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Kinematics of Electrically Elicited Eyelid Movement

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***Abstract*—Electrical stimulation has demonstrated potential for reanimating eye blink following facial paralysis caused by damage to the seventh cranial nerve. This study investigated the kinematics of lid movement caused by electrical stimulation of the orbicularis oculi muscle in both normal rabbit and rabbit with surgically induced seventh nerve lesion.**

I. Introduction

SEVENTH nerve damage or dysfunction often leads to paralysis of the facial musculature. This can result from a variety of etiologies, some of which demonstrate the potential for recovery and some of which lead to chronic impairment [1]. Clinically, the most significant effect of seventh nerve lesion is paralysis of the orbicularis oculi muscle, which results in loss of the ability to blink the eye [2]. Because eyelid closure is the primary mechanism for protecting and lubricating the eye, functional deficits can lead to corneal damage, infection, perforation, and loss of the eye. Current methods for maintaining eye health following facial paralysis include the use of gold weights for attachment to or implantation in the eyelid, the implantation of mechanical springs, the use of artificial tears, nerve and muscle transfer, and tarsorraphy [3]–[7]. All of these methods can help to preserve the eye, however, none of these techniques, even used in combination, are fully effective. Additionally they are often inconvenient and cosmetically unacceptable. Electrical stimulation may be able to provide a more elegant and effective method for restoring eyelid function, but in order to assess its potential a thorough understanding of the lid response is needed.

The ability to elicit eye blink using electrical stimulation of the orbicularis oculi muscle has been demonstrated in both dog and rabbit [8]–[14]. This has been performed in both normal animals and animals with surgically induced orbicularis paralysis. Until recently, quantitative analysis of lid closure due to electrical stimulation had not been reported [14]. The methods used to quantify lid closure are adaptable to studies of lid movement over time.

Normal eyelid movements have been studied extensively and their kinematics have been widely reported [15]–[25]. Studies have included a variety of species (human, cat, rabbit, and guinea pig) and types of response (voluntary, spontaneous, reflex, and conditioned), and have even included patients with varying degrees of facial nerve palsy. To our knowledge, however, this is the first study to investigate the kinematics of eyelid closure associated with electrical stimulation of the orbicularis oculi muscle. These results are relevant to the overall understanding of the nature of lid movement caused by electrical stimulation and its potential for restoring an effective and natural-looking blink following facial paralysis.

II. Methods

The orbicularis oculi muscle was paralyzed in 12 rabbits by sectioning the seventh cranial nerve. Three rabbits were paralyzed for each of the following durations: 1 week, 4 weeks, 8 weeks, and 16 weeks. In addition, 3 normal, non-paralyzed rabbits were used for comparison. At the end of the specified period, each rabbit was anesthetized and an electrode was inserted into the upper eyelid such that platinum metal contacts were positioned in the subcutaneous space near both the medial and lateral canthus. Biphasic, current controlled stimulation pulses were delivered through the electrode and a high-speed digital video camera was used to record the response of the eyelid to stimulation. Image-processing software was used to quantify lid movement over time.

A. Dissection of the Seventh Cranial Nerve

The seventh cranial nerve was identified and divided to create paralysis of the orbicularis oculi muscle. With the rabbit under anesthesia, a 1cm vertical incision was made through the skin, 1cm inferior to the center of a line drawn from the lateral canthus to the external auditory meatus and just anterior to the mandibular ramus. A combination of sharp and blunt dissection was used to divide the subcutaneous tissue and the parotid gland, revealing the facial nerve trunk and its three large branches adjacent to the surface of the masseter muscle. Stimulation of the intact nerve with a 0.5ms, 1mA biphasic current pulse produced simultaneous eye closure and ear movement. A 7mm section of the nerve and its branches were removed and both ends were cauterized. Complete interruption was confirmed by observation of only ear movement with stimulation of the proximal stump and only eye blink with stimulation of the distal nerve.

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B. Verification of Paralysis

Persistence of paralysis was verified at regular intervals and immediately prior to electrode insertion by observing the rabbit's response to a light touch of the cornea with the tip of a cotton swab. Normal eyelids demonstrated smooth and complete closure of the palpebral fissure with little or no eye retraction, while paralyzed eyelids demonstrated substantial eye retraction accompanied by narrowing of the palpebral fissure and lateral sliding of the nictitating membrane. This movement is consistent with the expected reaction after facial nerve section when the retractor bulbi muscle is left intact [19]. Eye health was maintained during paralysis by the retractor bulbi and nictitating membrane, which acted in combination to provide adequate protection and lubrication.

