Three-Dimensional Video Analysis of the Paralyzed Face Reanimated by Cross-Face Nerve Grafting and Free Gracilis Muscle Transplantation: Quantification of the Functional Outcome

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Background: Surgeons have found it difficult to quantify facial paralysis and its improvement by reconstructive surgery. This article presents the results achieved by free functional muscle transplantation for reconstruction of the paralyzed face, registered by three-dimensional video analysis of facial movements.

Methods: Of patients treated consecutively between 1997 and 2006, two groups were constituted: group 1 comprised 22 patients with reinnervation completed after a single cross-face nerve graft and a free gracilis muscle graft for reconstruction of the smile; group 2 comprised nine patients treated with two cross-face nerve grafts followed by a territorially differentiated gracilis muscle transplant for reconstruction of the smile and eye closure. Smiling with showing teeth, maximal showing of teeth, and closing the eyes as in sleep were analyzed in detail.

Results: In group 1, static asymmetry was reduced from 12.19 ± 8.73 mm preoperatively to −1.84 ± 7.67 mm at 18 months postoperatively. Smile amplitude increased from 9 to 60 percent of that on the healthy side in 10 incomplete facial palsies of this group, and from 0 to 62 percent in eight functionally successful muscle grafts among 11 patients with complete lesions. In group 2, static asymmetry improved from 7.24 ± 12.64 mm to −5.36 ± 9.07 mm; the overcorrection was intentional. Movement was improved in eight cases. Smile amplitude reached 68 ± 43 percent of that on the normal side. Lagophthalmus improved from 7.21 ± 3.59 mm to 1.38 ± 2.49 mm. All improvements were statistically significant ($p \leq 0.05$).

Conclusions: Three-dimensional video analysis provided an exact quantitative documentation of the degree of facial palsy preoperatively and the reconstructed movements. The value of free functional gracilis muscle transplantation was demonstrated for both variations of the technique. (*Plast. Reconstr. Surg.* 122: 1709, 2008.)

In 1976, Harii et al.[1] published the first report on clinical application of free functional muscle transplantation for reconstruction of the smile in facial palsy. Cross-face nerve grafting followed by free muscle transplantation performed 8 to 12 months later became the favored method for reanimating the irreversibly paralyzed face.[2,3] Reconstruction of emotionally directed movements was rendered possible by reinnervation of the muscle transplant through branches of the contralateral healthy facial nerve regenerated to the paralyzed side through the cross-face nerve graft.[4,5] In

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1984, Manktelow and Zuker reported on the use of two different innervation territories of the gracilis muscle transplant to cover two different functions such as eye closure and smile.[6]

The difficulty of assessing mimic function objectively was one of the reasons why the actual breakthrough of this reconstructive technique occurred two decades later. As this problem became evident while monitoring an international registry for neuromuscular reconstruction in the face,[7] we developed a new method with which to assess the quantity and quality of facial movements by three-dimensional video analysis.[8] In 1997, the new system was used to assess the outcome of reconstructive procedures in patients with facial palsy. In addition to demonstrating the effectiveness and quality of the treatment, the surgical techniques and strategies were improved significantly.[9–11]

We report the final results in patients with facial palsies treated consecutively by free functional muscle transplantation over a 10-year period. Three-dimensional movement analysis has been used to document the preoperative state of paralysis, the improvement of static and dynamic symmetry over time, and the final outcome.

PATIENTS AND METHODS

Between 1997 and 2006, cross-face nerve grafting and subsequent free functional muscle transplantation by means of a part of the gracilis muscle were performed in 62 consecutive patients. In 41 subjects (mean age, 41.7 ± 9.28 years), the gracilis muscle was used as a single transplant innervated by a single cross-face nerve graft for reconstruction of the smile only, whereas in 21 patients (mean age, 34.63 ± 9.38 years), the gracilis muscle was used as a territorially differentiated transplant innervated by two separate cross-face nerve grafts for reconstruction of the smile and closure of the eye.

In 41 patients (mean age, 45.63 ± 15.3 years) with a free gracilis muscle graft for reconstruction of the smile, a part of the temporal muscle was transposed to the paretic eye to achieve eye closure. Of 41 patients treated by a single gracilis muscle transplant, 22 (group 1: mean age, 40.3 ± 12.01 years; range, 13 to 60 years) and nine patients of 21 treated with a territorially differentiated gracilis muscle transplant (group 2: mean age, 36.33 ± 18.18 years; range, 8 to 62 years) were evaluated with respect to the final functional outcome for the purposes of the present study. The time point of the functional plateau was between 18 and 24 months after free functional muscle transplantation. Under the regulations of the Medical University of Vienna, no institutional review board involvement was needed for this study.

Surgical Procedures

A three-stage procedure was used to optimize the results of microsurgical reanimation in the paralyzed face. The concept and the surgical techniques have been published in detail elsewhere.[9]

Group 1: One Cross-Face Nerve Graft and Gracilis Muscle Transplantation for Reconstruction of the Smile

Cross-face nerve grafting was performed to bring the regenerating nerve fibers from the zygomatic facial nerve branch on the healthy side to the paralyzed side. After the regenerating nerve fibers controlling the function of smiling had grown to the end of the sural nerve graft, free transplantation of the gracilis muscle with microneurovascular anastomoses was performed in a second procedure 10 months later.[12–14] In adults dissatisfied with their degree of insufficient eye closure, we used a combination of transposition of the central portion of the temporal muscle to the upper and the lower eyelids to rapidly restore this essential function and thus protect the cornea.

Group 2: Two Cross-Face Nerve Grafts and a Territorially Differentiated Gracilis Muscle Transplant for Reconstruction of Eye Closure and Smile

In patients with an acutely compensated deficit in the ocular region such as congenital facial palsy, we reconstructed function around the eye and the mouth with the same muscle transplant, which can be divided into two parts supplied by different nerves. Furthermore, in children, any negative influence on the growing facial skeleton by a transposed masseter muscle can be excluded by this procedure. In these patients, the sural nerves of both lower legs were used as cross-face nerve grafts in the face. One is connected to a temporal branch of the healthy facial nerve controlling the function of eye closure, and the other extending to the zygomatic branch is responsible for smiling. The purpose of the first operation was to prepare the patient for the territorially differentiated gracilis muscle transplantation, which was performed at a second session 8 to 10 months later when nerve regeneration had progressed to the paralyzed side.

Methods of Evaluation

All patients treated for facial palsy were enrolled in an international multicenter registry and documented under standardized conditions using a three-dimensional video system that has been described extensively in former publications.[7,8] An obligatory functional assessment was performed preoperatively and 6, 12, 18, and 24 months postoperatively. The movement analysis quantified changes in the amplitudes of movements by surgery on the reconstructed side compared with the healthy side, and changes in static and dynamic symmetry.

Evaluation of Perioral Reconstruction

The corner of the mouth is regarded as the most important factor when quantifying the impact of surgical reconstruction of the perioral unit on the static symmetry of the face. The distance between the corner of the mouth and the ipsilateral tragus point on the paretic side, and the same distance on the healthy side with the patient's face at rest, are measured preoperatively (Fig. 1, *left*).

