Functional Magnetic Stimulation for Conditioning of Expiratory Muscles in Patients With Spinal Cord Injury

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ABSTRACT. Lin VW, Hsiao IN, Zhu E, Perkash I. Functional magnetic stimulation for conditioning of expiratory muscles in patients with spinal cord injury. Arch Phys Med Rehabil 2001;82:162-6.

Objective: To evaluate the effectiveness of functional magnetic stimulation (FMS) in conditioning expiratory muscles patients with spinal cord injury (SCI).

Design: A prospective before-after trial.

Setting: The Functional Magnetic Stimulation Laboratory of the SCI Health Care Group, VA Long Beach Health Care System, and the Spinal Cord Injury Services, Department of Veterans Affairs, Palo Alto Health Care System.

Participants: Eight men with tetraplegia.

Intervention: Expiratory muscle training was achieved by placing a magnetic stimulator with a round magnetic coil along subjects' lower thoracic spine.

Main Outcome Measures: Measures taken were the maximal expired pressure at total lung capacity (MEP-TLC) and at functional residual capacity (MEP-FRC), expiratory reserve volume (ERV), and the forced expiratory flow rate at TLC (FEF-TLC) and at FRC (FEF-FRC) by subjects' voluntary maximal efforts.

Results: After 4 weeks of conditioning, the mean ± standard error of the mean values were: MEP-TLC, 55.3 ± 8.6cmH_2O; MEP-FRC, 29.6 ± 5.6cmH_2O; ERV, .57 ± .08L; FEF-TLC, 4.3 ± 0.5L/s; and FEF-FRC, 1.9 ± 0.2L/s. These values correspond to, respectively, 129%, 137%, 162%, 109%, and 127% of pre-FMS conditioning values. When FMS was discontinued for 2 weeks, the MEP-TLC returned to its pre-FMS training value.

Conclusion: A 4-week protocol of FMS of the expiratory muscles improves voluntary expiratory muscle strength significantly, indicating that FMS can be a noninvasive therapeutic technology in respiratory muscle training for persons with tetraplegia.

Key Words: Magnetic stimulation; Muscles; Rehabilitation; Spinal cord injuries.

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IMPAIRED COUGH in patients with spinal cord injury (SCI) is among the most important causes of frequent respiratory complications such as mucus plugging, atelectasis, and pneumonia. Respiratory management of patients with chronic SCI includes frequent suctioning, chest percussion and postural drainage, quad-cough, and respiratory muscle–training exercises. Functional electric stimulation (FES) of the abdominal muscles and ventral thoracic spinal nerves is also effective in producing expiratory flow and pressure.[1,2] Despite the success of these techniques, there remains a need for a noninvasive and effective procedure that is suitable for long-term respiratory muscle conditioning.

Functional magnetic stimulation (FMS) is effective in stimulating the expiratory muscles in both humans and animals.[3-6] In patients with chronic SCI, FMS has resulted in expiratory function that was substantially above their maximal voluntary efforts.[6] FMS of the expiratory muscles is easy to use, is noninvasive, and does not require extensive preparation. Unlike FES, FMS is well tolerated by subjects with intact or partial sensation.

This study evaluated the effect of expiratory muscle conditioning with FMS on pulmonary function in patients with SCI. Expiratory functions of these patients were measured at several stages: baseline, 2-week conditioning, 4-week conditioning, and 2-week postconditioning.

METHODS

Eight men with chronic SCI were recruited for the study. Patients with cardiac pacemakers, other metallic devices, high blood pressure, or with active pulmonary conditions were excluded. Informed consent was processed in accordance with the Human Subjects Committee at the Department of Veterans Affairs, Palo Alto Health Care System, and at the Department of Veterans Affairs, Long Beach Health Care System. Each patient underwent a history and physical examination to establish eligibility for the study.