C. Electrode Placement

With the rabbit under anesthesia, a cutaneous stab incision was made, approximately 5mm lateral to the lateral border of the upper eyelid. A 14-gauge angiocatheter was inserted through the stab incision and subcutaneously advanced across the length of the upper eyelid, 2mm superior to the lid margin. The stylet of the angiocatheter was removed, and a stimulating electrode (Spencer Probe, Ad-Tech Medical Instrument Corporation, Racine, WI) was threaded through the lumen of the angiocatheter. The angiocatheter was withdrawn leaving the electrode in the subcutaneous space of the eyelid. An anchoring suture was used to secure the electrode to the rabbit's skin 2cm lateral to the entry site. See Fig. 1 for a diagram of electrode placement.

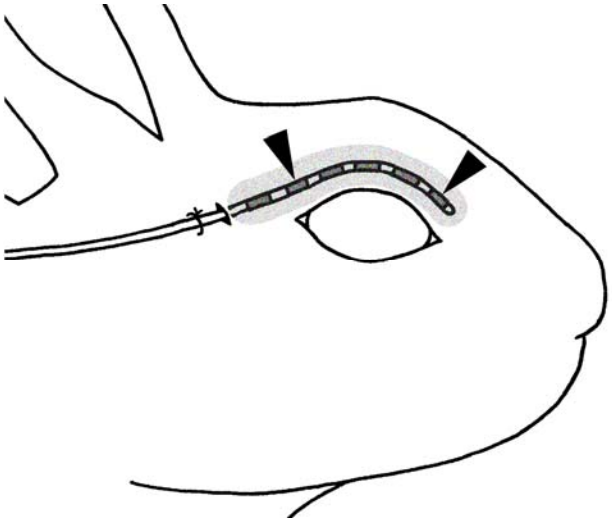

Fig. 1. Diagram of stimulating electrode inserted into the upper eyelid of a rabbit and secured with an external suture. The first and fifth contacts (indicated by arrows) were used for stimulation.

The stimulating probe was 1mm in diameter and included six 2.3mm long cylindrical platinum contacts spaced at 5mm intervals. The first and fifth contacts were used to deliver stimulation pulses, giving a dipole spacing of approximately 2cm.

In addition to the stimulated rabbits, two normal rabbits received sham implants in order to evaluate whether the presence of an implanted electrode would substantially affect eyelid closure. Following implantation, these rabbits were allowed to heal and later observed to qualitatively gauge the degree to which the sham implant affected normal lid closure during spontaneous and air-puff induced reflex blinks.

D. Electrical Stimulation Protocol

With the rabbit under anesthesia, biphasic square wave current pulses were delivered through the implanted electrode using a multifunction DAQ (PCI-6025E, National Instruments Corporation, Austin, TX) and analog stimulus isolator (Model 2200, A-M Systems, Inc., Carlsborg, WA).

The stimulation protocol was divided into three phases:

1) Thresholds for generating lid twitch were measured over a range of pulse widths from 0.1 to 100ms per phase.
2) Single biphasic pulses with amplitudes ranging from 1 to 7mA were delivered with pulse widths ranging from 0.5 and 100ms per phase.
3) Trains consisting of 5 and 10 pulses with amplitudes ranging from 1 to 7mA and pulse widths ranging from 0.5 to 10ms per phase were delivered at a rate of 50Hz.

Trials for individual parameter settings were separated by 20s. The electrode current was monitored to ensure that the stimulator compliance voltage did not limit output. During the experiments, it was determined that the maximum current that could be consistently delivered was slightly above 7mA.

E. Blink Recording and Data Analysis

A high-speed video camera (1M75-SA, Dalsa Corporation, Ontario, Canada) was used to record the response of the eyelid to stimulation. Video was captured with a resolution of 0.083mm and recorded at a rate of 192 frames/second. An interface was created using LabVIEW (National Instruments Corporation, Austin, TX) to coordinate the recording of video and delivery of stimulation pulses. Measurement of eyelid separation was automated using National Instruments, Vision Assistant software. A grayscale threshold value was set that allowed the exposed area of the pupil and iris to be automatically isolated from the rest of the image by the nature of their color contrast. The height of the exposed area was measured along a vertical axis crossing through the center of the pupil, giving a value for lid separation in terms of pixels. This was repeated for each frame and normalized with respect to lid separation prior to stimulation.

