Functional Electrical Stimulation to Enhance Cough in Quadriplegia*

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Respiratory problems are a major cause of death in the acute and chronic phases of cervical spinal cord injury (CSCI); CSCI paralyzes the intercostal and abdominal muscles, reducing ability to cough and clear secretions. Impaired cough due to neuromuscular disorders can be assessed with the maximum expiratory pressure (MEP). This study consists of two experiments with CSCI patients. In the first, MEP measurements were recorded with the following maneuvers performed: (1) spontaneous cough attempts, (2) manually assisted cough, and (3) cough attempts with functional electrical stimulation (FES) applied to the abdominal wall. In the second, spontaneous cough attempts and cough attempts with a portable FES unit were recorded. These CSCI patients were found to have a greatly reduced MEP when they coughed spontaneously. Either FES-assisted or manually assisted coughing increased the MEP in all patients studied. By increasing the MEP, abdominal muscle FES could enhance cough in quadriplegics. (Chest 1993; 103:166-69)

| CSCI = cervical spinal cord injury; FES = functional electrical stimulation; MEP = maximum expiratory pressure |

In the 1950s mortality from respiratory failure in acute traumatic cervical spinal cord injury (CSCI) was 100 percent, decreasing to 11 percent in the early 1980s. Respiratory problems still comprise a major cause of death in both the acute and chronic phases of CSCI. Respiratory impairment is caused by loss of supraspinal control of respiratory muscles below the spinal cord lesion. Loss of abdominal and chest wall expiratory muscles reduces ability to cough and clear secretions. In the pulmonary management of quadriplegia, secretion control is vital to prevent atelectasis and pneumonia. Fiberoptic bronchoscopy, endotracheal suction, and chest physiotherapy with chest percussion are used to clear secretions in patients unable to cough. Suction and the use of an artificial airway, such as a tracheostomy, are invasive and have the potential for damage to the bronchi due to irritation and trauma that can lead to infection. Tracheal suction also may lower the alveolar oxygen pressure. An oscillating bed facilitates postural drainage. The CofFlator, a mechanical device, was used in polio patients to clear respiratory secretions by delivering a positive pressure air volume followed by a negative pressure. It required an attendant trained in the use of the CofFlator for usage.

Training exercises to use pectoral (C-5) muscles may improve coughing. A recent study of 12 quadriplegics used isometric exercises of the clavicular portion of the pectoralis major muscle daily for six weeks. All subjects had sustained a complete CSCI at no higher than the fifth cervical (C-5) neurologic level at least three months prior to the study. Expiratory reserve volume was noted to increase, which should improve the ability of CSCI patients to cough. Pectoral muscle exercises would not be possible in CSCI patients with a level of injury at or above the fourth cervical (C-4) neurologic level.

Assisted coughing, which is performed by a trained attendant, is the practice of pushing the abdomen forcefully to generate the positive airway pressure needed to expel mucus. Best results are obtained with the chest fully inflated and the patient in the supine position. Coughing attempts also are improved by bending the patient forward when sitting.

The most sensitive indicator of respiratory impairment due to neuromuscular disorders is the maximum expiratory pressure (MEP). This parameter is greatly decreased among CSCI patients. Forced expiration during cough normally starts with maximum inflation of the lungs with closure of the glottis, followed by contraction of intercostal and abdominal muscles with opening of the glottis. A good cough requires maximal lung inflation, coordination of the glottis, and coordination of the expiratory muscles. Respiratory expiration action of the chest and abdomen in CSCI primarily is a passive action, dependent upon the recoil of the inflated chest as a result of paralysis of the intercostal and abdominal muscles.

In CSCI patients, the impairment of active expiratory pressures results in impaired cough and reduced ability to clear respiratory tract secretions. The MEP of noninjured patients ranges from 150 to 200 cm H2O depending on age. The CSCI patients have a MEP of less than 30 percent that of normal control subjects. Unlike the vital capacity, the MEP may not improve over time. One study measured intrathoracic pressures during cough using esophageal balloon manometry. Three quadriplegic patients achieved a mean...
pressure of 11.2 cm H₂O, which was below the mean pressure of 88.1 cm H₂O achieved by normal control subjects during coughing.  

