Functional Electrical Stimulation of Abdominal Muscles in Spinal Cord Injury: A Review and Synthesis

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Abstract

This paper deals with using functional electrical stimulation (FES) to restore function of upper motor neuron paralyzed abdominal muscles (AM) in spinal cord injury (SCI) for both inspiratory and expiratory function. Cough can be restored or improved by stimulating the AM in concert with an individual’s attempt to cough. Ventilation can be augmented by stimulating AM (FESAM) either in synchrony with naturally occurring expiration, or restored by repetitive cyclic stimulation in artificial ventilation dependent individuals.

1. Introduction and Background

The AM are the major muscles of expiration, and their innervation is diffuse, arising from mainly from thoracic spinal levels and their expiratory function improves with descending level of injury. During quiet breathing expiration is passive, thus the major consequence of expiratory muscle paralysis is reflected in impairment of the ability to cough. This can be treated by either suction or the so-called "manually assisted cough". Inability to cough increases the probability of pulmonary complications which is a major cause of death in this population. The use of FES of AM to restore cough in SCI is discussed in the first section of this paper. Clinical use of a commercially available stimulation system for restoring cough function is still limited at this time.

The most recent study by our group assessed the effects of applying transcutaneous electrical stimulation to paralyzed AM during pulmonary function testing (PFT) of individuals with SCI [4]. In ten male SCI subjects (level between C5 to T7) electrical stimulation was delivered to the AM during expiration in the PFTs forced expiration procedure. Subjects with the lowest percentage of predicted expiratory volumes and flows demonstrated the greatest improvement when electrical stimulation was delivered during forced expiration (Figure 1). The overall increases seen in percent of predicted for the study sample were 23% for forced vital capacity (FVC), 16% for forced expiratory flow in one second (FEV$_1$), and 22% for peak expiratory flow (PEF) [4].
Figure 1. Results of Standard Pulmonary Function Test under volitional (solid) and stimulated (dotted) conditions. Note increase in peak flow and Forced Vital Capacity when stimulation is applied.

There is a commercially available unit for electrical stimulation of AM to restore cough ("Quik-Coff"™, http://www.bandb-medical.com). The use of FES of AM during PFT is still in experimental phase.

### 3. Ventilation

The basis for our work is illustrated in figure 2. The traces show the time course of phrenic nerve activity, FESAM and lung volume under three conditions. Trace “a” represents a neurologically intact individual under normal resting conditions. Lung volume increases from FRC to FRC+VT during inspiration. Expiration is passive, and lung volume returns to FRC. Trace “b” represents an individual with reduced VT, the trace is essentially identical to trace “a”, except the VT is not as great. Trace “c” shows the effect of applying electrical stimulation to the individual with trace “b”. As the stimulation is applied, the expiration is enhanced, and driven below “normal” FRC down to the limit of RV. Then assistance to next inspiration occurs (light gray line between RV and FRC) due to elastic recoil of the chest, so that in theory, a normal tidal volume (VT) is achieved.

Our first study presented the feasibility of FESAM in neurologically intact subjects in synchrony with naturally occurring expiration.

![Figure 2](image-url) Figure 2: Schematic diagram indicating basis for FESAM to augment ventilation.

Frequency of respiration and VT were increased during periods of FESAM [5].

In our second study ventilation in neurologically intact subjects and SCI subjects with injury levels between C4 and C7 showed that pulmonary ventilation was augmented in both groups predominantly due to an increase in VT. Average increase in VT during FESAM for the neurologically intact group was 350 ml while in the SCI group it was 220 ml. The FESAM caused active volume decreases in both the lower thorax and upper abdomen which together appears to be the mechanism behind the increases seen in VT. The results indicate that FESAM should be more thoroughly explored as a potential technique of ventilatory support in SCI. The results also point to the necessity for further studies of maintaining the condition of the chest wall in the pulmonary rehabilitation of individuals with tetraplegia [6].

The most recent study by our group investigated whether FESAM could maintain pulmonary ventilation at clinically acceptable levels in individuals with SCI who are unable to breathe spontaneously [7]. Three individuals with complete SCI were studied; two were on mechanical ventilation (MV), one used mechanical ventilation, but also had an implanted phrenic nerve stimulator (PNS). Stimulation was applied with stimulator using self-adhesive electrodes in order to stimulate the rectus abdominis and lateral group of AM. The trains of pulses were delivered one second in duration at a breathing frequency of 20 breaths/min. Oxygenation was monitored with a pulse oximeter, with lowest acceptable saturation value of 0.92, when FESAM would be terminated and the patient re-connected to MV. Figure 5 shows data from a single individual on mechanical ventilation, who was supported briefly by FESAM alone. The upper trace represents flow with clear evidence of lower breathing rate
during MV (11 breaths/min), and higher one during FESAM (20 breaths/min). The middle trace represents volume changes: during MV changes of volume are above resting level (FRC), whereas during FESAM the volume changes are below FRC. More simply MV causes inflation of the trunk, while FESAM squeezes it. The lower trace represents stimulation pulse trains of 1 sec. duration. Figure 3 is a key demonstration of the feasibility of FESAM technique in subject without spontaneous breathing.

4. Discussion and Conclusions

Our studies have presented sufficient evidence that FES can improve cough in some individuals with SCI, and a special purpose stimulator to produce cough is now available. This technique appears to be emerging for daily management of patient with inability of adequate bronchial toilet. What is needed now is a long-term longitudinal study to determine clinical value of using stimulated cough.

Mechanical ventilation still remains the “gold standard” of ventilatory support in SCI patients with insufficient ventilation. There is another option (PNS), but only a limited number of individuals with SCI can use this technique [8].

Our research in the application of FESAM for ventilatory support shows clinical potential, but further research and development is needed. If the technique of combining phrenic nerve and FESAM could be firmly established as workable, one can envision an implanted system somewhat similar to the cardiac pacemaker: some parameter(s) associated with respiratory function is (are) monitored, and stimulation is delivered at the appropriate time to produce ventilation to ensure that it is adequate to the bodily demands. FESAM could also upgrade the present technique of MV or PNS as it might lower parameters of ventilation or change air distribution in the lungs.

For advanced clinical treatment of ventilatory dependent individuals with SCI, these findings should be further researched, developed and exploited, especially in combination with phrenic nerve stimulation, and/or mechanical ventilation techniques.

5. References