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Original Article

Electromyographic signal-activated functional electrical stimulation of abdominal muscles: the effect on pulmonary function in patients with tetraplegia

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Background: Paralysis of abdominal muscles is the main cause of respiratory dysfunctions in patients with lower cervical spinal cord lesion. Activation of the abdominal muscles using functional electrical stimulation (FES) improved respiratory function in these patients. But application of FES frequently requires a caregiver, and it may not be well synchronized with the patient's respiratory activity.
Objective: To perform preliminary examination of electromyographic (EMG)-activated FES for caregiver-independent and synchronized cough and expiration induction in tetraplegia.
Design: Self-controlled study.
Setting: Loewenstein Rehabilitation Center, Raanana, Israel.
Subjects: A total of 10 male patients with complete or almost complete tetraplegia.
Main outcome measures: Peak expiratory flow (PEF), forced vital capacity (FVC), and maximal voluntary ventilation (MVV).
Methods: The outcome measures were examined with the abdominal muscles unassisted or assisted by various methods. These included manual assistance or application of FES, activated by a caregiver, by the patient, or by EMG signals elicited from the patient's muscle.
Results: Manual assistance improved the mean PEF value by 36.7% ($P<0.01$) and the mean FVC value by 15.4% ($P=0.01$). FES did not significantly change most measurements, and patient-activated FES even reduced PEF ($P<0.05$). But following EMG-activated FES PEF and FVC values were higher than those following patient-activated FES ($P<0.05$ for PEF; $P<0.01$ for FVC), and their mean values were higher by 15.8 and 18.9%, respectively.
Conclusions: Abdominal FES failed to improve respiratory function in this study, but applying FES to abdominal muscles by EMG from the patient's muscle may promote caregiver-free respiration and coughing in persons with cervical SCL.
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Keywords: spinal cord lesions; tetraplegia; cough; functional electrical stimulation; electromyographic signals

Introduction

The diaphragm is the main inspiratory muscle. It is innervated through the cervical spinal cord segments C_3–C_5. Complete or almost complete spinal cord lesion (SCL) above the C_4 level disturbs the diaphragmatic movements and can cause respiratory impairments that may require mechanical ventilation. But respiratory disturbances are frequent in persons with SCL even if the lesion is located below the C_4 segment. Severe respiratory disturbances may occur in patients with lower cervical or high thoracic SCL because of paralysis of the abdominal muscles, which are required for expiration in upright position, support effective inspiration,[1,2] and enable coughing (forced expiration against partially closed glottis). Diaphragmatic power can be adequate in these patients, and they may have satisfactory breathing in the supine position, or when a constant passive pressure is applied to their abdomen by spastic abdominal muscles or an elastic band, because chest elastic recoil and the applied pressure return the diaphragm to a sufficiently high position after expiration.[3,4] Breathing can be further assisted by postural drainage with head-down tilt that helps remove respiratory tract secretions.[5,6]

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Nevertheless, constantly applied pressure and positioning cannot produce forced expiration or coughing, which is necessary for efficient removal of secretions and solid particles from the respiratory tracts.[7] Impairment of coughing may cause bronchial obstruction and consequent atelectasis pneumonia with severe respiratory disturbances.[1] Caregivers believe that these can be prevented if the patient's cough is assisted by intermittently applied artificial pressure to the abdomen.

Assisted cough is usually obtained by replacing the abdominal muscle activity with caregiver's manual activity.[5,8] Manual pressure intermittently applied to the anterior abdominal wall is capable of producing effective coughing, but assisted coughing needs to be repeated many times a day. Therefore, a person with severe tetraplegia who requires assisted coughing depends constantly on a caregiver.

Coughing can also be assisted by functional electric stimulation (FES) applied to abdominal muscles, as described in several studies since 1993.[2,9–12] All these publications suggested that coughing ability is improved by this method, and some found that it can be as effective as manually assisted coughing.[2,9]

Activation of the FES, however, requires turning on a switch, a task that is too difficult for many patients with tetraplegia. Even patients who can use a switch may be unable to do it with proper timing to allow synchrony of the FES-induced abdominal muscles contraction with the patient's coughing.[10] Therefore, FES-assisted coughing may not reduce the need for a caregiver and may not be sufficiently effective.