III. Results

Strength-Duration curves for twitch thresholds indicated that rabbits demonstrated persistent denervation at 1 and 4 weeks, but demonstrated evidence of at least partial reinnervation at 8 and 16 weeks (see Sachs *et al.* for more

detail) [14]. For comparison purposes, rabbits were therefore grouped into the following categories: *normal*, *denervated* (1-week and 4-week rabbits), and *reinnervated* (8-week and 16-week rabbits). Rabbits within each of these groups demonstrated similar movement characteristics as a result of stimulation (i.e. 1-week rabbits demonstrated a similar response to 4-week rabbits, and 8-week rabbits demonstrated a similar response to 16-week rabbits).

Eyelid movement in response to single biphasic pulses is shown in Fig. 2 as a function of time. Pulse amplitude was fixed at 5mA for pulse widths ranging from 0.5 to 100ms per phase. Data presented are averages within each group for a single biphasic stimulus.

Eyelid movement in response to trains of biphasic pulses is shown in Fig. 3 as a function of time. Pulse amplitude was fixed at 5mA and pulse width was fixed at 10ms per phase for single pulses and trains of 5 and 10 pulses. Data presented are averages within each group for a single

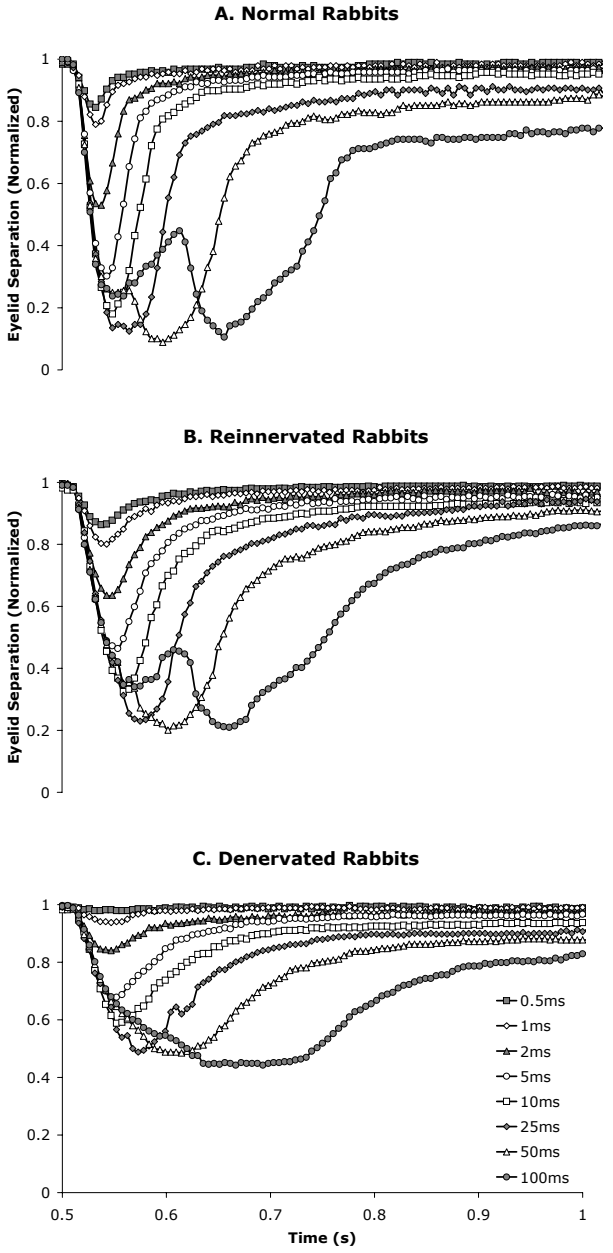

Fig. 2. Plots of eyelid response to single symmetric biphasic current pulses delivered with amplitude 5mA for A) normal rabbits, B) rabbits demonstrating evidence of reinnervation, and C) rabbits demonstrating evidence of persistent denervation. Pulses were initiated at *Time* = 0.5s. Pulses are listed according to *duration per phase*. Legend and axis labels apply to all plots. Normalized value of 1 is equivalent to maximum eyelid separation prior to stimulation and 0 is equivalent to complete closure.