As smiling is a submaximal movement and different patterns of smiles exist, it is necessary to compare the amplitude of the reconstructed smile with that on the healthy half of the face (Fig. 1, *right*). The ratio between the two amplitudes was determined. This ratio reflects best the dynamic symmetry of the mouth. It is defined as an index of dynamic symmetry. When this index is 1, optimal symmetry of the movement with the same excursion of the movement on the healthy and the reanimated sides is achieved. To determine the maximum tetanic force of the muscle transplant, we ask patients to perform a movement known as "maximum showing of the teeth": the patients pull both corners of the mouth laterally under maximum contraction of the muscle transplant in the reconstructed half of the face and the zygomatic muscles in the healthy half of the face. The parameters measured when smiling with showing one's teeth are measured here as well.

Evaluation of Ocular Reconstruction

To quantify the impact of surgical reconstruction on the width of the eye fissure, the distance between the upper and the lower eyelid points is measured with the patient's face at rest. This measurement is performed separately for the paretic eye and the healthy eye at the following time points: preoperatively and at 6, 12, 18, and 24 months postoperatively (Fig. 2, *left*). The difference between the width of the eye fissure on the paretic side and that on the healthy side is determined in millimeters and defined as the static asymmetry of the eye fissure.

To quantify the dynamic activity of the gracilis muscle transplant, the extent of lagophthalmus on intended closure of the eyes was determined. For this purpose, the distance between the upper and the lower paretic eyelids at the endpoint "closure of the eyes lightly as in sleep" was measured in millimeters before surgery and at 6, 12, 18, and 24 months after transplantation of the free functional muscle (Fig. 2, *right*).

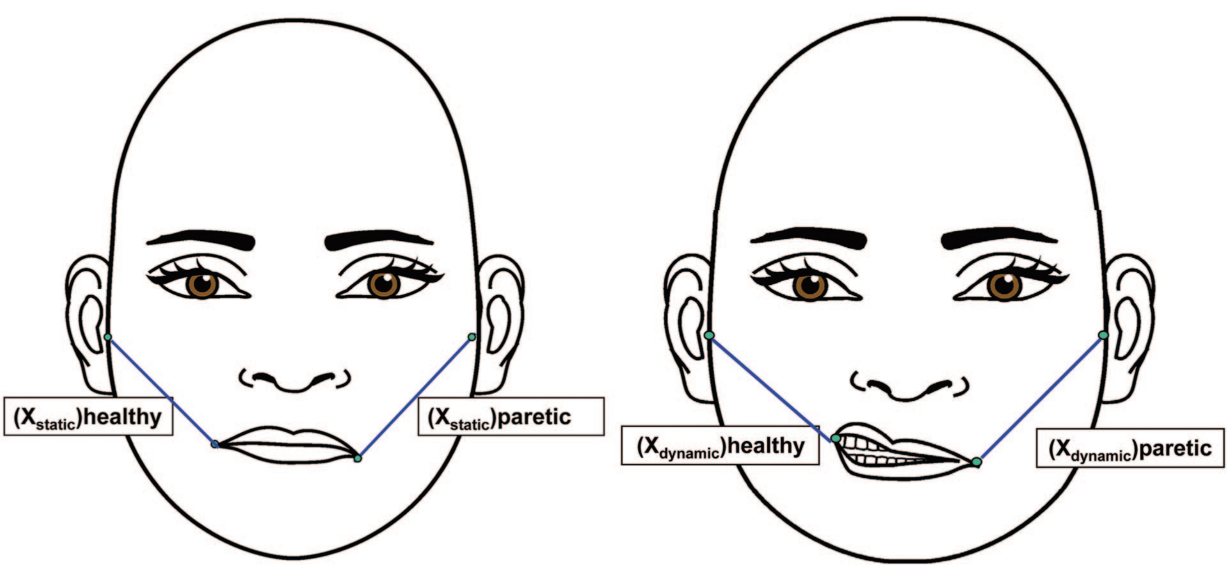

Fig. 1. (*Left*) Assessment of the static asymmetry of the mouth as the difference between the distance from the mouth corner to the tragus on the paretic side and on the healthy side of the face. (*Right*) Assessment of the amplitude of motion during the movement "smiling with showing teeth." The distance of the mouth corner to the tragus is determined at the endpoint of motion on both sides of the face and subtracted from the same distance measured in repose (*left*).

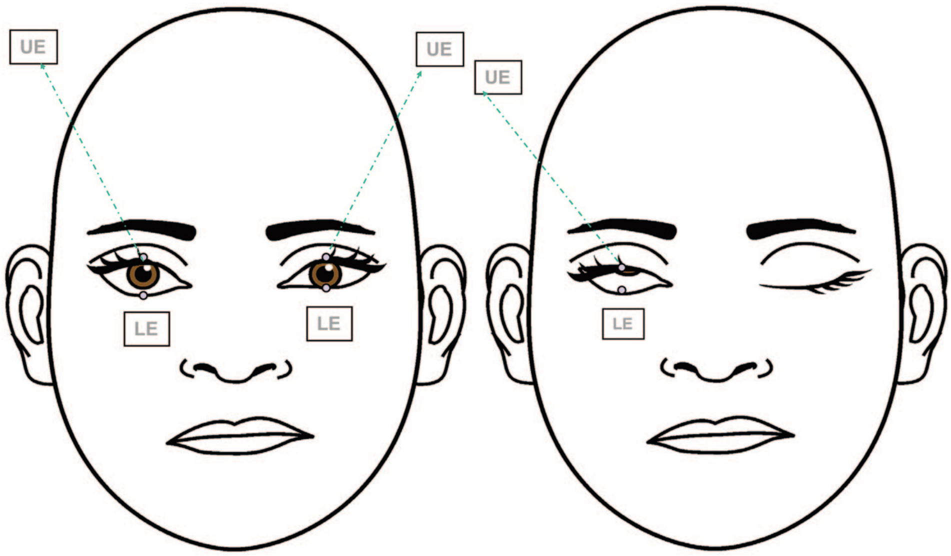

Fig. 2. (*Left*) Assessment of the static asymmetry of the eye as the difference between the distance of the upper and the lower eyelid points on the paretic side and the distance on the healthy side of the face. (*Right*) Assessment of the lagophthalmus as distance of the upper to the lower eyelid points on the paretic side of the face at the endpoint "closure of the eyelids as in sleep."

Statistical Methods

Continuous normally distributed data are described as means ± SD, and comparisons between measurements obtained before and after surgery were performed by paired *t* tests. Continuous but not normally distributed data are described with median, minimum, maximum, and lower and upper quartiles, whereas measurements before and after surgery were obtained by the use of Wilcoxon's signed rank test.

All p values are two-sided. The level of significance was set at $p \leq 0.05$.

