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Original Research

Functional Magnetic Stimulation of Inspiratory and Expiratory Muscles in Subjects With Tetraplegia

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Abstract

Background: Respiratory complications are major causes of morbidity and mortality in persons with a spinal cord injury, partly because of respiratory muscle paralysis. Earlier investigation has demonstrated that functional magnetic stimulation (FMS) can be used as a noninvasive technology for activating expiratory muscles, thus producing useful expiratory functions (simulated cough) in subjects with spinal cord injury.
Objective: To evaluate the effectiveness of FMS for conditioning inspiratory and expiratory muscles in persons with tetraplegia.
Design: A prospective before and after trial.
Setting: FMS Laboratory, Louis Stokes Cleveland VA Medical Center, Cleveland, OH.
Participants: Six persons with tetraplegia.
Method: Each subject participated in a 6-week FMS protocol for conditioning the inspiratory and expiratory muscles. A magnetic stimulator was used with the center of a magnetic coil placed at the C7-T1 and T9-T10 spinous processes, respectively. Pulmonary function tests were performed before, during, and after the protocol.
Main Outcome Measurements: Respiratory variables included maximal inspiratory pressure (MIP), inspiratory reserve volume (IRV), peak inspiratory flow (PIF), maximal expiratory pressure (MEP), expiratory reserve volume (ERV), and peak expiratory flow (PEF).
Results: After 6 weeks of conditioning, the main outcome measurements (mean $\pm$ standard error) were as follows: MIP, 89.6 $\pm$ 7.3 cm H_2O; IRV, 1.90 $\pm$ 0.34 L; PIF, 302.4 $\pm$ 36.3 L/min; MEP, 67.4 $\pm$ 11.1 cm H_2O; ERV, 0.40 $\pm$ 0.06 L; and PEF, 372.4 $\pm$ 31.9 L/min. These values corresponded to 117%, 107%, 136%, 109%, 130%, and 124% of pre-FMS conditioning values, respectively. Significant improvements were observed in MIP ($P = .022$), PIF ($P = .0001$), and PEF ($P = .0006$), respectively. When FMS was discontinued for 4 weeks, these values showed decreases from their values at the end of the conditioning protocol, which suggests that continual FMS may be necessary to maintain improved respiratory functions.
Conclusion: FMS conditioning of the inspiratory and expiratory muscles improved voluntary inspiratory and expiratory functions. FMS may be a noninvasive technology for respiratory muscle training in persons with tetraplegia.

Introduction

Respiratory complications are among the most common causes of morbidity and mortality in persons with spinal cord injury (SCI), especially among those with cervical and higher thoracic injuries [1-3]. These complications arise partly as a result of the loss of supraspinal control over inspiratory and expiratory muscles caused by a high-level SCI [4-7]. Consequently, subjects with chronic cervical SCI typically show abnormalities in inspiratory and expiratory patterns of ventilation consistent with restrictive respiratory dysfunction [8], thus predisposing them to respiratory tract complications. Major inspiratory muscles include the diaphragm (C3-C5), external intercostal muscles (T1-T6), and accessory muscles of the shoulder and the upper back, whereas major expiratory muscles include the abdominal muscles (T7-L1) and internal intercostal muscles. When the spinal cord is damaged, the respiratory muscles below the level of injury become paralyzed and are devoid of supraspinal control [8]. With complete injuries above C3, paralysis of all muscles involved with respiration may occur; this type of injury requires immediate and ongoing ventilatory support to sustain life. Subjects

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with complete injuries at levels between C3 and C5 (innervation of the diaphragm) may lose respiratory muscle activities at or below the level of injury, while maintaining partial voluntary diaphragmatic muscle function. These persons initially may require mechanical ventilatory support; some eventually may be weaned off this support. In persons with a complete SCI between levels T1 and T6, the intercostal volitional function may be impaired or lost, which may contribute to a modest decrease in inspiratory capacity with loss of expiratory capacity and ability to cough. Persons with a complete SCI between levels T7 and T12 will have relatively normal inspiratory function, but their expiratory capacity and ability to achieve an effective cough are impaired [9].

