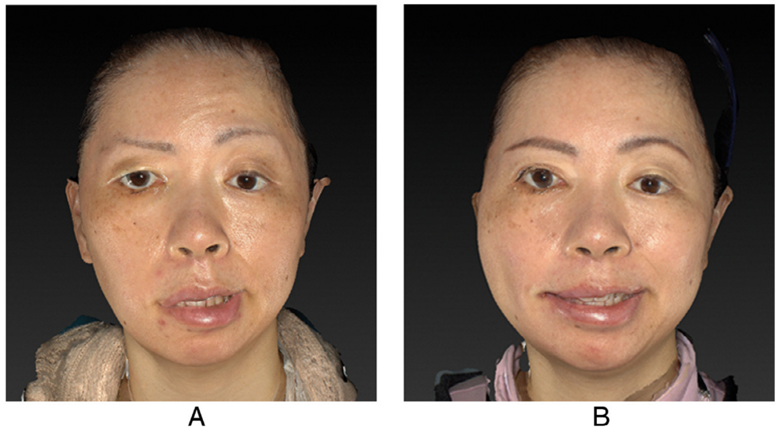

Figure 3 Case 1 (Patient 4) was a 46-year-old female with right-sided established facial paralysis after excision of a right cerebellopontine angle tumour. (A) Before surgery, facial asymmetry was evident at rest and during smiling. (B) Facial asymmetry was improved 14 months after surgery. Laterally balanced morphology of the nasolabial fold and corners of the mouth was acheived during a natural smile. Harii's criteria: 5.

nasal and 1 cm caudal to the tragus by partially dissecting the masseter, which ends at the zygomatic arch (Supplement Figure 5).[31,32] Normally, this masseter motor nerve consists of about two branches. The thinner branch was sutured end to end with the long thoracic nerve of the SA muscle. The other branch was directly sutured intramuscularly with the cranial side of the LD muscle (direct intramuscular neurotization, type 2 neurotization) with the aim of dual innervation (Supplement Figures 6 and 7; Supplement Video 4).

To ensure proper selection of the facial nerve on the healthy side and prevent a visible surgical scar on the cheek, this procedure was performed through a short-scar facelift incision followed by dissection under the SMAS.[30] Usually, two or three buccal branches of the facial nerve that were most closely involved in the elevation of the corner of the mouth and had minimum effect on periocular and lip movements were identified at the level of the anterior margin of the parotid gland using an electrostimulator. The thickest branch was selected and sutured end to end with the thoracodorsal nerve from the paralyzed side.

Fixation of the muscle flaps

The muscle flap fixation on the cranial side was performed after the completion of the vascular anastomosis and all nerve sutures. The direction and tension of the two muscle flaps were controlled with the aim of achieving a smile morphology on the affected side that is similar to that of the natural smile on the healthy sid

Smile rehabilitation using a mirror was initiated 2 months after surgery in all patients, as previously described.[12]

Results

The surgical procedure was performed on seven patients with established complete facial paralysis and relatively thick facial subcutaneous tissue between July 2015 and September 2017 (Table 1). The mean length of the harvested thoracodorsal nerve was 14.5 cm, which was adequate for accessing the buccal branch of the facial nerve on the healthy side from the paralyzed side. The mean length of the long thoracic nerve was 4.8 cm, enough to reach the masseter motor nerve on the paralyzed side. The mean length of the thoracodorsal artery and vein as feeding vessels was 9.4 cm, sufficient for reaching the facial artery and vein on the affected side(Table 2). There were no problems and no complications, such as impairment of shoulder elevation or a winged scapula, observed in any patient after surgery due to the harvest of the muscle flaps. SA contraction-induced elevation of the corner of the mouth was noted during biting at an average of 3.1 months after surgery. A natural smile by LD contraction appeared without specific rehabilitation at an average of 7.7 months after surgery (Table 3).

On simultaneous four-channel needle electromyography (grafted LD, grafted SA, paralyzed-side masseter, and healthy-side zygomatic muscles) performed 9 months after surgery, dual innervation of the LD muscle by the healthy-side buccal branch of the facial nerve and paralyzed-side masseter motor nerve branch was observed in all patients. Nerve regeneration, mainly from the paralyzed-side masseter motor nerve, was noted in the SA muscle. The results were evaluated according to Harii's evaluation criteria illustrated in Table 4,[1] which was based on a combination of clinical and electromyographic findings. Harii's mean evaluation criteria was 4.8 at 12 months or later after surgery (Table 3). At present, all patients obtained an excellent natural smile. Two cases are presented in Figure 3 and Figure 4.