A commercially available magnetic stimulator[a] with a round magnetic coil (20cm in outer diameter) was used. A cooling unit that circulated oil in and out of the coil was designed to allow continuous stimulation for 30 or more minutes. The stimulator could generate biphasic pulses (280-μs pulse width) with magnetic gradients up to 50kTesla/s. This time-varying magnetic field produced an induced electric current that facilitated activation of the nervous tissue.[7]

Baseline Pulmonary Function Tests Evaluation

Baseline pulmonary function tests (PFTs) were performed with a Vmax 229 Sensormedics System.[b] Subjects were tested between 1 and 3 PM. A 15-minute rest period was required to avoid the influences of daily activities on the PFT results. In this system, we used a respiratory pressure module to determine pressure and a heated pneumotach to measure volume and flow. The pressure transducers and pneumotachs were calibrated daily to ensure accurate measurements. The maximum expiratory pressure at total lung capacity (MEP-TLC), the expiratory reserve volume (ERV), and the forced expiratory flow rate at TLC (FEF-TLC) were measured as indicators of the expiratory muscle strength. For comparison, MEP and FEF at functional residual capacity (MEP-FRC, FEF-FRC) were also measured. Other PFT parameters, such as forced vital capacity (FVC) and forced expiratory volume (FEV_1), were recorded.

To detect patients' responses to magnetic stimulation, MEP, ERV, and FEF at FRC generated by FMS (MEP-FMS, ERV-FMS, FEF-FMS) was conducted on each patient. The stimulation parameters were 70% of maximum intensity, 20Hz frequency, 2-second burst length, and a T10 magnetic coil placement.[6] The stimulation was performed while the subjects were sitting in their wheelchairs.

FMS Conditioning Protocol

The experimental protocol continued for 6 weeks. In the first week, subjects underwent screening histories and physical examinations. Thereafter, a baseline PFT was evaluated and recorded with subjects in a sitting position. Physical examinations and PFTs were repeated in the final week. Before the conditioning protocol, subjects were instructed to maintain regular diets and their routine activities of daily living. At the beginning of the second week, each subject received a 4-week FMS conditioning program (20min twice a day, 5d/wk) in the SCI center. During this conditioning program, a PFT was repeated at 2-week intervals, ending with a 2-week postconditioning PFT. The subjects were asked to note any changes in their physical condition during the 4 weeks. Before each conditioning session, subjects were asked if they had any discomfort and/or abnormalities. After each session, subjects' skin was checked for possible thermal injury. Blood pressure was monitored before and every 5 minutes during the conditioning period to ensure patient safety. Magnetic stimulation parameters were initially set at 50% intensity, 20Hz frequency, and 2-second burst length. Intensity was gradually increased from 50% to 70%, depending on subject's comfort zone. The center of the magnetic coil was placed at T10 to T11.[4] FMS of the expiratory muscles was performed 5 days a week. In week 2 and at the completion of the training session (week 4), the expiratory muscle strength was evaluated by measuring the MEP, ERV, and FEF.

Statistical Methods

Data from the PFTs were expressed in mean ± standard error of the mean (SEM). Statistical analyses were performed by using a 2-way analysis of variance and Student's *t* test; $p < .05$ was considered significant.

RESULTS

Demographics

The mean age and time since injury of the 8 subjects were 51 ± 8 years and 18 ± 9 years, respectively. Seven subjects had a SCI level between C5 and C7, and one had a SCI level at T5 (table 1). All subjects completed the conditioning protocol.

Baseline PFT Results

Baseline PFT results are summarized in figures 1 through 3 and table 2. The mean baseline PFT results were: MEP-TLC = 48 ± 9.7cmH_2O, MEP-FRC = 24.3 ± 6.1cmH_2O, ERV = 0.4 ± 0.1L, FEF-TLC = 4.0 ± 0.5L/s, FEF-FRC = 1.6 ± 0.2L/s, FVC = 2.4 ± 0.1L, and FEV_1 = 1.9 ± 0.1L. Two parameters of interest were the percentage of the predicted normal value of the mean FVC = 50.7% ± 5.2% and the mean FEV_1% (FEV_1/FVC) = 82.8% ± 1.7%. The means of MEP-FMS, ERV-FMS, and FEF-FMS were 42 ± 4.9cmH_2O, 0.6 ± 0.10L, and 2.9 ± 0.42L/s, respectively.

