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Potential of an Electric Prosthesis for Dynamic Facial Reanimation

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Abstract

Chronic facial paralysis is a devastating condition with severe functional and emotional consequences. The current surgical armamentarium permits the predictable reestablishment of a protective blink as well as good resting symmetry. Yet the ultimate goal of symmetric, spontaneous emotional expression remains elusive despite significant progress in the areas of peripheral nerve grafting and free tissue transfer. This commentary explores the possibility of an implantable electrical prosthesis for facial reanimation. It reviews animal studies supporting this concept as well as recent human data suggesting that such an implant could rescue denervated facial musculature, thus overcoming a major hurdle for existing reanimation techniques.

Keywords

facial paralysis, prosthetics, biomedical engineering

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Over the past decade, facial plastic and reconstructive surgery has achieved a relative golden age in which surgeons have an astounding armamentarium of medical, surgical, and technological interventions by which to restore and enhance the structure, function, and beauty of the human face. Despite these advances, chronic facial paralysis remains a challenging reconstructive problem. A complete unilateral facial paralysis causes nasal obstruction, oral incompetence, and corneal exposure and, most important, results in the loss of spontaneous facial expression that is so integral to human social interaction and communication.

There have always been 3 basic goals in facial reanimation: to preserve function, produce static symmetry, and achieve dynamic mobility. As Hadlock and Cheney¹ emphasized, the field of facial reanimation has gone through an iterative process wherein the objectives have remained the same but the criteria for success have changed. For example, tarsorrhaphy was an early intervention for paralytic lagophthalmos that protected the cornea but caused a deforming cosmetic defect

and visual obstruction. Upper lid gold weights represented a significant improvement and have now been supplanted by low-profile platinum weights because of equal efficacy, better cosmesis, and a lower incidence of complications.² This same quality-improvement process has resulted in significant advances in managing other aspects of facial paralysis. A better appreciation for the different facets of paralytic ectropion and for nasal obstruction has led to more effective interventions in the midface and lower lid. Selective chemodeneration for synkinesis or hypertonicity on the paralyzed side, in combination with weakening on the intact side, can help achieve more perfect static symmetry. Indeed, with few exceptions we are now able to protect the eye, prevent oral incompetence, and achieve good or excellent static symmetry.

Reliable dynamic facial movement remains a challenge, however. Dynamic facial motion requires stimulatory input to functioning musculature. Options for input include the native nerve when available, the contralateral intact facial nerve via cross-facial nerve grafts, or various ipsilateral motor nerves including the hypoglossal and masseteric nerves. Chronic denervation leads to facial muscle atrophy. After a critical period, generally believed to be 18 to 24 months, reinnervation of these atrophic muscles will usually not result in facial movement. In the absence of functional native facial musculature, regional or free muscle transfer is required.

Regional muscle transfer provides both motor input and intact muscle bulk to the face. Various regional muscles have been used in different facial regions, in both a primary and an adjunct capacity. Use of the temporalis muscle to restore dynamic smile is the most common application of regional muscle. Over the past 10 years, Labbe and Huault³ have published extensively on temporalis tendon transfer for dynamic reanimation of the oral commissure. Through careful attention to the anatomy of the tendinous insertion on the mandible and to that of the normal smile, one can achieve impressive

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dynamic excursion rivaling that often seen with free muscle transfer and cross-facial nerve grafting.

The holy grail for facial reanimative surgeons is spontaneous, symmetric facial movement. The traditional teaching has been that cross-facial nerve grafting is the only method by which this can be accomplished, because it uses impulses from the intact facial nucleus to drive or pace the native or transplanted muscles on the paralyzed side. This technique involves 2 stages spaced roughly a year apart, requires a young patient with good axonization potential, and can have unpredictable results. Manktelow and others⁴ have challenged the status quo by demonstrating spontaneous, mimetic smile in more than half of patients with free muscle transfers driven by the masseteric nerve (instead of a cross-facial nerve graft). The explanation for this is cortical reorganization, a process well documented in patients with brachial plexus injury. Yaron and Labbe have even commented that some of their temporalis tendon transfer patients are able to achieve commissure excursion without biting down, although this is less well explored.⁵

Arguably the most impressive results have been obtained by Terzis's group. They use electromyography (EMG) extensively to identify and quantify remaining facial musculature. If moderately functioning facial musculature remains, an end-to-side minihypoglossal transfer to the distal facial nerve is performed, termed the "babysitter" procedure. This reestablishes axonal input to the affected muscles, providing tone and preserving muscle bulk. Prior to a second stage, muscle contraction is assessed with tongue-thrust. If there is strong contraction, cross-facial nerve grafting to multiple distal branches of the affected nerve is performed. The branches are chosen based on nerve stimulation and the movement produced, with a goal of reanimating blink, upper lip elevation, and lower lip depression. If some of the native facial musculature is present but too weak, the cross-facial nerve grafts can be transposed to a free-muscle transfer. Regional muscle transfer can supplement any residual asymmetries. The 2 main advantages of this technique are (1) to use as much native facial musculature, with its entirely natural thickness and vector, as possible and (2) to "pace" these muscles by the facial nucleus on the intact side, producing spontaneous, symmetric facial expression. Half of the patients achieved a good or excellent result based on Terzis's grading scale.⁶

