High-frequency blockade of the pudendal nerve using transcutaneous, capacitively coupled electrical stimulation

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Abstract

After spinal cord injury (SCI), external urethral sphincter (EUS) hyperreflexia often develops which can lead to an inability to properly empty the bladder. Short of catheterization and irreversible surgery, few options exist for managing this condition. High-frequency electrical stimulation can produce a reversible block of peripheral nerve conduction, and has been proposed as a way to block unwanted EUS contractions.

We investigated the feasibility of a new stimulation technique using transcutaneous, capacitively coupled electrodes to produce a conduction block of the pudendal nerve (PN). Adhesive surface electrodes were placed over subcutaneous "pickup" electrodes which were connected to nerve cuffs or hook electrodes on the PNs in three isoflurane anesthetized cats. A portion of the current delivered to the surface electrodes is captured by the subcutaneous electrode and routed to the target nerve. Using this "stimulus router system" (SRS), high-frequency stimulation produced graduated blockade of EUS contractions elicited by proximal low-frequency stimulation of the pudendal nerve. The SRS requires no implanted electronics and may aid in the management of EUS dysfunction after SCI.

1. INTRODUCTION

Lower urinary tract (LUT) dysfunction often occurs as a result of SCI and from a wide variety of conditions of both neurogenic and non-neurogenic origin. Normally, the LUT assumes one of two states under the control of supraspinal centers. During continence, active inhibition of the bladder as well as contraction of the bladder neck and EUS allow filling of the bladder without leakage. Alternatively, during micturition, bladder contractions accompanied by relaxation of the EUS allow low-pressure emptying of the bladder. After SCI, concomitant contraction of the bladder and EUS can prevent voiding and can lead to elevated intravesical pressures and upper urinary tract deterioration.

Attempts to develop neural prostheses to restore bladder and sphincter function after SCI have been made [1], however many of the resulting devices have either been ineffectual or poorly tolerated. Recently, some effort in LUT neural prosthesis research has focussed on stimulation of the PN which innervates the urethra and EUS. Stimulation of the PN can improve continence [2], elicit reflexive bladder contractions [3, 4] as well as block EUS contractions when high-frequency stimulation (HFS) is used [5, 6]. We investigated the feasibility of using a new stimulation technique using transcutaneous, capacitively coupled electrodes [7] to produce a conduction block of the PN. This stimulus router system (SRS) uses inexpensive implanted components coupled with an external stimulator capable of delivering high-frequency waveforms. With this system, we demonstrated that HFS of the PN blocks contraction of the EUS.

2. METHODS

Acute experiments were performed in isoflurane anesthetized (2-3% in carbogen, flow rate 1 L/min) male cats (n=3). The trachea was cannulated and connected to a closed loop anesthetic system that monitored respiration rate and ventilated the animal if necessary. Respiration and heart rate were monitored throughout the procedure. The jugular or cephalic vein was catheterized to allow administration of fluids and drugs. Body temperature was maintained using a heating pad.

The bladder was exposed via a midline abdominal incision and catheterized to allow intravesical pressure measurement and the addition and withdrawal of fluids. The PN was

exposed bilaterally by incisions lateral to the base of the tail and by blunt dissection of the ischio-rectal fossa. Bipolar nerve cuffs or hook electrodes (interelectrode spacing 2 mm) were placed on the PN trunks. The electrodes were connected via insulated wire to subcutaneous "pickup" electrodes. The pickup electrodes were either stainless steel disks or Peterson type electrodes. The skin over the pickup electrodes was carefully shaved and adhesive surface electrodes were applied. An indifferent surface electrode was placed some distance away for monopolar stimulation. Alternatively, a second pickup electrode and surface electrode were used with bipolar stimulation (see Fig 1). The surface electrodes were connected to either Neurolog (Digitimer Ltd., Welwyn Garden City, UK) modules NL304 (period generator), NL403 (delay-width), NL510 (pulse buffer) and NL800 (stimulus isolator) for constant current pulses or to a Grass (Grass-Telefactor, West Warwick, RI, USA) S48 stimulator for constant voltage pulses. In addition, nerve cuff electrodes or hook electrodes were placed on the PNs proximal to the SRS electrodes. These electrodes were connected to a Grass SD9 constant voltage stimulator to deliver low-frequency pulse trains (~ 20 Hz).

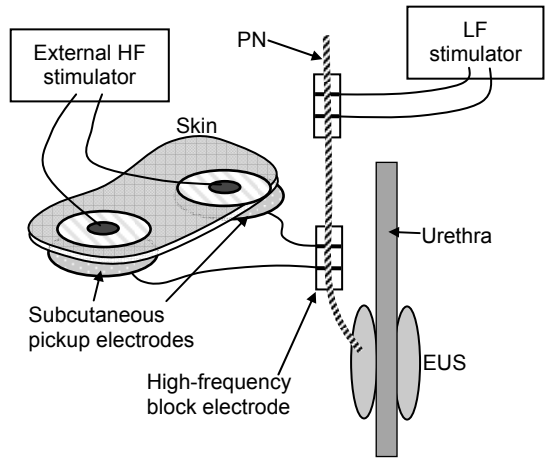

Figure 1. Experimental setup for HFS of the pudendal nerve using the SRS.

Activity of the EUS was determined by measuring intraurethral pressure. Bladder and intraurethral pressure were measured using Neurolog NL108D4/10 domes and NL108T4 isolated pressure transducers. Pressure signals were low-pass filtered and digitized at 100 samples per second using CED Power 1401 (Cambridge, UK) hardware and Signal v2.1. At the end of the experiment, the animals were euthanized with Euthanyl.