To assist breathing, improve the efficacy of FES-assisted coughing, and allow coughing without continuous caregiver help we introduced the use of electromyographic (EMG) signals from patient's own muscle to activate the FES appliance. In this study, we assessed the abdominal muscle contraction induced by this method, measuring its effect on respiratory functions and comparing it to the effects of other methods that increase the intra-abdominal pressure during expiration.

Methods

The study included 10 male patients aged 22–60 years, with a complete or almost complete tetraplegia, who were examined 1.5 months to 32 years after onset of a cervical SCL (Table 1). All applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research.

To assess the effects of different methods of increasing the intra-abdominal pressure during coughing and breathing, peak expiratory flow (PEF), forced vital capacity (FVC), and maximal voluntary ventilation (MVV) were measured in all patients in the supine position. PEF was measured during one attempted powerful cough into a Mini Wright flow-meter (Clement Clarke, Harlow, Essex, UK); FVC and MVV were measured with the Pony graphic device (Cosmed, Roma, Italy). The results of the respiratory tests were specified by the measured values and by percentage of the expected values in healthy people of the same size, according to the standards of the European Respiratory Society.[13]

Table 1 Patient data

Patient	*Age (years)*	*Time from injury (months)*	*Injury level*	*ASIA grade*
1	22	3	C_6	B
2	28	1.5	C_4	B
3	23	4	C_5	B
4	45	7	C_5	B
5	27	4.5	C_4	A
6	47	6	C_4	B
7	46	22	C_4	A
8	57	384	C_4	B
9	60	36	C_4	C
10	46	90	C_7	B

The respiratory tests were performed in all patients at same time of the day, between 15:00 and 17:00, under five conditions: without assistance, with manually assisted expiration (by one of two physiotherapists), FES-assisted expiration activated by a caregiver (one of the same two physiotherapists), with manually self-activated FES-assisted expiration, and with FES-assisted expiration activated by EMG signals elicited from the patient's own muscle. The patients were encouraged to achieve maximal capacity in the respiratory tests, and the best of three attempts was included in the analysis.

An EMG signal, from the patient's muscle activated when the patient tried to cough, triggered the Omnistim IV stimulator (Danmeter A/S, Odense, Denmark). In every patient, the EMG signal was elicited by surface electrodes attached to the muscle that supplied the triggering for the best expiratory response. The output signals of the stimulator were delayed by a manually adjustable interface for synchronization with the patient's cough. The delayed signal triggered the Quick Off muscle stimulator ('B'&'B' Medical Technologies Inc., Loomis, CA, USA). Each Quick Off stimulation transmitted a train of 50 0.3-ms electrical pulses through four superficial electrodes that were attached to the left and right upper and lower anterior abdominal wall muscles (Figure 1). Pulse intensity was adjusted to obtain visible abdominal muscle contractions with no patient discomfort, and did not exceed 100 mA.

Analysis of variance (ANOVA) with repeated measurements was used to compare the modes of breathing. For each variable (PEF, FVC, MVV) contrasts were used for multiple comparisons between all modes and unassisted or FES-EMG-activated breathing. Data were analyzed by SPSS for Windows (version 12; SPSS Inc., Chicago, IL, USA).

Results

PEF, FVC, and MVV values found in the unassisted patients were about 60% lower than those expected in healthy people, as shown in Table 2. Manual assistance improved the mean PEF value by 36.7% ($P<0.01$) and the mean FVC value by 15.4% ($P=0.01$). It also improved the mean MVV value by 23.5%, but this improvement was not statistically significant (Table 2).

FES did not significantly change most measurements, and patient-activated FES even reduced PEF ($P<0.05$; Table 2). But following EMG-activated FES PEF and FVC values were higher than those following patient-activated FES ($P<0.05$ for PEF; $P<0.01$ for FVC); their mean values were higher by 15.8 and 18.9%, respectively (Table 2).

