A Microprocessor-Based Multi-Channel Muscle Stimulator for Skeletal Muscle Cardiac Assist

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ABSTRACT

This paper describes a portable, multichannel skeletal muscle stimulator developed for use in research in skeletal muscle cardiac assist (SMCA). The primary features of the stimulator are that it allows selective stimulation through multiple nerve-cuff electrodes and that arbitrary voltage patterns can be delivered to each electrode. The electrodes are electrically isolated from one another to effect regional (selective) stimulation. Selective stimulation offers greater control over the spatial pattern of muscle stimulation and may allow for increased muscle efficiency during skeletal muscle cardiac assist.

INTRODUCTION

The treatment of heart disease is one of the most important public health issues. A new technique, skeletal muscle cardiac assist (SMCA), is currently being investigated as an alternative to heart transplants. SMCA has inherent advantages due to the use of autologous tissue: there is no danger of tissue rejection, there is no problem with donor shortages, and power requirements are low because skeletal muscle requires only minimal external energy to cause full contraction of the muscle.

In present SMCA practice a single pair of intramuscular leads is woven into the latissimus dorsi muscle (LDM) [1], which then stimulates the entire muscle simultaneously. However, the anatomy of the LDM, which has three indepentently innervated muscle segments (transverse, oblique, and lateral), makes selective stimulation possible. We believe selective stimulation can create more efficient muscle contraction patterns. For example, in cardiomyoplasty, in which the LDM is wrapped around the heart surface, there may be benefit in initiating contraction in the portion of the LDM near the heart's apex, and having this contraction progress towards the heart's base. Similarly, it may be more efficient for a skeletal muscle formed into an accessory skeletal muscle ventricle to contract from apex-to-base [2].

METHODS

Our goal was to design a highly flexible stimulator to be used in testing various modalities of SMCA. The design of our programmable multi-channel stimulator (PMCS) produces arbitrary waveforms on three independent, electrically isolated channels (to stimulate the three distinct regions of the LDM). The stimulator itself is built around a micro-controller (MC68HC11) and is connected to a host computer which runs a user-friendly GUI-based program for developing complex waveforms.

Fig. 1 shows the analog electronics for one channel. Digital outputs D_0, D_1 and D_2 are connected to a three-bit D/A convertor (8 discrete voltage levels); output range is determined by R_5. Analog switches S_1 through S_4 eliminate inter-channel crosstalk, in which current leaks from one channel to another, by disconnecting both anode and cathode from the circuit. With the switches open R_6 provides feedback necessary to keep the op-amp from saturating. With the switches closed R_6 has little affect on the circuit due to the shunting by the much lower resistance of the two analog switches. There may be a significant voltage drop across S_1 due to the large amount of current going to the electrode, but there will be little drop across S_2, since only very small currents go into the feedback network. This ensures that the voltage at the anode will be held constant despite any voltage drop across S_1. A similar scheme is employed at the cathode to keep it at ground potential. Resistors R_8 and R_9 were added solely to protect the CMOS analog switches from static electricity.

The stimulator has three of these circuits to deliver pulses stimultaneously to all three electrodes. Normally the channels are connected (switches closed) to prevent electrode polarization. To activate individual electrodes or pairs of electrodes, unactivated electrodes are disconnected (switches open). For example, if channel 1 is to be activated while channels 2 and 3 remain unactivated, the switches for channel 1 are closed to make the connection and the switches for channels 2 and 3 are opened to break their connection.

RESULTS

The capabilities of the system are outlined in Table 1. The limitations are set by the choice of analog electronics and the microcontroller. Presently, there are no meaningful constraints on the waveforms we can generate. The PMCS was tested in seven canine LDMs. The three branches of the thoracodorsal nerve were isolated and instrumented with bipolar nerve cuff electrodes. The PMCS successfully activated the individual nerve branches of the canine LDM with no cross-talk to the other branches as confirmed by measurement of the regional EMG. EMG activity was measured at 10° increments along an "arc" originating from the lateral border of the LDM as shown in Fig. 2. Results from a representative study are given in Fig. 3 where the RMS value at each measurement site is shown normalized to its maximum value. The legend gives the name of the nerve branch that was being activated. When each electrode was activated, the corresponding muscle region shows EMG activity, while the remaining muscle segments do not show activity.