Table 1: SCI Profile of Study Participants

Patient	Level of Injury	ASIA Classification	Age (yr)	Duration of Injury (yr)	Cause of Injury
1	C5–C6	A	57	18	MVA
2	C4–C5	A	47	23	Fall
3	C5–C7	A	49	26	MVA
4	C5	B	43	20	MVA
5	C4	B	40	6	MVA
6	C5–C7	A	66	27	DA
7	T5	A	53	20	MVA
8	C4–C5	A	55	2	MVA

Abbreviations: ASIA, American Spinal Injury Association; MVA, motor vehicle accident; DA, diving accident.

PFT Results After 2 Weeks

All subjects completed the first 2 weeks of training. Conditioning sessions were at approximately the same time each day. No unusual alterations in daily activities or diets, including medications, were reported. No medical complications or side-effects were noted. A routine skin check after stimulation showed no inauspicious conditions. Blood pressure remained within subjects' normal values during FMS conditioning. The 2-week conditioning PFT results showed that the mean MEP-TLC, MEP-FRC, ERV, FEF-TLC, FEF-FRC, FVC, and FEV_1 were 56 ± 10.1cmH_2O, 28 ± 5.9cmH_2O, 0.51 ± 0.1L, 4.1 ± 0.4L/s, 1.9 ± 0.3L/s, 2.5 ± 0.1L, and 2.0 ± 0.1L, respectively. These values showed a 22%, 24%, 40%, 4%, 20%, 10%, and 9% increase from subjects' respective mean baseline PFT results, respectively. Significant improvements ($p < .05$) were seen in MEP-TLC and MEP-FRC (fig 1). FEF-TLC and FEF-FRC showed moderate increases (fig 2). The results were not statistically significant. FVC and FEV_1 had negligible changes. Among all the parameters, ERV showed the most improvement after the first 2 weeks of conditioning (fig 3). When asked for their reaction to FMS conditioning, 6 subjects said that they experienced "tightening" or "strengthening" of their abdominal muscles, and an improved ability to cough up secretions. These changes occurred within the first week of conditioning. Two subjects reported no changes. None of the subjects had any negative responses or complaints about FMS.

PFT Results After 4 Weeks

All subjects continued the second half of the conditioning protocol. No medical complications or adverse effects were reported in the final 2 weeks. The consensus of the participants was that FMS training of expiratory muscle was not painful, was well tolerated, and was helpful. The 4-week conditioning PFT results showed that the mean ($n = 8$) MEP-TLC, MEP-FRC, ERV, FEF-TLC, FEF-FRC, FVC, and FEV_1 were 55.3 ± 8.6cmH_2O, 29.0 ± 5.6cmH_2O, 0.6 ± 0.1L, 4.3 ± 0.5L/s, 1.9 ± 0.2L/s, 2.5 ± 0.1L, and 2.0 ± 0.1L, respectively. These values showed increases of 29%, 37%, 62%, 9%, 27%, 7%, and 10% of subjects' respective mean baseline PFT results, respectively. The improvements were significant ($p < .05$) for MEP-TLC, MEP-FRC, and ERV. FVC and FEV_1 increased by ≤10% of their normal values after 4 weeks of training and were not significant ($p > .05$). Final physical examinations showed no new abnormalities. The increases of MEP-TLC, MEP-FRC, ERV, FEF-TLC, FEF-FRC, FVC, and FEV_1 from the second week to the fourth week of FMS conditioning were 6%, 12%,