Though impressive, there are downsides to this technique, including significant technical difficulty, potential facial nerve injury on the unaffected side, and somewhat unpredictable results even in the most experienced hands. Furthermore, this technique requires multiple surgeries and a long treatment course with at least 1 year between the initial surgery and the return of movement. Might not an electrical prosthesis be a way to produce symmetric and spontaneous facial motion more quickly and reliably? There is some evidence that it could.

The Facial Implant

The idea of electrical pacing has been around since at least 1977, when Zeale and Dedo⁶ reported that they electrically stimulated paralyzed cricothyroid muscles in dogs using the

contralateral nonparalyzed muscle to initiate and control the response elicited. In 1986, Rothstein and Berlinger⁷ definitively showed in a rabbit facial nerve injury model that contraction of the orbicularis oculi and zygomaticus muscles could be detected via EMG and used to stimulate their denervated counterparts on the opposite side of the face.⁸ That same year, Otto et al demonstrated the same in a canine model.⁹ They would later show that eye-blink could be rehabilitated continuously for 6 weeks in rabbits.¹⁰

Between 1987 and 1991, Broniatowski's group published a 3-part series of articles using a slightly different model with several modifications to Otto's design. Broniatowski and colleagues believed that the EMG signal from the intact muscles was somewhat unreliable; they wanted a more graded response and so used small strain gauges placed on the skin overlying the rabbit's midface instead. Additionally, the investigators were worried about fibrosis around electrodes implanted on the paralyzed side. To avoid this, they harvested nerve/muscle pedicles from the ansa cervicalis and strap muscles and implanted them into the desired paralyzed muscle (ie, zygomaticus). The strain gauge on the intact side sensed firing, which created an impulse that was routed through and interpreted by a small computer intermediary, which then stimulated a perineural electrode placed around the nerve-muscle pedicle.¹¹ This is the only group to have used this technique, but it allowed them to achieve a graded and synchronous response in both rabbits and dogs.

There is no clear reason why the idea of electrical pacing to rehabilitate facial paralysis has failed to gain momentum despite proof of principle in good animal models. One likely contributing factor has been the lack of appropriate electrode technology and the unavailability of adequately small computers for implantation. Recent advances in microelectrode technology have yielded very thin (20 μm thick), flexible arrays that harbor a large number of precisely placed electrode sites for recording or stimulation along the surface of a muscle.

These technological advances permit the realistic development of a permanent electrical prosthesis for facial paralysis. The envisioned implant would electrically pace several denervated facial muscles using EMG impulses from the paired muscles on the unaffected side. Incoming impulses would be routed via fine electrodes to a completely implantable processor placed superior to the auricle. Stimulatory electrodes would pass from the processor to the paired denervated muscles, allowing simultaneous facial expression (**Figure 1**).

One obvious concern regarding this model is atrophy of the denervated muscles over time. The relative importance of neurotrophic factors versus muscle activity in the maintenance of muscle mass, contractile properties, and fiber-type characteristics has been greatly debated. Studies have shown that electrical stimulation is effective in limiting denervation-induced atrophy and in improving muscle force and recovery after reinnervation. One remarkable investigation in Europe, the RISE trial, looked at paraplegic patients with conus cauda (lower motor neuron) injuries to see whether extreme muscle