RESULTS

Complete documentation of palsy before the beginning of treatment and every 6 months after muscle transplantation until a functional plateau is achieved were considered prerequisites for evaluation of functional results. Some of the patients included in the present study underwent secondary corrective procedures after the functional plateau of muscle transplantation had been achieved. In most cases, this was performed 18 months after muscle transplantation. As the aim of the present study was to examine functional outcome after free functional muscle transplantation in patients with facial palsy, the endpoint of follow-up for patients who were operated on after muscle transplantation was set directly before the secondary procedures. By doing so, the effect of muscle transplantation on the functional outcome could be clearly discerned from the effect of additional procedures for improvement of outcome.

Group 1

Twenty-one of 22 patients treated by a single gracilis muscle transplant for reconstruction of the smile demonstrated a considerable static asymmetry of the mouth preoperatively (Table 1). On average, in group 1, the distance from the corner of the mouth to the tragus on the paretic side was 12.19 ± 8.73 mm *longer* than the corresponding distance on the healthy side (static asymmetry, 12.19 ± 8.73 mm). The single patient with no static asymmetry before surgery had already been treated with free functional latissimus dorsi muscle transplantation to the mouth at a different center but with an insufficient vector of motion and missing emotional control. Static asymmetry was measured in all patients after a functional plateau had been achieved; this was between 18 and 24 months after muscle transplantation. The distance between the corner of the mouth and the tragus on the paretic side was on average 1.84 ± 7.67 mm *shorter* than the corresponding distance on the healthy side (static asymmetry, −1.84 ± 7.67 mm). An average and statistically significant improvement of −14.03 ± 9.93 mm was registered ($p < 0.0001$).

If all patients of group 1 are considered, the index of dynamic symmetry when smiling and show-

Table 1. Averages of Demographic Data and Measured Values of the Patients in Group 1*

	Incomplete Palsy with Minor Deficit (Index of Dynamic Symmetry, >0.4) (n = 3)		Incomplete Palsy with Significant Deficit (Index of Dynamic Symmetry, 0.1–0.4) (n = 4)		Complete Palsy (Index of Dynamic Symmetry, <0.1) (n = 12)	
	Average	SD	Average	SD	Average	SD
Age at onset, years	2.33	2.52	18.00	13.98	30.58	12.30
Duration of palsy, years	36.33	13.65	20.50	10.12	9.38	8.05
Age at surgery, years	38.67	14.50	38.50	4.20	40.46	12.14
Static asymmetry, mm†						
Preoperatively	2.17	12.29	18.95	8.76	13.12	6.33
Postoperatively	−9.10	12.64	1.81	4.58	−3.01	6.47
Mean difference	−11.27	9.59	−17.14	8.74	−16.13	9.80
Index of dynamic symmetry during smiling with showing of the teeth‡						
Preoperatively	0.61	0.15	0.17	0.06	−0.28	0.33
Postoperatively	0.92	0.49	0.58	0.27	0.62	0.37
Mean difference	0.31	0.38	0.42	0.25	0.90	0.42
Amplitude of motion of the mouth corner during maximal showing of teeth, mm						
Preoperatively	4.62	5.80	2.98	6.04	−1.84	3.18
Postoperatively	9.60	3.82	9.34	3.83	7.97	3.09
Mean difference	4.98	2.99	6.35	5.77	9.81	4.36

*One cross-face nerve graft and gracilis muscle transplantation for reconstruction of smile.
†Difference of the distance from the tragus to the mouth corner on the paretic hemiface and healthy hemiface.
‡Ratio of the amplitude of motion of the mouth corner on the paretic hemiface to the one on the healthy hemiface.

ing teeth was on average −0.06 ± 0.40 preoperatively and reached 0.55 ± 0.44 postoperatively. This amounts to a 55 percent reanimation of movement compared with the contralateral healthy side. On average, an improvement of 0.61 ± 0.48 was registered on the dynamic symmetry index, which is statistically significant ($p < 0.0001$).

The amplitude of motion on the paralyzed side achieved by maximum showing of the teeth was −0.22 ± 4.72 mm preoperatively and 6.85 ± 5.31 mm postoperatively. This reflects the amplitude of the muscle graft under maximal contraction. Movement of the corner of the mouth was improved by 7.07 ± 5.54 mm, which is statistically significant ($p < 0.0001$).

Of 22 patients treated with a single gracilis muscle transplant for the mouth, seven patients had a positive amplitude of motion ($A_{TR\text{-}MC} > 0$) preoperatively. Three of these patients had a considerable amplitude of motion at 9.3, 8.54, and 9.14 mm, respectively. Although the amplitude of motion when smiling was sufficient, the quality of motion was inadequate in all three patients. The purpose of treatment in these three cases was to improve the quality of motion rather than increase the amplitude of motion. Only one patient experienced a measurable improvement in the amplitude of motion when smiling and showing teeth after free functional gracilis muscle transplantation, whereas the remaining two patients did not. Postoperatively, the amplitude of motion on the paretic side of the face when smiling and showing teeth was 8.59 mm (preoperatively, 9.3 mm), 8.92 mm (preoperatively, 8.54 mm), and 13.72 mm (preoperatively, 9.14 mm) in the three patients. However, all three patients experienced improvement in the dynamic symmetry of motion, which was evidenced as an improved vector of motion in the first patient and elimination of synkinesia in the second and third patients.

The remaining four patients with a positive but minor amplitude of motion preoperatively experienced a substantial improvement: the amplitude of motion on the paretic side increased from 2.13 ± 0.97 mm preoperatively to 7.56 ± 1.61 mm postoperatively. The ratio between the amplitude of motion on the paretic side and the corresponding amplitude of motion on the healthy side when smiling and showing teeth increased from 0.17 ± 0.06 preoperatively to 0.58 ± 0.27 postoperatively.

Of 15 patients with negative or no amplitude of motion on the paretic side preoperatively when smiling and showing of the teeth, three patients experienced no improvement at the final follow-up and the amplitude of motion maintained its negative sign. In the first of these patients, however, a lymphoma was diagnosed 5 months after cross-face nerve grafting and the patient underwent chemotherapy before free functional muscle transplantation, which was performed 4 months later. The second of these patients who had facial palsy because of an acoustic neurinoma had a rather complicated and, in part, ambiguous follow-up with a recurrence of the acoustic neurinoma 18 months after free functional muscle transplantation. Although an exact report of the excision of the recurrent tumor was not available, postoperatively the patient had a partial lesion of the ninth and tenth cranial nerves, with difficulties in deglutition and hoarseness. The function of the muscle transplant decreased and the amplitude of motion again turned negative. No regeneration of muscle function has been registered since. In the third patient, who was 20 years old at the time of free functional muscle transplantation and suffered from an idiopathic facial palsy, no concomitant diseases or interfering factors were identified. However, the static symmetry of the mouth improved substantially and the muscle transplant showed visible contraction, although no measurable amplitude of motion occurred. Clinically the movement was not efficient.