Discussion

The new method described in this paper aimed to achieve a more natural and reliable smile reanimation than conventional methods by modifying the one-stage free LD muscle transfer using the dual innervation method we first reported

Table 1 Summary of the patient backgrounds.

Patient	Age (years)	Sex	Etiology	Type	Duration of facial paralysis (years/months)	Preoperative H-B Score
1	45	Male	Brain tumor	Complete	10y	V
2	43	Female	Brain tumor	Complete	3y3m	V
3	47	Female	Brain tumor	Complete	3y9m	V
4	46	Female	Brain tumor	Complete	2y11m	V
5	63	Female	Brain tumor	Complete	3y2m	V
6	46	Female	Brain tumor	Complete	2y11m	V
7	65	Female	Brain tumor	Complete	1y7m	V
Average	50.7	-	-	-	3y10m	-

Table 2 Characteristics of the LD-SA combined muscle flap.

Patient	Muscle size (width × length × thickness, cm)		Nerve length (cm)		Pedicle length(cm)
	Latissimus Dorci muscle	Serratus Anterior muscle	Thoracodorsal nerve	Long thoracic nerve	
1	3 × 9 × 1	6th:3 × 11 × 0.4	17	5	8.5
2	4 × 8 × 1	7th:2.7 × 7.5 × 0.7	13	6	9.5
3	4 × 10 × 0.9	7th:3 × 10 × 0.8	13	4	8.5
4	3.5 × 7.5 × 0.8	6th:3 × 6 × 0.6	16	5	8.8
5	3.5 × 8 × 0.8	6th:3 × 8 × 0.7	16	5.3	12
6	3 × 9 × 0.7	6th:2.5 × 8 × 0.8	14	4.5	12
7	4 × 13 × 0.8	6th:2.5 × 11 × 0.7	13	4	6.5
Average	-	-	14.5	4.8	9.4

Table 3 Postoperative course of the patients.

Patient	Complication	Time to muscle contraction after surgery (months)		Harii's criteria	Follow-up period (months)
		LD	SA		
1	None	7	2	5	41
2	None	8	4	5	39
3	None	8	2.5	4	36
4	None	8	3	5	29
5	None	7.5	4	5	17
6	None	7	3	5	15
7	None	6	3.5	5	12
Average	—	7.7	3.1	4.8	27

LD, Latissimus Dorci muscle; SA, Serratus Anterior muscle

in 2009.[12] The first point of improvement in the new method is the achievement of stable muscle contraction by changing the mode of nerve regeneration in the dual innervation method. The second is reconstruction by double muscle transfer using the LD and SA muscles to acquire the morphology of elevation of the corner of the mouth corresponding to the characteristics of the natural smile of each patient.

We first discuss the selection of the motor neural source and the nerve regeneration mode. It has been 40 years since Harii et al. described the first one-stage reanimation by free gracilis muscle transfer for established facial paralysis in 1976 at our hospital.[33] One of the motor nerve branches of the trigeminal nerve, the temporalis muscle motor nerve, was used as the motor neural source, but the elevation of the corner of the mouth was unnatural in forming a smile by biting motion and strong muscle movement. Many modifications were made after that, and currently, the use of a motor neural source for a natural smile in the CFNG-mediated healthy-side buccal branch of the facial nerve is the standard approach. However, the weak muscle contractility of the motor neural source is still considered to be problematic.[5,6,34]

In the past ten years, it has been reported that stable muscle contraction can be obtained through the selection of the paralyzed-side masseter motor nerve [8,9,35] However, the differences between patients who can and cannot spontaneously smile through the masseter motor nerve have yet to be clarified.[36,37,38,39]

Takushima et al. reported that the outcome of reconstruction by one-stage LD muscle transfer is significantly poorer in 30- to 45-year-old Asians than in other age groups and suggested selecting the ipsilateral masseter motor nerve because facial subcutaneous fat is abundant and the cheek is heavy in this age group.[6]

Table 4 Harii's evaluation criteria.