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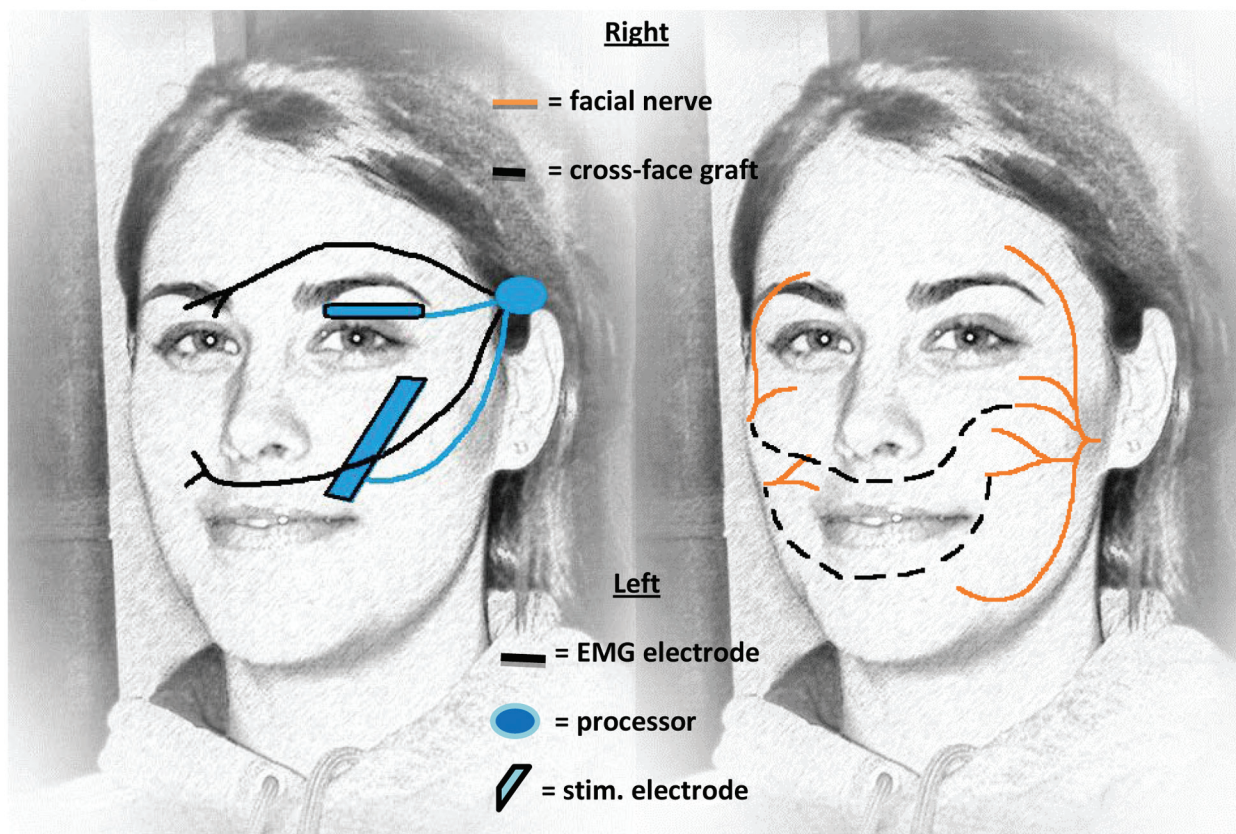


Figure 1. On right, typical cross-facial nerve grafting used to address the eye and midface. Dashed lines represent nerve grafts. On left, demonstration of how cross-facial electrodes could be used in a similar fashion, with implantable microprocessor placed above the auricle and behind the hairline. Black electrodes are electromyographic (EMG) leads and blue bands represent stimulatory microelectrodes.

wasting and fibrosis could be reversed by functional electrical stimulation (FES). After 1 year of home FES, participants exhibited significant increases in muscle excitability, increased muscle bulk, a doubling of myofiber size, and the new ability to stand in 20% of subjects. The muscle force increase was significantly greater than would be expected based on fiber size alone, suggesting that ultrastructural changes in the T tubules and Ca^{2+} -sensing units must have occurred.¹² Thus, electrical stimulation appears able not only to maintain muscle structure but to reverse changes seen in chronic denervation as well. This is important because it suggests that a relatively basic and low-powered implant could serve as a “babysitter” for the facial musculature in cases where facial nerve recovery was possible but uncertain.

Once placed, the facial implant could be tailored to a particular patient’s face much like a cochlear implant is customized today. The electrodes would have numerous contacts to the facial musculature, so different combinations of electrodes and amounts of energy could be selected to achieve the most complete and symmetric expression. Optimizing such an implanted system would require ongoing adjustment, but audiology departments are already quite familiar with cochlear implants and EMG and have the basic hardware and staff

requisite for these kinds of manipulations. Because many patients with facial paralysis develop problems with self-esteem and even psychiatric difficulties, preventing optimal work productivity, an effective facial implant would likely be worth the significant up-front and maintenance costs.

Conclusion

Surgical rehabilitation of chronic facial paralysis is difficult. The most aggressive techniques using multiple cross-facial nerve grafts and free muscle transfer produce occasionally excellent, but still unpredictable functional results and often require multiple stages with prolonged periods of facial immobility. Recent advances in electrode and microcomputer fabrication should allow the substitution of cross-facial nerve grafts with cross-facial electrodes that would have immediate functionality. Electrical stimulation has been shown not only to maintain muscle structure but to reverse atrophy after prolonged denervation. Large animal models have proven the utility of this principle for eye-blink. A more limited implant could be placed to provide dynamic function and to maintain muscle health in patients who are expected to recover, and then the implant could be removed. The infrastructure to monitor and fine-tune such an implant already exists in the audiology world.

Author Contributions

Garrett R. Griffin, background research, writing manuscript, creating figures; **Jennifer C. Kim**, background research, editing final manuscript.

Disclosures

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