3. RESULTS

Figure 2 shows an example of the reduction in intraurethral pressure produced by HFS of the PN using the SRS. EUS contractions, generated using low-frequency stimulation (LFS) (20 Hz) of the proximal pudendal, resulted in intraurethral pressures from 60-80 mmHg. Monopolar HFS (2 kHz, 3 mA) of the distal PN using the SRS resulted in a relaxation of the EUS returning intraurethral pressure to near baseline.

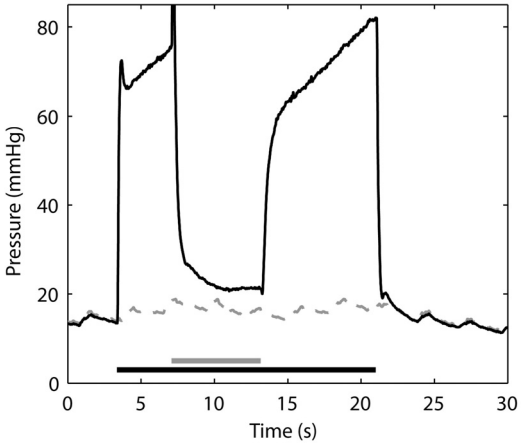

Figure 2. Effect of PN blocking in one animal using HFS. Intraurethral pressure (black line) and bladder pressure (dashed gray line) are shown. Stimulation durations for proximal LFS (black bar) and distal HFS (gray bar) are shown below. LFS was applied proximally on the PN with a monopolar hook electrode directly connected to the stimulus generator. HFS was applied distally on the PN with a monopolar hook electrode connected to a stimulus generator via the SRS. LFS pulse parameters (4 V amplitude, 200 μs pulsewidth and 20 Hz). HFS pulse parameters (3 mA amplitude, 150 μs pulsewidth and 2 kHz).

When stimulation is applied through the surface electrode, 10% - 15% of the current is generally captured by the SRS and delivered to the target [8]. Since the externally applied currents are much higher than what is required to activate peripheral nerve, one concern is whether or not local muscle contractions occur at the site of the surface electrodes. In these animals, high-frequency block could always be attained at amplitudes below the threshold for local contractions.

Figure 3 shows the results obtained in one cat as stimulation frequency and amplitude were varied and the efficacy of the PN block was observed. The efficacy was measured by

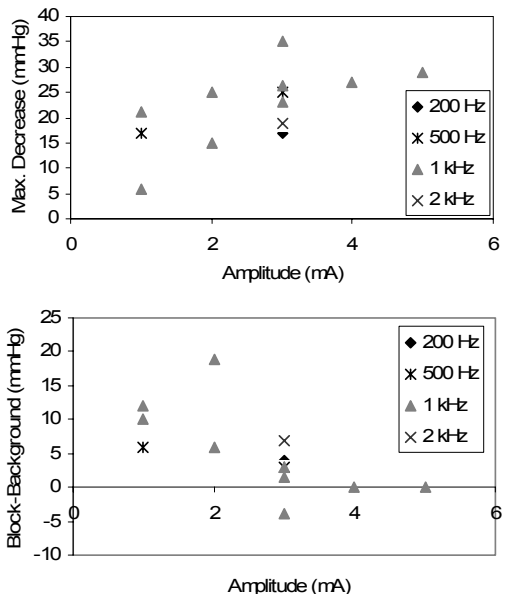

Figure 3. Effect of frequency and amplitude on PN blocking in one animal. (A) Maximum decrease in urethral pressure elicited by stimulation of the PN at different amplitudes and frequencies. (B) Difference between background intraurethral pressure and the intraurethral pressure obtained during HFS. The most complete blocking was achieved with stimulation amplitudes of 3 mA and higher. At stimulation amplitudes of 3 mA, all tested frequencies elicited a nearly complete block.

observing changes in the intraurethral pressure. The maximum decrease in intraurethral pressure (Fig 3A), was defined as the difference between the intraurethral pressure immediately before HFS was applied and the minimal pressure obtained during HFS. Frequencies higher than 2 kHz were not examined, and varying amounts of blocking were observed at different frequencies. Within the frequency range explored, there appeared to be a trend towards larger decreases in intraurethral pressure at higher stimulation amplitudes.

Figure 3B summarizes the effect of stimulation frequency and amplitude on the ability of HFS to return the intraurethral pressure to baseline. This provides a measure of the completeness of the block.

4. DISCUSSION AND CONCLUSIONS

The SRS was successfully used to produce high-frequency conduction block of the pudendal nerve in isoflurane anesthetized cats without local contractions under the surface electrodes. Reductions in intraurethral pressure to baseline or near-baseline levels were achieved, indicating that complete or near-complete conduction block of the PN occurred. The immediate recovery of high intraurethral pressures generated by the proximal LFS suggests that the decreased intraurethral pressure was not due to muscular fatigue.

Optimal stimulation parameters have not yet been determined and frequencies greater than 2 kHz have yet to be explored for PN blocking with the SRS. The issue of potential nerve damage with long term HFS has yet to be addressed.

Since no implanted electronics are required, the implant is both simple and inexpensive. Coupled with an external stimulator, which is not subject to the same practical constraints such as size and power consumption as an implantable stimulator, the SRS could be used to eliminate hyperreflexive EUS contractions that occur after SCI.

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