Grade	Description
5	Symmetric balance and good facial tone at rest Sufficient muscle power upon voluntary contraction Synchronous and natural expression upon emotional facial movements, especially upon smiling EMG demonstrating relatively high amplitudes with full interference patterns and high evoked potentials obtained upon stimulation of the contralateral facial nerve
4	Symmetric balance and good facial tone at rest Active muscle contraction acquired but not sufficiently synchronous (too strong or slightly weak) EMG demonstrating good interference patterns and evoked potentials
3	Symmetric balance and good facial tone at rest Insufficient contraction of the muscle Low volitional EMG spikes with discrete interference patterns
2	Reduced symmetric balance upon smiling No effective contraction of the muscle EMG with no interference patterns
1	No correction Electrically silent EMG
0	No follow-up

Table 5 Watanabe's classification of neurotization.

Type	Definition	Intensity
Type 1	Nerve-to-nerve reinnervation Standard neurotization	Strong
Type 2	Nerve-to-muscle reinnervation Direct Intra-Muscular Neurotization	Moderate
Type 3	Neurotization:Muscle-to-muscle reinnervation Musclar Neurotization	Weak

We have consistently focused on the use of the facial nerves as the motor neural source in natural smile reanimation without the need for specific rehabilitation. We have classified nerve regeneration in the muscle flaps in the reanimation of facial paralysis into three types (Table 5).[37] Type l neurotization using nerve-to-nerve reinnervation is standard neurotization in which nerve regeneration is attempted by end-to-end suture of the motor nerve, innervating the paralyzed mimetic muscle or muscle flap with the facial nerve or masseter motor nerve. Type 2 neurotization using nerve-to-muscle reinnervation is direct intramuscular neurotization.[38] This method attempts to facilitate nerve regeneration by directly suturing the peripheral stump of the motor nerve intramuscularly with the paralyzed mimetic muscle or muscle flap.[39] It is used when the nerve suture of the motor nerve innervating the muscle directly from the central side is challenging, i.e. when nerve reconstruction by type 1 neurotization is difficult. Nerve regeneration may be weaker than that achieved in type 1 neurotization. Type 3 neurotization uses muscle-to-muscle reinnervation, through which nerve regeneration is attempted by direct contact between the innervated normal muscle and paralyzed muscle.[40,41,42] This method is used when nerve reconstruction by type 1 or 2 neurotization is difficult. The nerve regeneration mode is that of the dual innervation method.[12] Nerve regeneration may be weak and limited compared with nerve reconstruction using type 1 or 2 neurotization.

In our dual innervation method, the motor nerve of the grafted LD muscle was connected with the healthy-side facial nerve as the main motor neural source by an end-to-end suture (type 1 neurotization). The affected-side masseter motor nerve was handled cautiously to prevent interference with nerve regeneration of the thoracodorsal nerve by the healthy-side facial nerve. As a supplemental motor neural source, nerve regeneration was induced for the masseter motor nerve by direct contact with the grafted LD muscle (type 3 neurotization).[12]

In the new method, masseter motor nerve regeneration was modified from type 3 neurotization by direct contact with the LD muscle to type 2 neurotization by direct suture of the stump of the thin masseter motor nerve branch intramuscularly with the grafted LD muscle. This change was made because of the instability and weakness of the reinnervation of the muscle flap by type 3 neurotization. Using type 2 neurotization, the grafted LD muscle may achieve moderate reinnervation by the affected side masseter motor nerve without interference with reinnervation by the healthy-side facial nerve. Action potentials were detected in the SA muscle during smiling on simultaneous four-channel needle electromyography 9 months after surgery in case 2 (Figure 5). These were probably due to thoracodorsal nerve-transmitted stimulation from the healthy-side buccal branch of the facial nerve to the LD muscle, and contact between the LD and SA muscles inducing SA muscle contraction (type 3 neurotization). Similar action potentials were observed in all patients. Therefore, the SA muscle achieved dual reinnervation with the masseter motor nerve as the main motor neural source and the healthy-side buccal branch of the facial nerve as the supplemental motor neural source.