The remaining 12 patients experienced a substantial improvement of the amplitude of motion when "smiling with showing teeth": from −2.24 ± 1.64 mm preoperatively to 6.48 ± 3.45 mm postoperatively. The ratio between the amplitude of motion on the paretic side and the corresponding amplitude of motion on the healthy side when smiling and showing teeth increased from −0.28 ± 0.33 preoperatively to 0.62 ± 0.37 postoperatively. This signifies a two-fold enhancement of the preexisting function to two-thirds of that on the healthy side postoperatively.

Group 2

Eight of nine patients who were treated with a territorially differentiated gracilis muscle transplant for both the eye and the mouth had a considerable static asymmetry of the mouth preoperatively (Table 2 and Figs. 3 through 6). The distance from the corner of the mouth to the tragus on the paretic side was on average 7.24 ± 12.64 mm *longer* than the corresponding distance on the healthy side (static asymmetry, 7.24 ± 12.64 mm) in patients of group 2. The single patient with no static asymmetry preoperatively had already been treated by static procedures of suspension at a different center. Static asymmetry was measured again 6, 12, 18, and 24 months after free muscle transplantation. The distance between the corner of the mouth and the tragus on the paretic side was on average 5.36 ± 9.07 mm *shorter* than the corresponding distance on the healthy side (static asymmetry, −5.36 ± 9.07 mm). This higher and more lateral positioning of the angle of the mouth on the reanimated side was intentional. An average shortening of −12.55 ± 12.32 mm was registered, which is statistically significant ($p = 0.0154$).

The average index of dynamic symmetry during the movement "smiling and showing teeth" increased from −0.11 ± 0.16 preoperatively to 0.68 ± 0.43 postoperatively (Fig. 2). An average improvement of 0.79 ± 0.47 was registered, which is statistically significant ($p = 0.001$).

Of these nine patients treated with a territorially differentiated gracilis muscle transplant, preoperatively, two had a positive but insignificant amplitude of motion on the paretic half of the face when smiling and showing teeth (1.52 and 0.43 mm, respectively). All patients but one experienced an improvement in the amplitude of mo-

Table 2. Averages of Demographic Data and Measured Values of the Patients of Group 2 (*n* = 9)*

	Average	SD
Age at onset, years	23.89	16.57
Duration of palsy, years	12.44	11.83
Age at surgery, years	36.33	18.18
Reconstruction of smile		
Static asymmetry, mm†		
Preoperatively	7.24	12.64
Postoperatively	−5.36	9.07
Mean difference	−12.59	12.32
Index of dynamic symmetry during smiling with showing of the teeth‡		
Preoperatively	−0.11	0.16
Postoperatively	0.68	0.43
Mean difference	0.79	0.47
Amplitude of motion of the mouth corner during maximal showing of teeth, mm		
Preoperatively	−0.85	2.70
Postoperatively	7.43	5.84
Mean difference	8.28	6.70
Reconstruction of eye closure		
Static asymmetry, mm§		
Preoperatively	1.34	1.06
Postoperatively	−2.22	4.07
Mean difference	−3.56	5.05
Lagophthalmus after closing the eyes as in sleep, mm‖		
Preoperatively	7.21	3.59
Postoperatively	1.38	2.49
Mean difference	−5.83	3.17

*Two cross-face nerve grafts and territorially differentiated gracilis muscle transplant for reconstruction of eye closure and smile.
†Difference of the distance from the tragus to the mouth corner on the paretic and healthy hemifaces.
‡Ratio of the amplitude of motion of the mouth corner on the paretic hemiface to the one on the healthy hemiface.
§Difference of the distance from the upper to the lower eyelid points on the paretic and healthy hemifaces.
‖Distance from the upper to the lower eyelid points on the paretic hemiface.

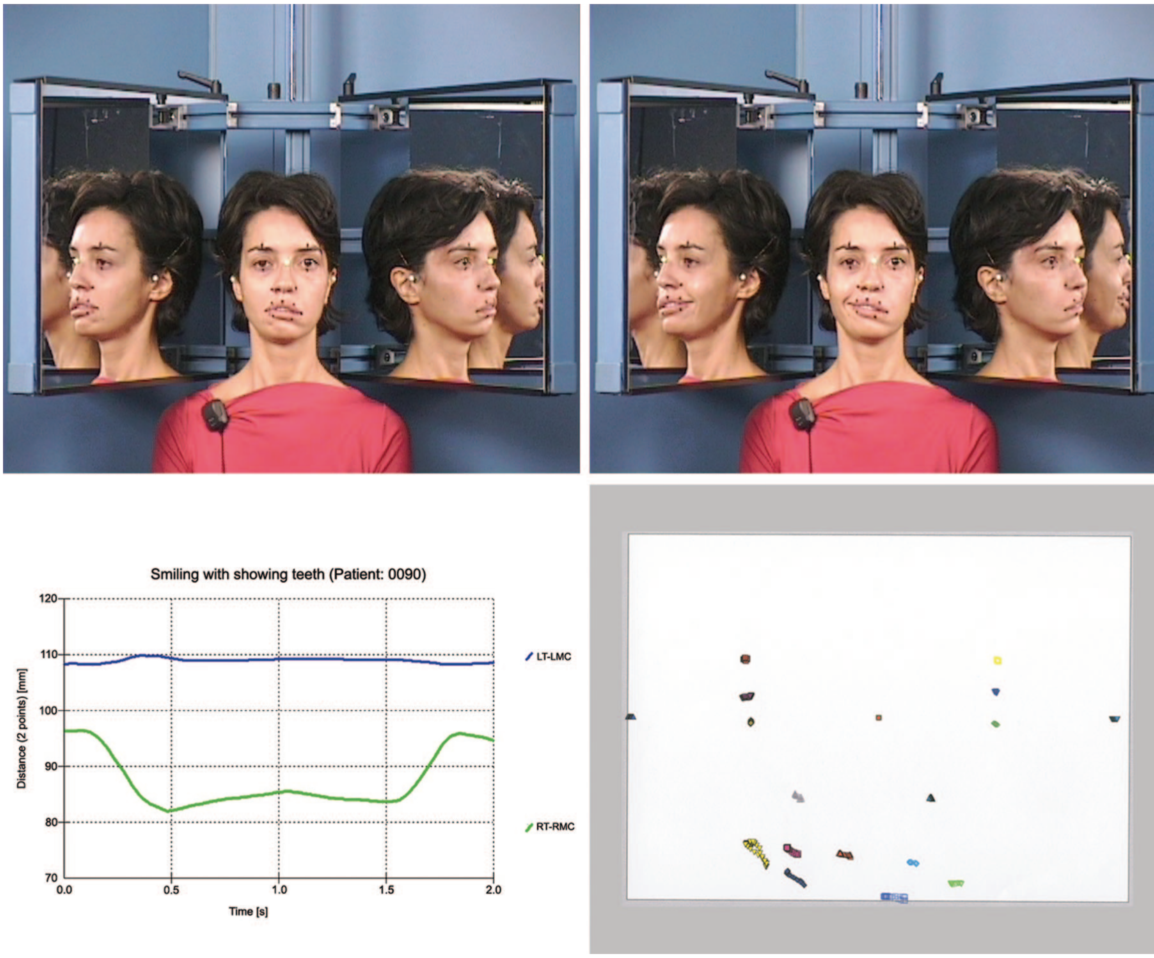

Fig. 3. (*Above*) A patient with irreversible complete and total facial palsy of the left hemifaces preoperatively (*above*, *left*) in repose and at the endpoint "smiling with showing teeth" (*above*, *right*). (*Below*, *left*) Graph showing the two-dimensional course of the distance of the mouth corner to the ipsilateral tragus during the time on the paretic (*blue curve*) and healthy sides (*green curve*) of the face. (*Below*, *right*) A three-dimensional view of all marked landmarks of the face during the movement "smiling with showing teeth."

