

Electrical Stimulation and Neuroprostheses for Restoring Swallowing Function

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Introduction

A neuroprosthesis is an electrical stimulator device that provides short bursts of electrical impulses to the nervous system to produce sensory and/or motor functions. Over the past four decades, neuroprostheses for a wide variety of applications have been developed. Some have achieved great success, such as cochlear implants for the hearing impaired (Lenarz, 1998; Gstoettner, Adunka, Hamzavi, & Baumgartner, 2000; Higgins, Chen, Nedzelski, Ship, & McIlmoyl, 2002) and bladder management stimulators (Rijkhoff, Wijkstra, van Kerrebroeck, & Debruyne, 1997; Schurch, Rodic, & Jeanmonod, 1997), which are produced in large volume worldwide. Other neuroprostheses, such as those for upper limb function (Smith, Peckham, Keith, & Roscoe, 1987; Ijzerman et al., 1996; Adams, Takes, Popovic, Bulsen, & Zivanovic, 2003) and lower limb function (Graupe, Davis, Kordylewski, & Kohn, 1998; Taylor et al., 1999), have not yet matured to a level that creates a significant consumer demand. In the field of dysphagia rehabilitation, neuroprostheses have had very little impact to date. Attempts to develop electrical stimulation devices for assisted swallowing have been few, however, researchers have begun building a foundation for future developments. In this article, we discuss neuroprosthesis technology in general terms, and then we discuss the research that has been carried out on electrical stimulation for assisted swallowing, focusing on the poten-

tial role of neuroprostheses in the treatment of chronic dysphagia.

Physiological Overview

In nerve cells, information is coded and transmitted as a series of electrical impulses called "action potentials," which represent a brief change in cell electric potential. Nerve signals are frequency modulated; that is, the number of action potentials that occur in a unit of time is proportional to the intensity of the transmitted signal. An action potential can be elicited artificially by changing the electric potential of a nerve axon by inducing electrical charge into the cell. This process when used to generate useful body functions is termed *Functional Electrical Stimulation* (FES).

Where sufficient electrical current is provided to a nerve cell, localized depolarization of the cell wall occurs, resulting in an action potential that propagates towards the end of the axon; this is termed *orthodromic* propagation. Concurrently, an action potential will propagate backwards towards the cell body, which is termed *antidromic* propagation. Typically, FES is concerned with orthodromic impulses and their use in generating muscle contractions by stimulating motor end plates. Until recently, antidromic impulses were considered a useless side effect of FES. However, there is new interest in the potential role of antidromic impulses in neural rehabilitation (Rushton, 2003).

The placement of electrodes is very important, because it will determine which nerves are stimulated and, consequently, which muscles will contract. A site on the skin where an active electrode will elicit a contraction of a certain muscle is called a *motor point*. A second electrode located nearby is necessary to complete the electrical circuit. In some primitive FES systems, this second electrode may stimulate muscles if it is located on a motor point as well. Another way to activate muscles is to stimulate the ascending axons of sensory neurons that trigger reflex arcs or possibly contribute to cortical motor reorganization. The case where electrical stimulation is used to stimulate sensory neurons and, thereby, alter reflexes or central nervous system functions is described by the term *neuromodulation*.

Technology

Neuroprostheses come in many different shapes and sizes and serve many different purposes. The common components in all neuroprostheses are: (a) a power source, (b) a stimulus generator, (c) a user-control interface, and (d) electrodes. Most modern neuroprostheses use batteries, disposable or rechargeable, as a power source. Some still use external AC power. Stimulus generators have been miniaturized dramatically over the years. Nowadays, commercial and laboratory-class stimulators tend to be lightweight (less than 1 kg) and handheld. User-control interfaces usually consist of a simple control panel with standard manual con-

trols—such as switches, buttons, dials, and sliders—plus some kind of visual output—such as light emitting diodes or, on more sophisticated models, a liquid crystal display. The most sophisticated neuroprostheses use advanced control techniques with real-time feedback, which requires sensors to provide continuous state feedback, such as goniometers, accelerometers, gyroscopes, and so on.