In persons with an SCI, respiratory dysfunction, measured by pulmonary function tests, is considered a restrictive lung disease. A restrictive lung disease is a breathing disorder resulting from impairment of the elastic properties of the lung and chest wall and marked by static or reduced lung volumes and capacities [6,10]. Subjects with cervical SCI have paralysis of both inspiratory and expiratory muscles and therefore have a marked reduction of vital capacity, little or no expiratory reserve volume (ERV), and an inspiratory capacity equivalent to vital capacity [11,12]. Decreases in both maximum inspiratory pressure (MIP) and maximum expiratory pressure (MEP) also indicate the impairment of respiratory muscle functions.

Functional electrical stimulation of the respiratory muscles has been demonstrated in subjects with chronic SCI [13]. Phrenic nerve pacing has been used clinically to assist with ventilation in conditions associated with bilateral diaphragm paralysis, such as in persons with high cervical SCI [14]. Upper intercostal muscle pacing via ventral root stimulation also has been demonstrated to generate large inspiratory volumes in dogs [15-17] and in humans [18]. Similarly, direct stimulation of the upper intercostal muscles using intramuscular electrodes in dogs also resulted in significant inspiratory volumes [19]. Functional electrical stimulation of the lower intercostal nerves via ventral roots in dogs [20] and in persons with cervical SCI [21] were demonstrated to produce significant expiratory pressure and flow rate. Direct abdominal muscle stimulation in persons with SCI also resulted in significant expiratory pressure and flow rate [22].

Functional magnetic stimulation (FMS) can be defined as a technique that uses magnetic stimulation to produce useful bodily function. Advances in magnetic stimulator technology have provided investigators with a tool to noninvasively stimulate deep tissues such as the brain, spinal nerves, and other deep peripheral nerves. Magnetic stimulation of the phrenic nerves [23,24], upper intercostal nerves [25], and lower intercostal nerves [26-29] has been demonstrated in our laboratory. In a study of animals [24], we demonstrated that FMS of the phrenic nerves produced substantial inspiratory volume and pressure by placing a round magnetic coil (MC) at the carotid triangle and at the C6-C7 spinous processes, respectively. In another study of animals [25], functional magnetic ventilation was achieved for 2 hours in dogs with C2 spinal cord transection. Tidal volumes generated by FMS ranged from 0.25 to 0.75 L during 2 hours of ventilation. Mean blood Pa_{CO_2} increased from the baseline of 33.2 $\pm$ 0.1 mm Hg to 80.9 $\pm$ 6.1 mm Hg. In a study of humans [26], FMS of upper intercostal nerves resulted in significant inspiratory pressure, which was consistent with the aforementioned study with animals [24]. Magnetic stimulation of the lower thoracic nerves was applied in healthy persons [26,27] and in persons with SCI [28], which produced substantial expiratory pressure, volume, and flow rate. In an expiratory muscle training study, a 4-week FMS conditioning protocol of expiratory muscles was performed by stimulating lower thoracic nerves in persons with SCI [29]. The results showed significant improvements in voluntary maximal expiratory pressure (116%), volume (173%), and flow (123%) compared with their baseline data.

The purpose of this study was to evaluate the effectiveness of FMS conditioning on inspiratory muscles and expiratory muscles in persons with tetraplegia. The success of this study may offer a noninvasive alternative to condition the respiratory muscles, thus potentially preventing respiratory complications and improving health and quality of life.

Methods

Six men with cervical SCI who had sustained their injury at least 6 months before the start of the study earlier were recruited from the Louis Stokes Cleveland VA Medical Center. Persons with cardiac pacemakers, other metallic devices, high blood pressure, or active pulmonary conditions were excluded. Informed consent was processed in accordance with the local Institutional Review Board Committee at the Louis Stokes Cleveland VA Medical Center. Each subject underwent a history and physical examination to establish eligibility for the study.

Nerve Conduction Studies

For screening purposes, preliminary nerve conduction studies of upper and lower intercostal nerves were performed by using single-pulse magnetic stimulation. A commercially available MagPro R30 magnetic stimulator (Medtronic, Skovlunde, Denmark) was used with a racetrack MC designed by our FMS Laboratory. The stimulator could generate biphasic pulses (280-μs pulse width) with magnetic gradients up to 50 kT/s. This time-varying magnetic field produced an induced electric current that facilitated activation of the nervous tissue [30]. The compound muscle action potential (CMAP) recordings were made by using a standard