It is apparent that the loss of effective coughing is a major problem in quadriplegia. Consequently, it is important to develop techniques or devices that might improve coughing in these patients.

Functional electrical stimulation (FES) of muscle partially or totally paralyzed due to an upper motor neuron lesion may be used to elicit muscle contractions. Functional electrical stimulation is a modality used in the physical therapy of a variety of conditions, such as hemiplegia, cerebral palsy, spinal cord injury as well as general muscle strengthening to increase athletic endurance.  

When FES is applied to the abdominal muscles causing them to contract, it may compress the air in the lungs enough to generate a cough. This study was designed to determine whether abdominal wall FES would produce increased intrathoracic pressures with the potential to improve cough in CSCI patients.

METHODS

This study was conducted at the Spinal Cord Injury Service at the VA Medical Center in Palo Alto, Calif., a 30-bed inpatient service with access to approximately 400 quadriplegic patients. The study was approved by the institutional review board of Stanford University prior to its initiation. Informed consent was obtained from each participant prior to beginning the study.

Between April and August 1990, a group of eight quadriplegic patients was enlisted for a study with a stationary FES unit. These patients had the following characteristics: (1) at least three months had passed since injury to the cervical spinal cord, (2) there was no evidence of abdominal pathology, and (3) there was no primary lung disease as determined from history, physical examination, and chest x-ray film. All patients in the study were men with a mean age of 38±11.4 years. The patients had been injured for an average of 12.3±9.3 years before the study. All subjects had sustained a complete CSCI. Two patients had a level of injury at the C-4 level, with the remainder at or below the C-5 level. A group of three patients was enlisted for a second experiment with the use of a portable FES system which was designed by the primary investigator that took place during February 1991. They had the same characteristics as the first group with a mean age of 36.7±7.2 years. These patients had been injured an average of 18±6.1 years before the study. All subjects had sustained a complete CSCI. One patient had a level of injury at the C-4 level, with the remainder at or below C-5.

Baseline pulmonary function measurements were obtained using an automated pulmonary function laboratory (Medical Graphics system 1070, St. Paul, Minn). Measurements included baseline spirometry (vital capacity and expiratory reserve volume) and lung volume measurements (total lung capacity, residual volume and functional residual capacity). These measurements were performed with the patient sitting and restrained from excessive truncal motion.

Next, MEP measurements were performed based on a method described earlier. Measurements were made using an automated pulmonary function laboratory (Medical Graphics system RPM, St. Paul, Minn).

In the first experimental group of eight patients, MEP measurements were obtained with the following three maneuvers: (1) spontaneous coughing, (2) assisted coughing and (3) coughing with FES electrodes applied to the abdominal wall. In the second group, MEP measurements were made first with spontaneous coughing and then with a portable abdominal binder incorporating electrodes for the delivery of FES. Among the first experimental group, all maneuvers were performed with the patient supine; during the second experiment, maneuvers were performed with the patient sitting up and restrained from excessive truncal motion. During MEP measurement, each patient used a flange mouthpiece and a nose clip. Each patient practiced to familiarize himself with the equipment and performed each of the maneuvers until three uniform attempts were achieved.

Functional electrical stimulation in both experiments was delivered through four to eight high-conductivity gel skin electrodes located on the abdominal wall. The electrical impulse was conducted in a synchronous mode using commercially available FES stimulators and was increased to maximum intensity, which was observed to cause generalized abdominal muscle contraction.

The electrodes were applied to the abdominal wall at positions observed to cause maximum contractions. These positions that allowed delivery of maximum stimulation are the abdominal wall motor points and varied slightly among patients. The electrodes were placed individually on the abdominal wall motor points in the first group without any binder. In the second group, an abdominal binder was used to hold the electrodes in formation. The FES was set at 50 Hz, with a pulse width of 300 microseconds (µs), an asymmetrical biphasic waveform, and an intensity 100 percent of maximum with zero rise time. Stimulation was limited to 2 to 3 s.