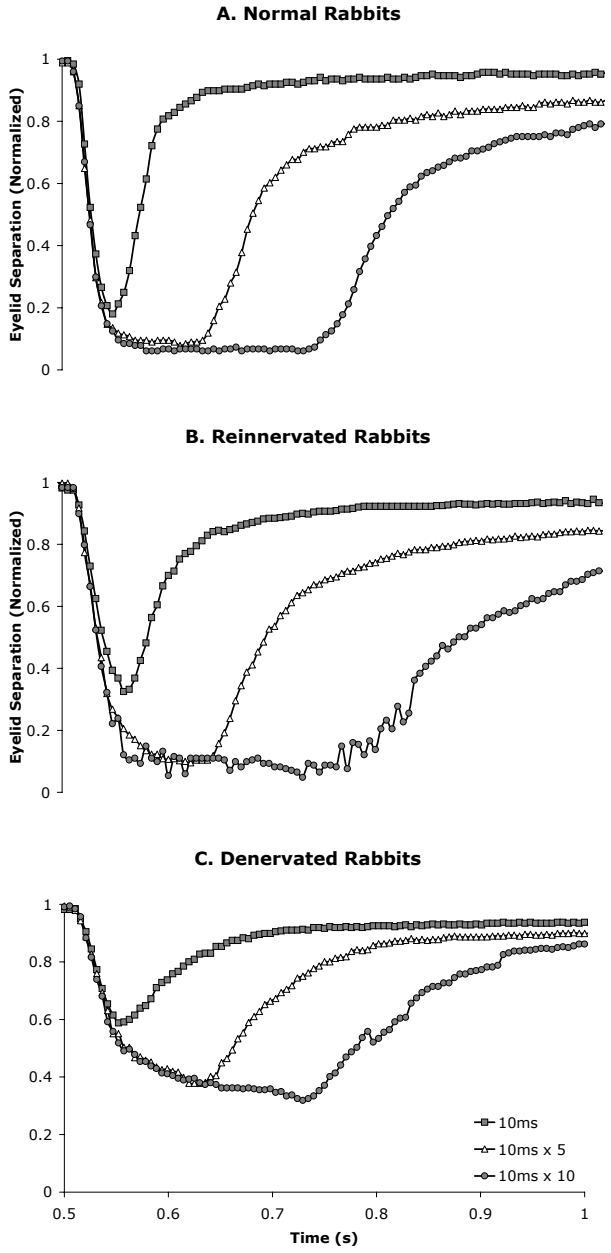

Fig. 3. Plots of eyelid response to trains of symmetric biphasic current pulses delivered with amplitude 5mA at a rate of 50Hz for A) normal rabbits, B) rabbits demonstrating evidence of reinnervation, and C) rabbits demonstrating evidence of persistent denervation. Pulses were initiated at *Time* = 0.5s. Pulses are listed according to *duration per phase* x *number of pulses*. Legend and axis labels apply to all plots. Normalized value of 1 is equivalent to maximum eyelid separation prior to stimulation and 0 is equivalent to complete closure.

biphasic stimulus or stimulus train.

Qualitative assessment of spontaneous and reflex blinks with sham implants did not indicate a noticeable effect on normal lid closure due to the presence of the implant. Quantitative analysis with sham implants was not performed.

IV. Discussion

A. Comparison Among Groups with Electrical Stimulation

Normal rabbits and rabbits with evidence of reinnervation demonstrated similar kinematics in response to electrical stimulation of the orbicularis oculi, with reinnervated rabbits exhibiting a slight decrease in both closing and opening velocity (as demonstrated by the decreased slope of the response curves). Denervated rabbits demonstrated a much lower closing and opening velocity than the other two groups. This is most evident in the comparison of response to single biphasic pulses with pulse width of 100ms per phase. Independent activation occurred with each phase for all groups, however, the slower kinematics of the denervated rabbits resulted in a synergistic effect while the faster kinematics of the normal and reinnervated rabbits resulted in two nearly independent contractions.

Increases in pulse width and number of pulses did not have a significant effect on closing velocity, as all response curves within each group tended to following the same slope during the closing phase. These did affect the duration of lid movement, however, and therefore the overall amount of closure, with increases in pulse width and number of pulses generally leading to decreases in the amount of eyelid separation at the peak of closure.

B. Comparison with Reported Values for Normal Blinks

Reported values for natural blinks in humans range from approximately 80 to 100ms for the duration of the closing phase and from approximately 150 to 250ms for the duration of the opening phase [23]. These values fall within the range of durations reported here for eyelid movement in response to electrical stimulation of the orbicularis oculi in rabbit.

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