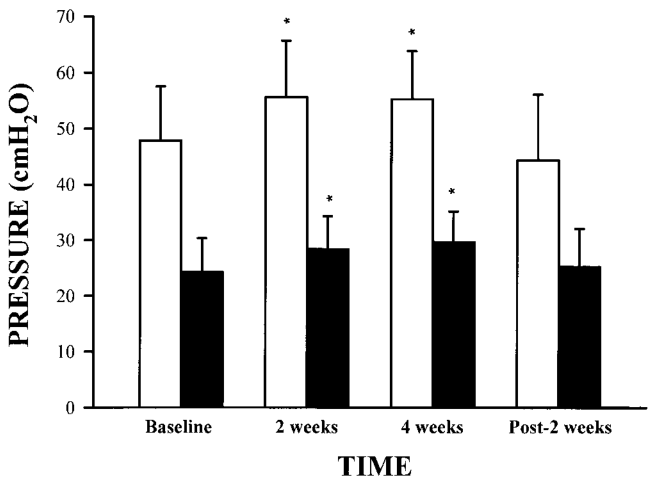

Fig 1. MEP improvements at TLC and FRC. Changes in airway pressure (cmH_2O) throughout the conditioning protocol. (□), MEP-TLC; (■), MEP-FRC. *Versus baseline, $p < .05$.

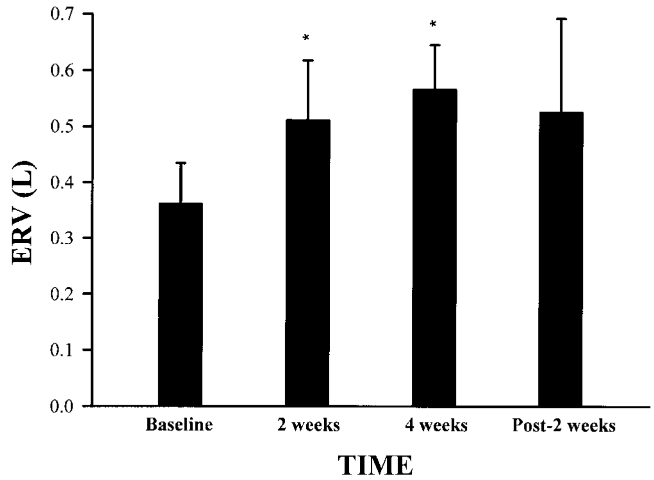

Fig 3. ERV improvement. Changes in lung volume (L) throughout the conditioning protocol. *Versus baseline, $p < .05$.

19%, 4%, 6%, 0%, and 2%, respectively. However, no statistical significance was observed for any of the parameters in the last 2 weeks of conditioning ($p > .05$).

PFT Results at 2 Weeks Postconditioning

Six subjects returned 2 weeks after completing the conditioning protocol. The mean values of MEP-TLC, ERV, FEF-TLC obtained during this postconditioning protocol showed decreases of 13%, 16%, and 5%, respectively, from their values at the end of the 4-week conditioning protocol. The poststimulation data, when compared with the baseline data, showed no statistically significant differences.

DISCUSSION

Persons with chronic cervical SCI typically show a restrictive respiratory pattern with both inspiratory and expiratory dysfunction.[8] Their PFT results showed low mean TLC, vital capacity, and inspiratory capacity as well as a high FEV_1: FVC ratio, in addition to low expiratory pressure, flow, and ERV, indicating a decrease or absence of expiratory muscle function.[6,8,9] Patients with thoracic spinal lesions may have only expiratory dysfunction with preserved inspiratory capacities.[8]

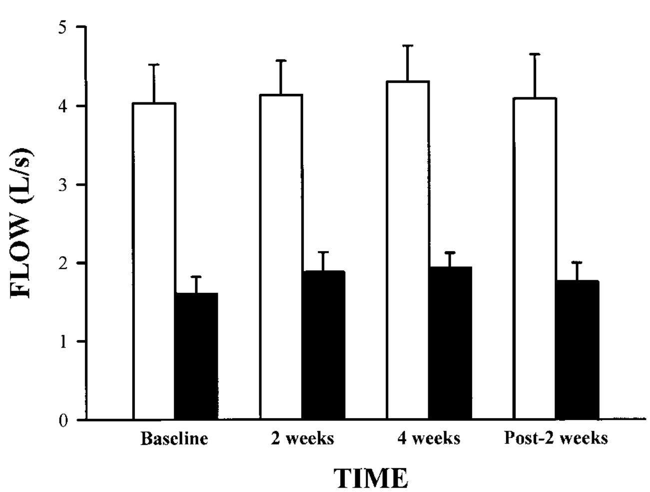

Fig 2. FEF improvements at TLC and FRC. Changes in airway flow (L/s) throughout the conditioning protocol. (□), FEF-TLC; (■), FEF-FRC.