tion on the paretic side of the face postoperatively. The single patient who experienced no improvement in the amplitude of motion of the smile achieved, surprisingly, complete closure of the eye postoperatively. Sufficient contraction of the muscle transplant around the eye was accomplished, but the contraction of the muscle transplant around the mouth was very weak and did not improve even after a secondary corrective procedure by which the transplant was tightened and functionally coupled to the healthy half of the orbicularis oris muscle using a tendon graft. The amplitude of motion achieved by this patient when smiling and showing teeth increased from 1.52 mm preoperatively to 1.98 mm at 26 months after muscle transplantation. In two patients, the amplitude of motion achieved a positive sign but rather minor values. The amplitude of motion improved from −2.23 mm of passive motion preoperatively to 3.42 mm of active motion in the first patient and from −3.44 mm to 2.3 mm in the second patient.

The average amplitude of motion on the paretic side during maximum showing of the teeth for all patients in group 2 increased from −0.85 ± 2.70 mm preoperatively to 7.42 ± 5.84 mm postoperatively. A mean improvement of 8.28 ± 6.70 mm was observed, which is statistically significant ($p = 0.006$). One patient showed no improvement between preoperative and postoperative values in the amplitude of motion on the paretic side during maximum showing of the teeth.

In all nine patients who were treated with a territorially differentiated gracilis muscle transplant for reconstruction of eye closure, the eye fissure was wider preoperatively on the paretic side than on the healthy side. The median static asymmetry was 0.96

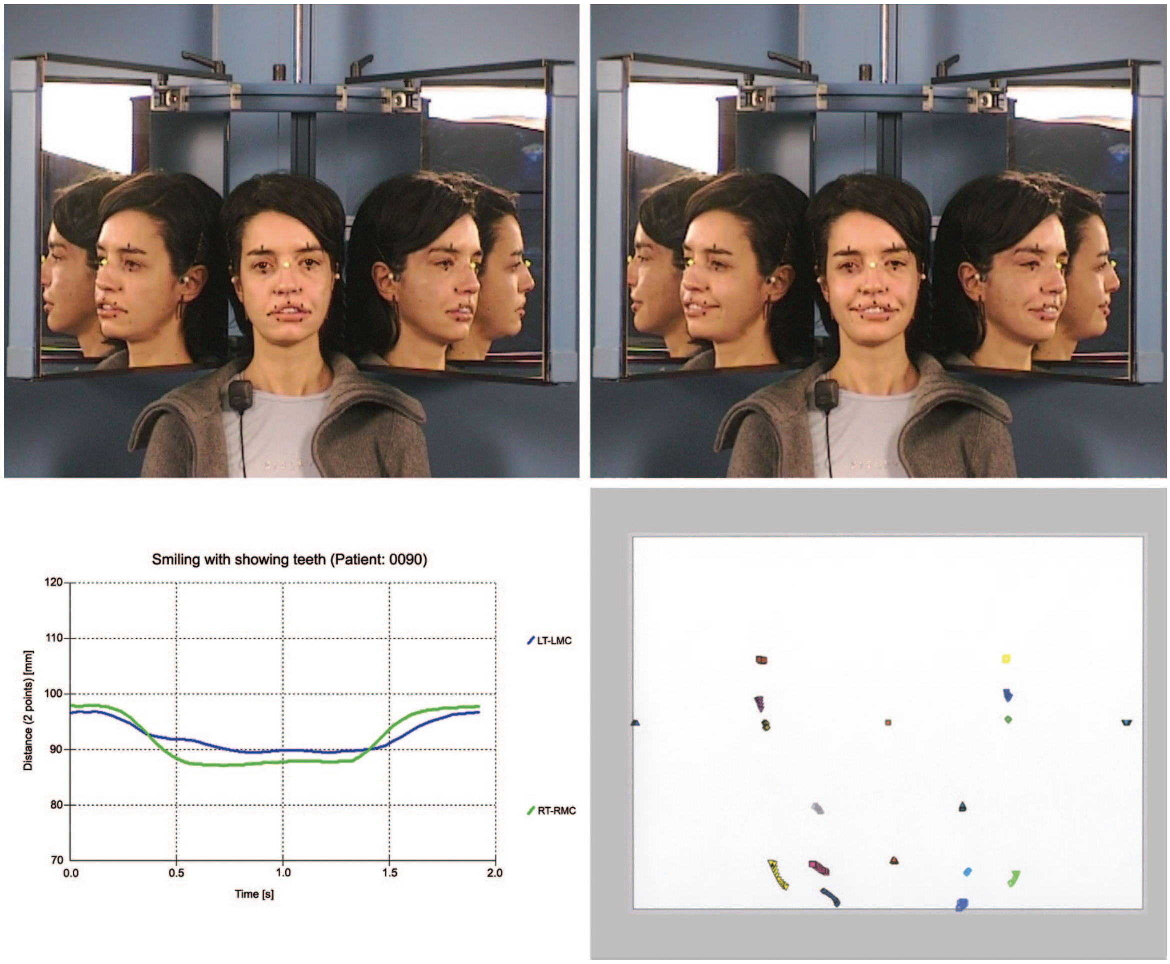

Fig. 4. (*Above*) The same patient as shown in Figure 3 18 months after free functional transplantation of a territorially differentiated gracilis muscle transplant for reconstruction of the smile and eye closure showing the face of the patient in repose (*above*, *left*) and at the endpoint "smiling with showing teeth" (*above*, *right*). (*Below*, *left*) Graph showing the two-dimensional course of the distance of the mouth corner to the ipsilateral tragus during the time on the reconstructed (*blue curve*) and healthy sides (*green curve*) of the face. (*Below*, *right*) A three-dimensional view of all marked landmarks of the face during the movement "smiling with showing teeth."

mm (range, 0.22 to 3.76 mm) preoperatively. Remarkably, in seven of nine patients, the eye fissure became narrower postoperatively compared with that on the healthy side. The median static asymmetry achieved postoperatively was −1.67 mm (range, −12.31 to 1.97 mm). In one patient, the tonus of the muscle transplant was, in fact, too strong and had to be weakened by muscle reduction at a subsequent operation. A median narrowing of the wider paralyzed eye fissure of −2.87 mm (range, −16.07 to 1.48) was observed, which is statistically significant ($p = 0.0195$).