DISCUSSION

We have developed a portable, highly flexible stimulator for skeletal muscle cardiac assist applications. Though selective stimulation has long been used in functional electrical stimulation, only recently has it been suggested for SMCA. There are preliminary reports of selective stimulation in SMCA applications using mutiple electrodes positioned around the main thoracodorsal nerve branch [2,3]. Our system differs from these in that we position electrodes around each nerve branch so there is no need to "tune" our system after the electrodes are attached.

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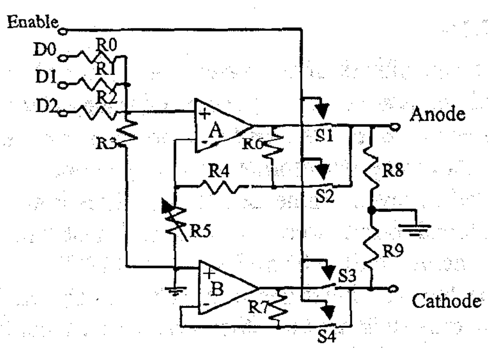

Figure 1. Schematic diagram of analog of electronics.

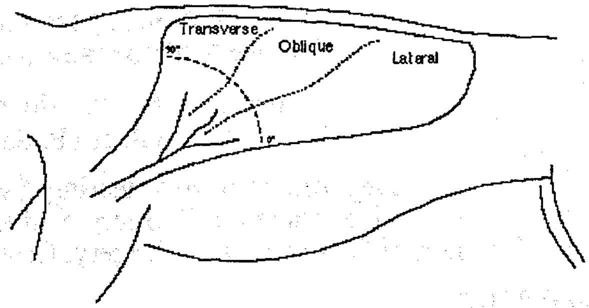

Figure 2. Schematic diagram of latissimus dorsi muscle and neural anatomy. The main branch of the thoracodorsal nerve bifurcates twice into three separate nerve branches. Also shown is the arc over which the EMG signal was recorded to confirm selective stimulation.

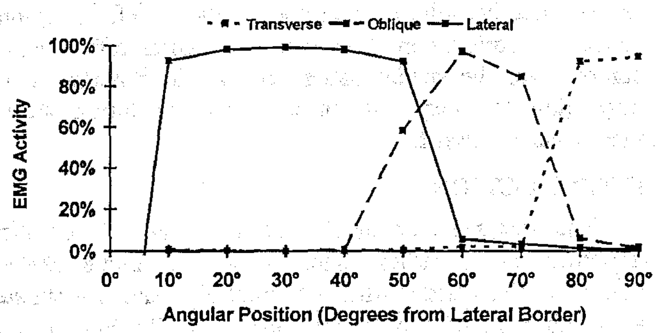

Figure 3. Regional activity measured as a percentage of maximum RMS while the three branches of the thoracodorsal nerve were individually activated.

Table 1: Summary of the capabilities of the programmable multi-channel stimulator.

General	
Number of isolated channels	3
Stimulation mode	constant voltage
Electrode combination	any
Electrode stimulus order	any
Voltage output	12 V (max), 8 discrete levels
Current output	35 mA per channel max
Time resolution	30 µsec (min)
Rectangular-Pulse Stimulus Patterns	
Pulse width	30 µsec (min), 8 µsec
Interpulse interval	30 µsec (min), 8 µsec
R-wave delays	30 µsec (min), 8 µsec
Number of pulses in train	682
Train length	44 seconds (max)
Train repetition rate	Train length + 10 msec
Communication	RS-232 at 9600 baud