FES signals typically consist of a train of pulses. In most applications, the duration of each pulse ranges from 50 to 300 ms. The strength of an induced muscle contraction can be modulated by increasing or decreasing the pulse width, which is directly related to the number of nerve cells recruited. Recruitment can also be modulated by increasing and decreasing the stimulation current. Higher levels of current will penetrate the nerve deeper and create action potentials in more nerve cells, resulting in more forceful contractions. A third way to modulate contractile force is to alter the stimulation frequency (i.e., the number of pulses delivered per second). Frequencies below 5 Hz will only generate small twitches; higher frequencies will result in more forceful contractions, because the twitches overlap and sum up. At 50 Hz, the contraction becomes maximal or *tetanic*, and further increases in frequency will not produce greater muscle forces. The selection of appropriate stimulation parameters is of great importance for any neuroprosthesis, because these parameters will determine the number of nerve cells recruited and the intensity of the generated signals.

Nerves can be stimulated using either surface (transcutaneous), percutaneous, or implanted electrodes. *Surface electrodes* contact the skin. They are non-invasive, easy to apply, and generally inexpensive. However, due to the impedance of the skin and dispersion of current,

much higher intensity signals are required than with subcutaneous electrodes. Current amplitude typically ranges from 10-150 mA in surface stimulation, depending on the application. One limitation is that some nerves, for example those innervating the hip flexors, are too deep to be stimulated by surface electrodes. *Percutaneous electrodes* consist of thin wires, which are inserted through the skin and into muscular tissue, remaining in place for a temporary period of time. In percutaneous stimulation, current amplitude is rarely higher than 25 mA. The third class of electrodes is *implanted electrodes*, which are permanently implanted by surgery. Compared to surface electrodes, implanted and percutaneous electrodes potentially have higher stimulation selectivity with much less electrical charge applied, both being desired characteristics of FES systems. The drawback is that implants require a lengthy, invasive surgical process to install and percutaneous electrodes can be used only temporarily and may cause infection at the site of penetration.

There is a miniature brand of electrode called the BION™ that can be implanted via hypodermic needle (Loeb, 2002). They are cylindrical in shape with a diameter of 2mm and a length of 15mm. Once implanted, they are powered and controlled via radio waves from an external controller that can be worn by the patient.

Swallowing

To date, few neuroprostheses for assisted swallowing have been proposed or implemented (Grill, Craggs, Foreman, Ludlow, & Buller, 2001). Some preliminary studies have been carried out to assess the feasibility of electrical stimulation in the treatment of chronic dysphagia, but results are suggestive at best. The major problems with the proposed neuroprostheses are that they use very primitive forms of elec-

trical stimulation and do not aim to produce specific muscle actions that contribute to the dynamic process of swallowing.

In a pilot study, Park, O'Neill, and Martin (1997) attempted to apply neuromodulation to facilitate the swallowing reflex. They built a very simple neuroprosthesis that consisted of an appliance worn on the palatal surface. A continuous train of electrical pulses was delivered to the soft palate via a pair of electrodes at 1 Hz (very low frequency), with a pulse width of 200 ms and current intensity ranging from 0.5 to 39.5 mA, depending on the user's tolerance. In this manner, the researchers were attempting to facilitate the swallow reflex. The stimulation was well tolerated by all four stroke subjects who participated with no serious adverse effects. The researchers presented somewhat positive results, concluding that swallowing may be facilitated by FES applied to the soft palate, but that further research would be necessary. Unfortunately, this study was never followed up.

It is interesting that Park and colleagues chose to stimulate the soft palate continuously, as opposed to synchronizing the stimulation with the movement of a bolus. The approach used suggests that continuous, twitch-like stimulation of the soft palate can heighten the sensitivity of the swallow reflex, but there is no physiological theory to support this. What effect this mode of electrical stimulation has on the nervous system is entirely unknown.

Freed, Freed, Chatburn, and Christian (2001) devised another system in which a pair of surface electrodes located on the neck delivered electrical pulses at 80 Hz and 300 ms continuously. Current intensity ranged from 2.5 to 25 mA, depending on the subject's tolerance. The electrodes were placed in one of two configurations: one electrode above the lesser horns of the

hyoid bone and the other roughly 4 cm below it; or both electrodes above the lesser hyoid bones bilaterally. The digastric and thyrohyoid muscles likely received direct stimulation from this electrode placement. The neuroprosthesis was applied as an intervention for 60 minutes per day and was tested against another intervention: thermal-tactile stimulation (Lazzarra, Lazarus, & Logemann, 1986). While the authors reported overwhelming success, their methodology raises serious concerns. The treatment groups were not randomized, and all results were based on a subjective outcome measure that has never been validated. A 2-channel version of the neuroprosthesis described by Freed et al. has been commercialized as the VitalStim™, and has received approval from the Food and Drug Administration.