The preoperative lagophthalmus was on average 7.21 ± 3.59 mm and was reduced postoperatively to 1.38 ± 2.49 mm (Figs. 3 and 4). A statistically significant improvement of −5.83 ± 3.17 mm was observed ($p = 0.0006$).

Patients in both groups reported a marked reduction in their subjective need for artificial tears and ointments for the eye because they seldom experienced irritation caused by wind or dust. No patient needed ointments at night and all used artificial tears less than three times per day. Sufficient coverage and protection of the cornea at night was achieved by all subjects.

Synkinesia

Group 1

The phenomenon of synkinesia was examined before and 18 to 24 months after reconstruction. In seven of 22 patients who had been treated by free functional muscle transplantation for reconstruction of the smile, only synkinesia was observed within

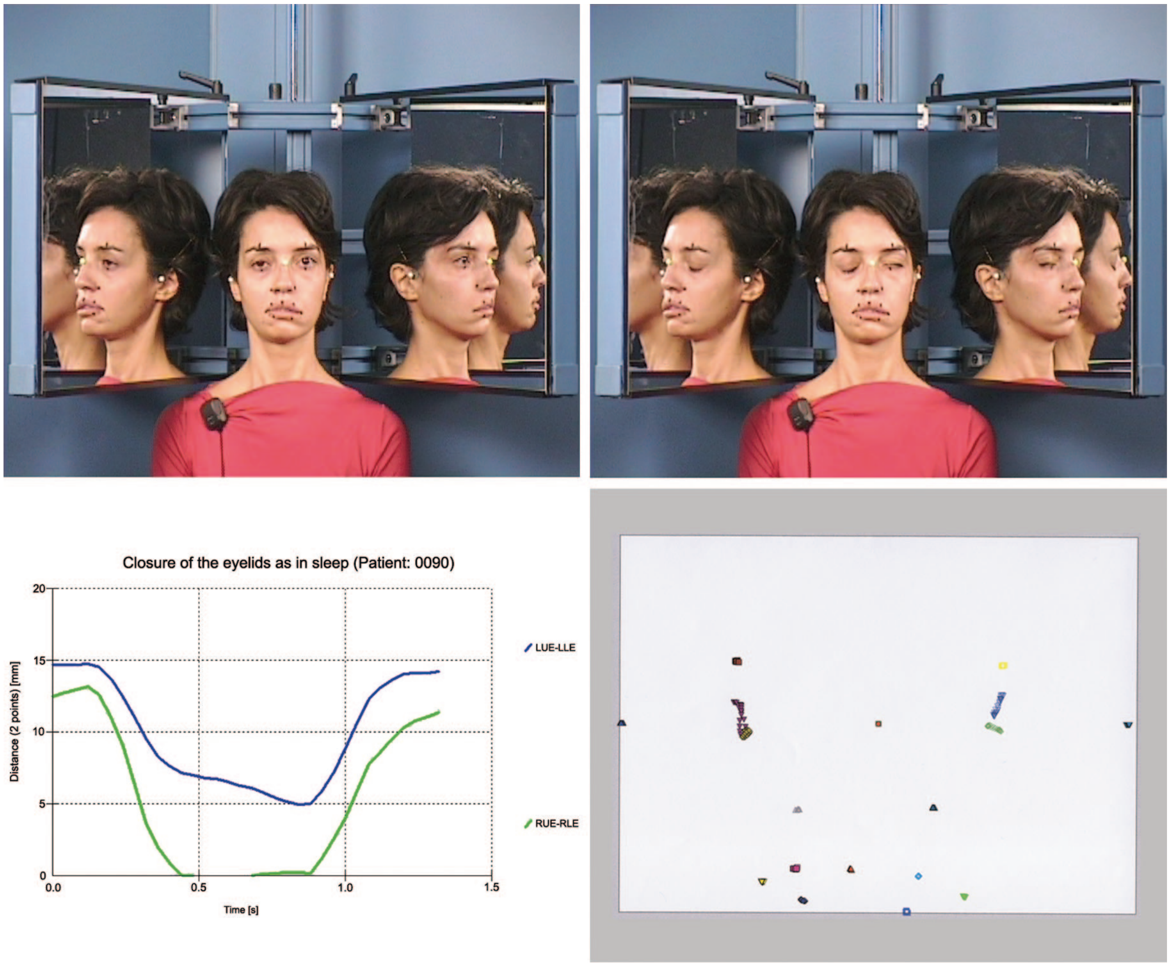

Fig. 5. The same patient as shown in Figure 3 preoperatively showing the face of the patient in repose (*above*, *left*) and at the endpoint "closure of the eyes as in sleep" (*above*, *right*). (*Below*, *left*) Graph showing the two-dimensional course of the distance of the upper to the lower eyelid during the time on the paretic (*blue curve*) and healthy side (*green curve*) of the face. (*Below*, *right*) A three-dimensional view of all marked landmarks of the face during the movement "closure of the eyes as in sleep."

the ipsilateral mouth region during closure of the eyes as in sleep. In six of these patients, reconstruction of eye closure had been performed by means of temporalis muscle transposition. One patient had synkinesia at both corners of the mouth during closure of the eyes as in sleep. A further patient had synkinesia before surgery. This was a woman who had developed a posttraumatic incomplete facial palsy at the age of 5 and was operated on at the age of 34. She achieved complete eye closure and only her smile was reconstructed by free gracilis muscle transplantation to the mouth. No patient demonstrated synkinesia in the eye region when smiling and showing teeth.

Group 2

In three of nine patients who had been treated by free functional gracilis muscle transplantation territorially differentiated for the eye and mouth, synkinesia was observed at the time of the functional plateau in the ipsilateral region of the mouth during closure of the eyes as in sleep (Fig. 4, *right*). Synkinesia was not observed preoperatively in any of these patients. No synkinesia was observed within the ipsilateral eye region when smiling and showing teeth.

DISCUSSION

Since 1997, we have been using a three-dimensional video analysis system of facial movement in all patients treated for facial palsy. The exact degree of facial paralysis before any reconstructive surgery and every 6 months postoperatively was determined to monitor functional improvement until a final result had been achieved. Global and indirect parameters have been used thus far to describe the results of treatment or spontaneous