In this study, we applied FMS to restore the impaired expiratory function in SCI patients by using a 4-week FMS expiratory muscle-training program. This is a continuation of our previous efforts, which showed efficacy in magnetically stimulating the expiratory muscles by placing a magnetic coil in the lower thoracic region.[3-6] By conditioning the expiratory muscles for only 2 weeks, we observed significant improvement in voluntary MEP (22%), FEF (20%), and ERV (40%). We also observed continued improvement after 2 additional weeks of conditioning. According to the present protocol, expiratory muscles were stimulated for 20 minutes twice a day. The stimulation intensity was set with a minimum intensity of 50%, and a burst length of 2 seconds, which produced a substantial contraction of the expiratory muscles.[3]

Recent respiratory training protocols have focused on inspiratory and expiratory efforts against a closed airway or airway resistance loading for respiratory muscle training.[10] In patients with SCI, reports have shown improvement in inspiratory muscle strength and endurance after inspiratory resistance training.[10,11] Biering-Sorensen et al[12] showed that the peak expiratory flow of 10 cervical injured patients improved by 11% (from 371 to 412L/min) by using a 6-week inspiratory resistance training protocol. Suzuki et al[13] reported a 25%

Table 2: PFT Profile of Study Participants

Patient	FVC (L)	FEV_1 (L)	IC (L)	ERV (L)
1	3.09	2.34	2.56	0.53
2	2.87	2.47	2.19	0.68
3	2.67	2.02	2.35	0.32
4	2.17	1.52	1.84	0.33
5	2.24	1.29	2.04	0.20
6	2.75	2.36	2.32	0.43
7	0.56	0.56	0.56	0.00
8	3.13	2.52	2.71	0.42
Mean	2.44	1.89	2.07	0.36
SEM	0.11	0.10	0.10	0.07

Abbreviation: IC, inspiratory capacity.

increase in MEP after 4 weeks of threshold pressure training (at 30% of MEP) by using healthy subjects. Their subjects were trained for 15 minutes twice daily for 4 weeks at their own breathing frequency and tidal volume. The length of training and stimulation duration were comparable with our protocol. Smeltzer[14] reported a similar finding in patients with multiple sclerosis. They observed an increase in MEP of 19.4 + 9.9cmH_2O from a baseline value of 53.6 + 14.9cmH_2O after 3 months of expiratory muscle training by using a threshold training device.

The goals of FMS expiratory muscle conditioning in patients with SCI are to restore strength and endurance of the disused expiratory muscles. Muscle disuse usually leads to a decrease in muscle mass, in the proportion of type I (fatigue resistant) fibers, and in oxidative enzymes, and results in reduced strength and endurance. There are 3 major principles of muscle training: overload, training specificity, and reversibility.[15] The muscle must be overloaded above a threshold to a point at which the muscle will be activated more than usual. The stimulation protocol given to the muscles has to be specific to the desired effect. The training effect is reversible once training is stopped. This study has shown significant contraction of the expiratory muscles with stimulation and functional improvement of the expiratory muscles, as well as the reduction of expiratory function after the conditioning protocol. The clinical significance of our results is that FMS restored partial strength of the disused expiratory muscles and potentially improved coughing capacity in patients with tetraplegia. The limitation of this study is that we have not provided results on respiratory muscle fatigue or muscle biopsies. Nevertheless, this is the first report on the effects of FMS in the conditioning of the expiratory muscles.

Two weeks after the conditioning protocol ended, the voluntary expiratory function decreased sharply to a level comparable with the baseline. This functional decrease is comparable to that seen by Gurney et al,[16] which showed decreased skeletal muscle performance after cessation of training in SCI. This also suggests that for FMS to be beneficial to subjects with SCI, persistent training is required.