In the two previous studies discussed, FES was applied at a constant frequency and pulse width, the values of which were probably chosen arbitrarily. The effect of varying stimulation frequency, intensity, and duration was examined by Fraser and colleagues (2002). Their system delivered FES to the pharynx via a pharyngeal catheter equipped with electrodes. Frequencies of 1, 5, 10, 20, and 40 Hz were used; stimulation intensities of 25, 50, and 75% of maximum tolerance were used; and stimulation duration was tested up to 150 minutes. Two of the 8 healthy subjects experienced occasional twitch contractions during stimulation. The researchers demonstrated using functional magnetic resonance imaging and transcranial magnetic stimulation that neuromodulation of the pharynx resulted in reorganization of the cortical projection to swallowing muscles. They also showed that the excitability depends on the stimulation parameters; this has functional relevance for voluntary swallowing movements. These results suggest that there is potential for neuromodula-

tion in the pharynx to stimulate cortical motor reorganization. How this can be harnessed to bring about recovery of swallowing function is not known.

So far, almost all neuroprostheses for restoring swallowing function use continuous stimulation with no feedback. Leelamanit, Limasakul, and Geater (2002) introduced the first neuroprosthesis for assisted swallowing that uses feedback control to synchronize the electrical stimulus with activity of the tongue. It consists of three surface electrodes placed on the neck and ear to record an electromyogram (EMG) of the posterior tongue, and two stimulation electrodes placed over the thyrohyoid muscle. The device detects when swallowing is initiated by monitoring the EMG signal, and then the two electrodes on the neck deliver FES at 60 Hz to the thyrohyoid muscle, causing laryngeal elevation. The stimulus intensity is controlled by voltage instead of current (an outdated stimulation method). The pulse width was not reported. Twenty of the 23 patients who used the device for 4 hours per day improved their swallowing. Unfortunately, some weaknesses in the design of this study (i.e., selective recruitment, subjective outcome measure) do not permit strong conclusions to be drawn.

A more recent study looked at different muscle recruitment strategies for augmenting laryngeal elevation via FES (Burnett, Mann, Cornell, & Ludlow, 2003). It was concluded that stimulating the mylohyoid and the thyrohyoid each bilaterally (or both ipsilaterally) increased the laryngeal elevation and the swallow velocity compared to stimulation of any muscle by itself.

Conclusions

The first modern FES devices were developed over 40 years ago; since then there has been a great deal of innovation resulting in scores of new neuroprostheses for

different applications. The most successful of these technologies, in terms of consumer acceptance, are cochlear implants: More than 30,000 units have been implanted worldwide. Bladder management stimulators have also achieved wide acceptance, but not quite to the same degree.

The use of neuroprostheses for restoring swallowing function in patients with chronic dysphagia is a very new technology that currently lacks a significant scientific foundation. It appears that there is a potential role for neuromodulation in improving swallowing function based on the evidence of cortical motor reorganization (Fraser et al., 2002). However, much research remains to be done to understand how this can be exploited clinically. There is also significant potential for neuroprostheses that augment swallowing function by directly stimulating the muscles involved in swallowing. Neuroprostheses for assisted swallowing may someday contribute to multidisciplinary interventions that combine several therapeutic modalities.

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Therese O'Neil-Pirozzi, Column Editor

Student Abstracts

The purposes of this Student Abstracts column are:

1. To provide a mechanism for Division 13 affiliates to be updated on recent quality field-related research, and
2. To provide graduate students with an opportunity to identify a recent swallow-related research article of interest, review it, and abstract if for the division affiliates.

To date, abstracts have been published from students attending Arizona State University, Eastern Washington University, Edinboro University of Pennsylvania, Florida International University, Florida State University, George Washington University, Illinois State University, Louisiana State University Health Sciences Center (New Orleans), Louisiana State University Health Sciences Center (Shreveport), Louisiana Tech University, Northeastern University, Northern Arizona University, Southeastern Louisiana University, Southern Illinois University, Teachers College-Columbia University, University of Central Arkansas in Conway, University of Kansas, University of Memphis, University of New Hampshire, and University of Wisconsin-Madison. **Please invite all of the graduate students who you teach and/or supervise** to consider taking advantage of this opportunity. The abstract guidelines are as follows:

1. Select a quality swallowing related experimental/prospective research article that has been published within the past 12 months;
2. Select an article from any journal other than *Journal of Speech, Language, and Hearing Research* and *American Journal of Speech-Language Pathology: A Journal of*