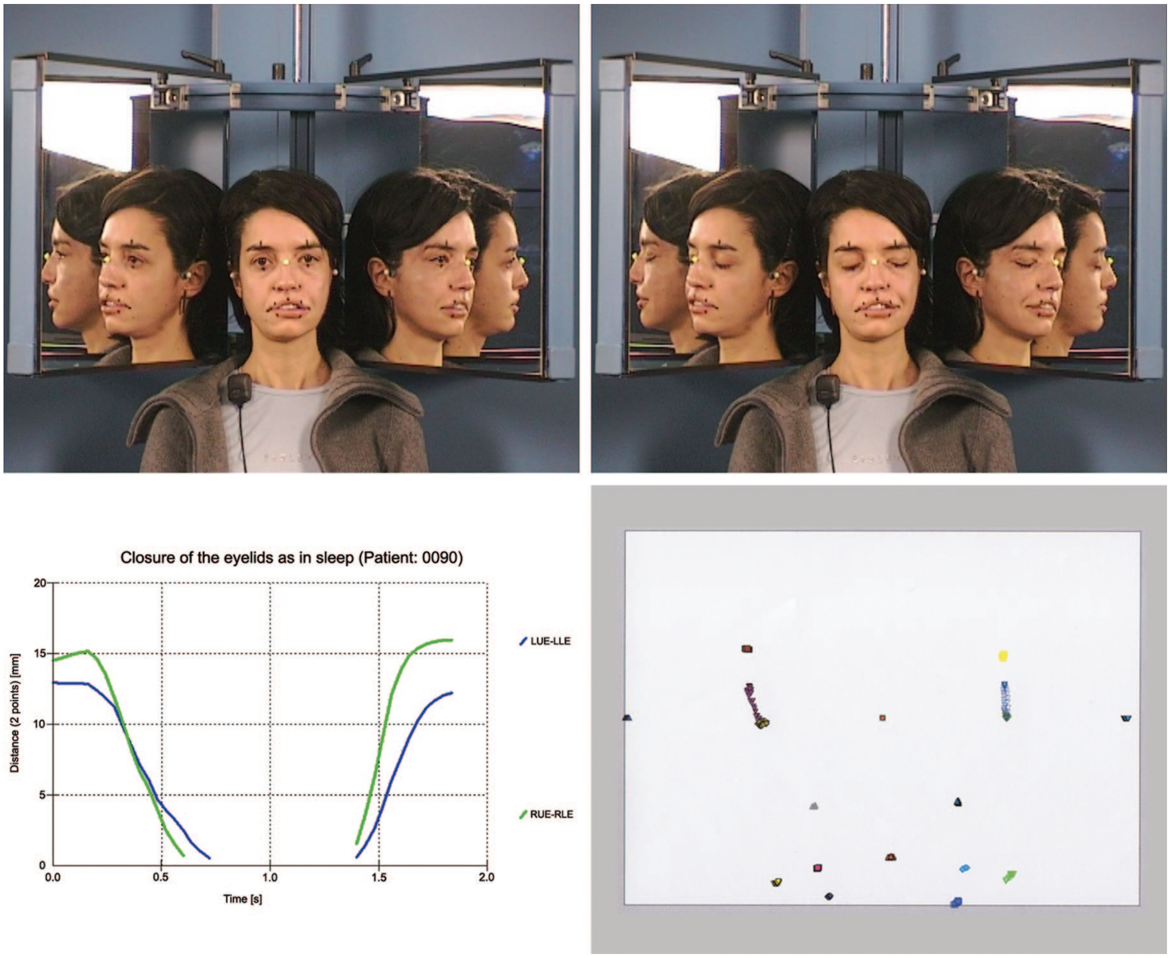

Fig. 6. The same patient as shown in Figure 3 18 months after free functional gracilis muscle transplantation for reconstruction of the smile and eye closure showing the face of the patient in repose (*above*, *left*) and at the endpoint "closure of the eyes as in sleep" (*above*, *right*). (*Below*, *left*) Graph showing the two-dimensional course of the distance of the upper eyelid to the lower eyelid during the time on the reconstructed (*blue curve*) and healthy sides (*green curve*) of the face. (*Below*, *right*) A three-dimensional view of all marked landmarks of the face during the movement "closure of the eyes as in sleep."

recovery of facial paralysis.[15,16] The majority of authors still use the House-Brackmann grading system,[17,18] although we published our method of assessing the quantity and quality of facial movements by three-dimensional video analysis in 1999.[8] However, others use personal grading systems, which are even more inexact and subjective than the House-Brackmann system.[19–21]

Johnson et al. attempted to simplify the complex method of three-dimensional video analysis by analyzing the vectors and amplitudes of the movements in only one frontal plane and by their maximal static response assay of facial motion.[22,23] Manktelow et al.[24] and Zuker and Manktelow[25] measured the amplitude of the smile preoperatively and postoperatively with a ruler. These measurements were performed free hand on a frontal perspective of the movement. Before the method of three-dimensional video analysis of facial movement had been developed, we used a digital caliper to directly measure distances during rest and maximal movement three-dimensionally.[7,26] Tomat and Manktelow have attempted to overcome the problems of the two-dimensional approach and the disturbing effect of measurements on the face of patients by using overlaid images at rest and during maximal movement from videos taken with an image plane, which is as parallel to the plane of movement as possible.[27] Although this facial reanimation measurement system is less time consuming than our three-dimensional video analysis system, it does not measure real distances but is only an approximation. Besides, it does not analyze entire movements and thus fails to document a number of parameters for evaluation. The complexities of movements of the entire face over the entire run of a single specific facial movement are missed. In a recent report on smile reconstruction in adults with free muscle transfer innervated by the masseter motor nerve, this group used their movement measurement technique FaceMS.[28] The measurements are restricted to the movement of the commissure and the mid upper lip point. Static and dynamic symmetry cannot be analyzed accurately because the moving points are not related three-dimensionally to static points. The vector of movement is simplified as being constant all over the movement instead of considering the changing vector along a complex movement curve. Although the FaceMS is an approximated objective tool, a great deal of information is lost.

Our study of free functional muscle transplants to the paralyzed face included three-dimensional video analysis of the facial movements on the healthy and the paralyzed sides and, subsequently, on the surgically reanimated side of the face. All patients treated by muscle transplantation since 1997 were investigated in this manner. Results achieved more than 18 months after muscle transplantation, but before further corrective procedures for improvement, were included in this report.

In group 1, which included patients who had undergone one cross-face nerve graft and a gracilis muscle transplant with microneurovascular anastomoses to the paralyzed mouth region, a significant improvement of static asymmetry was achieved. The preoperative asymmetry of the distance between the tragus point and the corner of the mouth was reduced from 12.19 ± 8.73 mm to -1.84 ± 7.67 mm. In other words, the angle of the mouth on the paralyzed side was altered from a very low position to a highly symmetric position, with some overcorrection expressed by the negative prefix. This degree of intended overcorrection results in a near-normal horizontal position of the lips and reduces the dynamic asymmetry when the amplitude of the smile movement is shorter on the reconstructed side than on the healthy side of the face. To determine standard values of healthy facial movements, we performed three-dimensional video analysis of facial movements in healthy volunteers,[29] which showed that the normal asymmetry between the right and left sides of the face for subjects aged 40 to 50 years ranges from 0.68 to 5.62 mm.

The claim has been made that this technique of microsurgical reanimation of the unilaterally paralyzed face achieves the best emotionally controlled smile. The advantage of analyzing facial movements preoperatively by three-dimensional video analysis lies in an exact and objective estimation of the degree of paralysis, region by region and movement by movement. Group 1 consisted of 22 treated patients. Fifteen had an irreversible complete facial palsy and seven patients had an incomplete palsy.