FES of the respiratory muscles has been an active area of research in recent decades. Devices have been designed to stimulate the phrenic nerves,[17] ventral roots,[18] intercostal nerves,[19] diaphragm, and abdominal muscles.[1,2] By placing surface electrodes on the abdomen, significant expiratory function was observed.[1,2] DiMarco et al[20] showed impressive expiratory function in dogs by using plate electrodes implanted in the ventral aspect of the spinal cord near T9. Electric stimulation conditioning of denervated skeletal muscles at 20Hz, 5-second bursts, 15 minutes to 8 hours a day for 24 weeks increases the proportion of type I fibers, and enhances endurance properties of the paralyzed muscles.[21] FES techniques require placing electrodes on the muscles or on the nerve tissues, which requires skin preparation or surgical procedures. These procedures may be inconvenient, painful to patients with preserved sensation, or they may result in medical complications.[2]

In contrast to FES, FMS is relatively easy to use, is noninvasive, and is not painful. As shown in an earlier study,[3,6] the optimal placement of the magnetic coil in patients centers near T10–T11 spinous process. This placement stimulates spinal nerves between T7 and L2, which activate most of the expiratory agonists such as the internal intercostal muscles, internal and external oblique, transversus abdominis, and rectus abdominis. This placement was further supported by another study in which we sequentially placed the magnetic coil between T1 through L5.[5] The size of the coil and its configuration are important factors for stimulation effects.[22] With magnetic coil placement near the spinous process, the loci of spinal nerve activation is at the neuroforamen.[23] Activation of the spinal nerves at the foramina leads to simultaneous contraction of the major expiratory muscles. Depending on the appropriate design and placement of the coil, significant inspiratory or expiratory function can be produced.[6] In unimpaired subjects, FMS produced expiratory function similar to the subjects' voluntary maximum. In tetraplegic patients, FMS reached a mean expired pressure, volume, and flow rate of 121%, 167%, and 110%, respectively, of their voluntary maximum.[6]

The mechanism underlying the effect of long-term FMS conditioning is likely the myosin isoform shifts induced by near maximal muscle contraction.[24] The intensity of FMS that is applied to reload the disused muscles in patients with SCI may also induce transient muscle fiber injuries.[25] It is proposed that exercise-induced injury initiates muscle fiber proliferation and phenotype remodeling.[26,27] Whether FMS conditioning applied in the present study induces changes in muscle mass and other metabolic or morphologic properties attracts great attention.

The benefits of FMS of the expiratory muscles were not limited to improvement of voluntary cough function, thus, reducing the risk of life-threatening respiratory complications. We also observed improvement of inspiratory function after the 4-week conditioning protocol. The inspiratory capacity increased approximately 5% after 4 weeks of training and was associated with a 6% increase of the FEF-TLC (fig 2). Similar improvements occurred in FVC and FEV_1. We propose that to achieve the optimal respiratory muscle conditioning results, both expiratory and inspiratory muscles should be trained. In addition to patients with SCI or with other neurologic pathologies, patients with respiratory dysfunction, or who are under sedation, or are in intensive care settings, may benefit from such a controlled expiratory muscle stimulation technology. In addition to the respiratory muscles, FMS has been used to stimulate the bladder and gastrointestinal tract successfully.[28,29] Placing the magnetic coil near the lumbosacral region activates pelvic nerves that facilitate micturition and colonic transit in patients with SCI.[30,31] In unimpaired subjects, FMS of the calf muscles has also proven useful in improving fibrinolysis.[32] In the sedentary population, FMS may be an attractive option for abdominal muscle strengthening.

CONCLUSION

Expiratory muscle conditioning was achieved by placing a magnetic coil along the subject's lower thoracic spine. A 4-week conditioning protocol resulted in significant improvement in voluntary expiratory pressure, volume, and flow when compared with baseline. Two weeks after the conclusion of the FMS conditioning, the voluntary expiratory function decreased sharply to baseline. For patients with SCI to benefit from the FMS technology, persistent stimulation is required. FMS of the expiratory muscles is noninvasive and easy to use. FMS may be an attractive therapeutic tool for patients with SCI or other neurologic disorders.

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Suppliers

a. Dantec MagPro; Dantec Medical Inc, 3 Pearl Ct, Allendale, NJ 07401.
b. SensorMedics Corp, 22705 Savi Ranch Pkwy, Yorba Linda, CA 92687.