The length of the entire stimulation session was not longer than 30 min to avoid fatigue. The mean measurement from each of three maneuvers was then compared.

No skin breakdown was observed in the subjects studied. Some increase in abdomen and lower extremity spasms was noted during stimulation but was uniformly transient and tolerated by all subjects.

RESULTS

All subjects had a decreased vital capacity (2.59±0.89 L), expiratory reserve volume (0.43±0.32 L), and total lung capacity (5.43±0.89 L) as compared with normal control subject values. The residual volume was found to be increased (3.19±0.96) over normal control subject values. The decrease in vital capacity and expiratory reserve volume was consistent with prior pulmonary function measurements in CSCI.

In the first group, the measured MEP increased significantly from baseline spontaneous cough values when FES was applied (Fig 1). The mean difference

![Figure 1. Automated tracing of the expiratory pressure developed in a quadriplegic patient during an FES-assisted cough and a spontaneous cough.](http://journal.publications.chestnet.org/pdfaccess.ashx?url=/data/journals/chest/21663/ )
Figure 2. Mean ± SE MEP measurements in quadriplegic patients during spontaneous coughing, manually assisted coughing and FES-assisted coughing. Results of two experiments are shown. The MEP measurements during manually assisted coughing were not performed in experiment 2.

in MEP between spontaneous coughing and FES-assisted coughing was 33.3 cm H$_2$O. The mean MEP generated from spontaneous coughing was 27.3 ± 6.4 cm H$_2$O, from assisted coughing was $83 ± 18.7$ cm H$_2$O and from FES-assisted coughing was $60 ± 22.8$ cm H$_2$O (Fig 2). In all patients in the study, the MEP increased with abdominal muscle FES as well as with manually assisted cough.

The results of the second experimental group confirmed those found for the first group. The use of a portable FES increased the mean MEP from 32.3 (23.7 mm Hg) to 58 cm H$_2$O (42.6 mm Hg), an increase of 79.4 percent (Figure 2). There was no evidence of difference in the results between the two experimental patient groups.

There was a significant effect of group cough maneuver on the variability within patients ($p = 0.0001$), as determined by repeated measures analysis of variance on the data from experiment 1 ($n=8$). Furthermore, there were significant differences in post hoc comparisons between all pairs of cough maneuvers. Figure 2 presents the mean ± SE MEP measurements from the three cough maneuvers for each of the two groups.

**DISCUSSION**

The first phase of this study has shown that abdominal muscle FES significantly enhances MEP in CSCI patients. The mean MEP increase was 33.3 cm H$_2$O ($p = 0.0016$). Based on this observation, a second experiment with the use of a portable abdominal binder holding FES electrodes in an optimal anatomic position was conducted. This portable FES apparatus also was shown to increase the mean MEP by 79.4 percent. Although the second group was small, there was no indication of effect of the change in position from supine to sitting or the placement of an abdominal binder by itself on measured MEP.

Since a decrease in MEP is associated with impaired cough, this suggests that abdominal muscle FES significantly enhances cough in CSCI patients. Further studies are needed to quantify the effective tracheobronchial clearance produced by abdominal muscle FES. Patient tolerance also needs to be further assessed. For a quadriplegic, an abdominal muscle FES binder which significantly enhances cough would reduce dependence on the presence of a health professional or attendant for manually assisted coughing or invasive treatment for proper pulmonary secretion removal. Managing a ventilatory impaired patient without a tracheostomy which would require the services of a licensed nurse to perform tracheal suctioning has been estimated to produce cost savings of $500 per day.

Surface muscle FES also is used as physical therapy in non-spinal cord injury patients. The potential to enhance cough in non-spinal cord injury patients could be studied.

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