Fifteen patients in group 1 had complete palsies with a negative amplitude at the corner of the mouth even when smiling. This fact is indicative of a deformity in the shift of the paralyzed side of the mouth to the activated contralateral side. In three patients, no improvement in dynamic asymmetry was achieved, although visible contractions verified reinnervation of the muscle transplant and static symmetry was improved in two of them. The reasons for these limited dynamic effects were intermittent oncologic disease in two patients. Only one patient revealed an obvious functional failure of the muscle transplant. The remaining 12 patients smiled on the originally completely paralyzed side with an amplitude of 62 percent of that on the healthy side on average, more than 18 months after gracilis muscle transplantation. This is a good final result of reanimation surgery if one considers the fact that smiling and displaying teeth is a submaximal but clinically most relevant movement in the face. According to the standard values determined by the three-dimensional video analysis system of facial movement, the asymmetry between the right and left sides of the face for healthy individuals aged 40 to 50 years ranges from 0.65 to 3.2 mm.[29]

Incomplete lesions were noted in two subgroups: in three patients, the amplitude of movement at the corner of the mouth when smiling was approximately 9 mm. In these cases, missing emotional control of the smile, disturbing synkinesia, or wrong direction of the movement was the indication for surgery. The existing pathologic movement was replaced by a more natural movement of the transplant. Thus, the quality, and not the quantity, of mimic movements was improved in all three patients. The remaining four patients with incomplete palsy had a minimal range of motion of 2.13 ± 0.97 mm preoperatively. Thus, the improvement was from 17 to 58 percent of the amplitude of the smile on the healthy side.

Maximal contraction with respect to force and amplitude is provided by the transplanted muscle during the movement involving maximum display of teeth. Overall, the mean improvement in amplitude was from -0.22 ± 4.72 mm to 6.85 ± 5.31 mm. The advantage of presenting the amplitude of this movement in millimeters lies in the fact that this movement is produced by maximal contraction in the muscle graft with maximal effort, whereas smiling is better represented in its quality by the degree of symmetry of the movement of both sides. As expected, the three patients with significant amplitude of this movement preoperatively did not show any improvement.

In group 2, nine patients were treated with a territorially differentiated gracilis muscle transplant to improve their smile and eye closure simultaneously (Figs. 3 through 6). Two of them had minimal function. The differentiated muscle graft reinnervated by two cross-face nerve grafts improved the static asymmetry of the position of the angle of the mouth from 7.24 ± 12.64 mm to a slight overcorrection of -5.36 ± 9.07 mm. In combination with smaller amplitude of the smile on the reconstructed side, this overcorrection resulted in a more balanced overall result. Only one of the nine patients showed no improvement in the amplitude of the smile but complete eye closure secondary to the transplanted muscle. In fact, the amplitude of the reconstructed "smiling with showing teeth" was, on average, 68 ± 43 percent of that on the normal side. The average reconstructed "maximum showing of the teeth" achieved an amplitude of 7.42 ± 5.84 mm. Eye closure was reconstructed to a great extent in all nine patients in whom the gracilis muscle graft was used for this purpose in addition to reconstruction of the smile. The eye fissure is best expressed by the distance between the upper and the lower eyelid points. Facial palsy leads to a wider eye fissure and lagophthalmus during closure of the eyes. For the purpose of analysis, the static asymmetry of the open eyes and the remaining lagophthalmus during "closure of the eyes as in sleep" are of clinical interest. The median static asymmetry before surgery was 0.96 mm and represented a wider eye fissure on the paralyzed side during rest and with open eyes. The postoperative median value was -1.67 mm and represented a smaller eye fissure on the reconstructed side. The reason was overcorrection by muscle function that was too strong, particularly in the upper eyelid, which even had to be reduced by surgical excision of that part of the muscle graft in one patient. By comparison, the standard values for asymmetry between the right and the left eye fissure in the resting position for healthy individuals aged 20 to 30 years, determined by three-dimensional video analysis of facial movement, was on average 0.7 mm.[29] Clinical symptoms around the eye were improved significantly in all patients by reducing the lagophthalmus during closure from 7.21 ± 3.59 mm preoperatively to 1.38 ± 2.49 mm postoperatively. Conjunctivitis was resolved completely and was a great relief for all patients. The need for artificial tears was restricted to rare stressful situations such as wind, extreme sunshine, or prolonged computer work.

Synkinesia is an important parameter of the quality of microsurgical reanimation of the paralyzed face but has been rarely described by other authors. Observing all functional areas during the same movement by three-dimensional video analysis (Figs. 3 through 6, *below*, *right*) offers the unique possibility of documenting disturbing synkinesia. These patients either had synkinesia before surgical treatment caused by aberrant spontaneous reinnervation, or their synkinesia had been caused by using a branch of the facial nerve to connect to the cross-face nerve graft, which contains some nerve fibers that control the function of smiling and also exert some control on eye closure. This fact cannot be excluded in some cases, even when the branch of the facial nerve is selected very carefully and as distally as possible. A further reason is the impossibility of separating the functional territories of the gracilis muscle when dissecting the muscle graft. This results in an overlap between the areas supplied by the muscle nerve and synkinesia.

In the present study, seven of 22 patients in group 1 showed synkinesia in the muscle transplant in the mouth region when closing the eyes. In one patient, this condition existed before surgery, and a further patient had synkinesia on both sides. No patient had synkinesia in the eye region when smiling, which would be a more compromising form of synkinesia from the clinical point of view.

With regard to synkinesia, we registered very similar results in group 2, although the surgical differentiation of two functional parts of the muscle graft and the possibility of overlapping reinnervation might have been expected to exert an additional effect in this group. There was no preexisting synkinesia. One-third of the patients had synkinesia in the mouth region when closing the eyes, but no synkinesia was registered around the eyes when smiling.

Thus, synkinesia was not the major clinical problem. Two aspects of surgical techniques for preventing synkinesia are the use of intraoperative electrostimulation to select a facial nerve branch with only the smile function or the eye closure function on the normal side, and nerve coaptation between a distalmost healthy facial nerve branch and the cross-face nerve graft when using nerve fibers focused on the target muscles for the purpose of reinnervation. Our results show that synkinesia may be attributable to anatomical variations that cannot be prevented even by highly sophisticated operative techniques.

CONCLUSIONS

The combination of cross-face nerve grafting and free functional gracilis muscle transplantation is a highly efficient two-stage procedure for reanimating the paralyzed mouth region alone or the paralyzed eye sphincter and the paralyzed mouth region simultaneously. The high probability of achieving a clinically relevant smile or eye closure and emotionally controlled movements by the use of the contralateral healthy facial nerve for reinnervation makes this technique the first choice for reanimation of unilateral irreversible facial palsy. Significant improvement may also be achieved in cases of incomplete lesions or spontaneous recovery of misdirected movements.

The quality of reconstruction of the mimic muscles was demonstrated on preoperative and postoperative videos of standardized facial movements and also by exact three-dimensional video analysis of the different movements in the different areas of the face. The time-consuming three-dimensional video analysis must be rendered automatic before it can be recommended for general clinical use. This is the subject of an ongoing research project.

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