The second point of improvement in the new method is double muscle (LD and SA) transfer to reconstruct the nat-

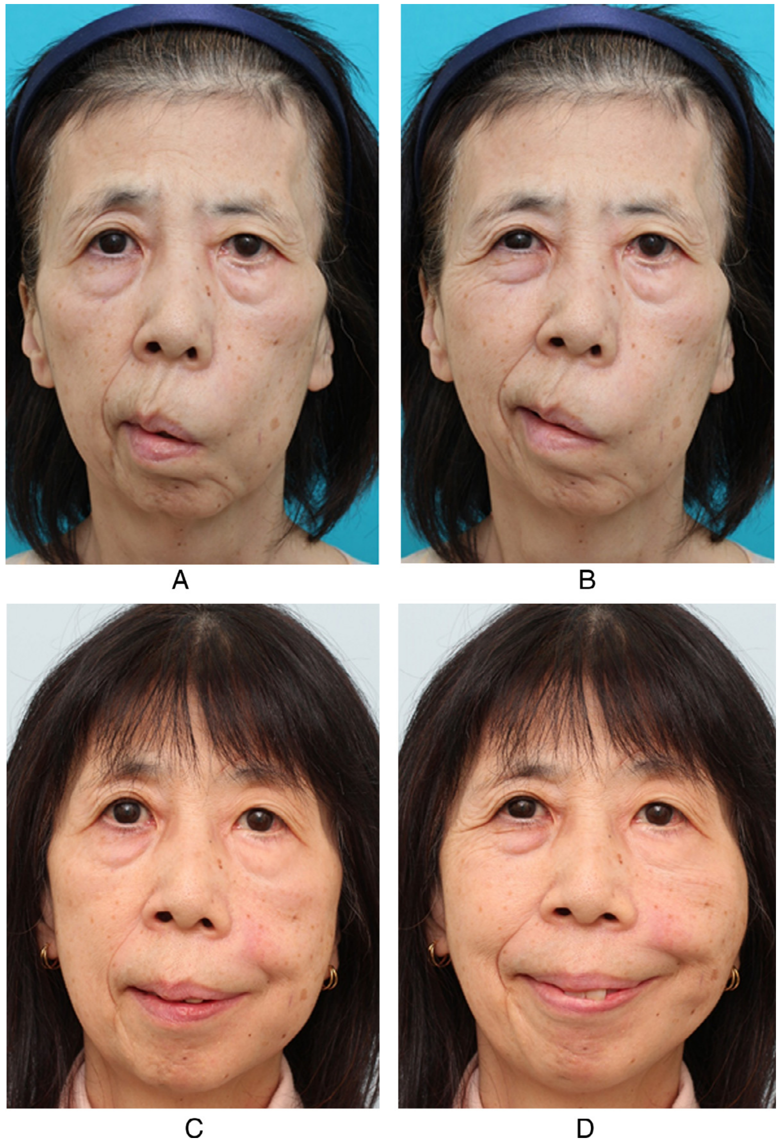

Figure 4 Case 2 (Patient 7) was a 65-year-old female with left-sided established facial paralysis after left acoustic neuroma excision (Supplement Video 5). (A, B) Before surgery, facial asymmetry was evident at rest (A), during smiling (B). (C, D) At 12 months after surgery. (C) At rest, the symmetry of the morphology of the corners of the mouth was retained. (D) During a full smile, the patient was able to produce a spontaneous and symmetric smile. Harii's criteria: 5 (Supplement Video 6).

ural morphology of elevation of the corner of the mouth corresponding to the characteristics of the smile of each patient. Since a smile involves multiple mimetic muscles, such as the zygomatic, levator labii superioris, zygomaticus minor, risorius, and buccinator muscles, the reconstruction of a high-quality smile may require reconstructed motion of at least two mimetic muscles corresponding to the smile morphology on the healthy side.[23,24,43,44,45,46]

The arrangement of the two muscle flaps was adjusted during surgery to reproduce the healthy-side smile morphology on the affected side. This achieved a degree of freedom for the corner of the mouth morphology that is difficult to acquire with conventional single muscle transfer. Masseter activity simultaneously increases with an oblique lateral elevation of the corner of the mouth in a natural smile.[47] Accordingly, in a full smile, the masseter motor nerve activity level increases, and the SA muscle contraction induces a favourable elevation and morphology of the corner of the mouth.

Although there were only 7 cases, we believe this method can be further improved in the future to make it better. The merits of our method are: (1) dual innervation of two muscles (2) Each muscle acts from different direction to make the smile more natural because each muscle (LD and SA) is put at different position. (3) The nerve of each muscle is long and does not need nerve graft.

There are several matters that have yet to be addressed in our method. These include adjustments of the volume of the two muscle flaps and the level of masseter motor nerve reinnervation. An adequate number of cases is necessary to resolve these issues. Nerve regeneration from the masseter motor nerve also tends to be reliable. To

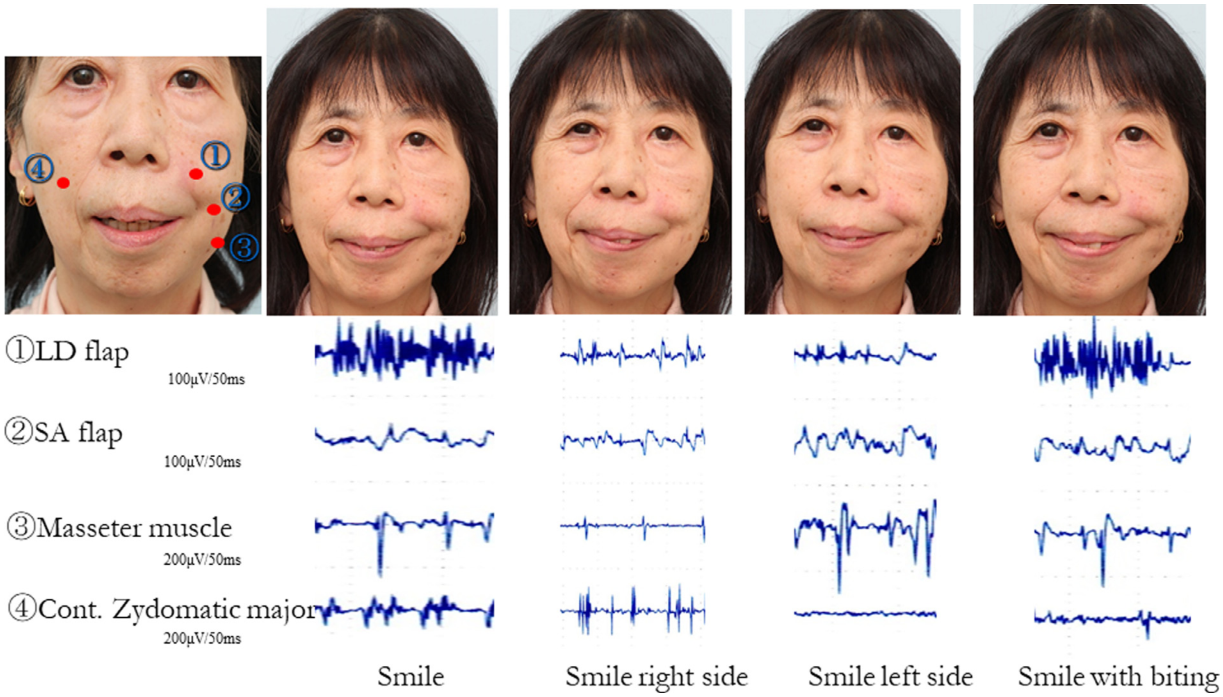

Figure 5 Simultaneous four-channel needle electromyography (EMGs) of the transferred LD muscle, SA muscle, and masseter muscle on the paralyzed side and more significant zygomatic major muscle on the contralateral healthy side at 9 months after surgery in case 2 (Patient 7). A high-action potential was detected during smiling in the LD muscle, and an action potential was also noted during biting, showing that the LD muscle was mainly reinnervated by the healthy-side buccal branch of the facial nerve and supplementally by the paralyzed-side masseter motor nerve branch, i.e. dual reinnervation.

prevent excessively strong reinnervation of the LD and SA muscles by the masseter motor nerve, we currently adjust the nerve by using as thin a branch as possible. Future studies are required to adjust the strength of reinnervation by the masseter motor nerve and to better elucidate the specific benefits of this method of reconstruction over a single-innervation-single-muscle transfer. Therefore, it is necessary to continue research on this subject and conduct comparative clinical studies.

Conclusion

The one-stage procedure using a LD-SA combined muscle flap with dual reinnervation by the healthy-side facial nerve and affected-side masseter motor nerve has the potential to improve the quality of reconstructed smile and the unstable results of conventional single-innervation-single-muscle. This approach increases the degree of freedom of reconstruction based on the characteristics of natural smile for each patient.

Declaration of Competing Interest

None.

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None of the authors has a financial interest in any of the products, devices, or drugs mentioned in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.bjps.2020.01.032.

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