Discussion

This is the first description of FES-assisted respiration that is activated by EMG signals from the patient's own muscles. The method uses the electrical activity of muscles that contract in synergy with patient breathing or coughing to augment the contraction of muscles that produce forced expiration and cough.

Cough is normally produced by a reflex initiated by irritation of the larynx or of some part of the tracheobronchial tree. Afferent impulses of the cough reflex pass mainly through the vagus nerves to the medulla, and after medullary processing cause a series of events in the following order: (1) air inspiration; (2) tight closure of the vocal cords to trap the air within the lungs; (3) forceful contraction of abdominal muscles and accessory expiratory muscles; and (4) sudden opening of the vocal cords and outward explosion of the air under pressure.[14]

Figure 1 The EMG-activated FES system, demonstrated on a healthy person: Recording surface electrodes (1), the Omnistim IV stimulator (2), manually adjustable interface (3), the quick off muscle stimulator (4), and abdominal stimulating surface electrodes (5)

Although it has been suggested that the cough reflex triggered by laryngeal irritation may be initiated by expiration,[15] repeated coughs must include inspiratory phases before expiratory air bursts. The electrical activity signals of muscles that contract during the inspiratory phase of cough synchronously precede the cough expiratory muscle contraction. With amplification and proper delay, these signals can activate stimuli that augment the contraction of the cough expiratory muscles.

The pectoralis major muscle, which is active in patients with tetraplegia during cough[3,4] and has been shown to be active during both the inspiratory and the expiratory phases of cough in cats,[16] was the first muscle chosen in this study as a source of triggering signals. Signals obtained from other muscles, however, such as the deltoid, which also contracted in our patients during inspiration or the inspiratory phase of cough, produced a stronger expiration. Therefore, the muscle that supplied the best triggering signal was chosen in every patient by trial and error.

The delay of each EMG signal was also adjusted by trial and error to achieve the best expiration. The delay of this signal determines the timing of the abdominal muscle stimulation, which may be critical for cough efficacy. The efficacy depends on the accuracy of the sequence of inspiratory, laryngeal, and expiratory muscle contraction. The timing of the laryngeal and of the main inspiratory muscle contraction during cough is not expected to be impaired in patients with lesions below C_4, but the timing of the contraction of the main expiratory (abdominal) muscles depends on the timing of artificial stimulation in these patients. Therefore, we expected the stimulus that affects these muscles to have a better timing and efficacy when activated by delayed inspiratory EMG signals than by switch.

We also expected that in addition to improving assisted coughing by synchronization of abdominal muscle contraction with the patient's own cough, EMG-activated FES would assist respiration continu-

Table 2 Effect of manual and electrical assistance on the mean values ±SD of respiratory functions

Coughing or breathing	*PEF (l/min) (% expected)*	*FVC (l) (% expected)*	*MVV (l/min) (% expected)*
Without assistance	212.0±47.1 (40.1)	1.7±0.3 (38.9)	57.9±22.8 (40.4)
With manual assistance	290.0±73.9 (54.5)	1.9±0.3 (43.8)	71.5±37.5 (52.9)
Caregiver-activated FES	214.0±46.2 (40.4)	1.6±0.4 (36.1)	57.4±16.2 (41.8)
Patient-activated FES	183.0±51.0 (33.9)	1.4±0.5 (31.5)	68.5±17.7 (52.7)
EMG-activated FES	212.0±51.1 (42.3)	1.7±0.4 (38.9)	64.8±26.8 (49.2)

EMG, electromyographic; FES, functional electrical stimulation; FVC, forced vital capacity; MVV, maximal voluntary ventilation; PEF, peak expiratory flow; SD, standard deviation ously. This cannot be achieved by manual or electrical switch-activated respiratory assistance, which is intermittent.

The achievements of FES were disappointing. In this study, we were not able to demonstrate the improvement in breathing and coughing ability described before.[2,9–12] Moreover, it seems that the unsynchronized stimulus elicited when the patient turns on the switch weakens the patient's residual respiratory capacity. This may be related to specific reactions of some patients in our small group or to stimulating signal characteristics that should be improved.

The failure of FES to improve breathing in this study may be attributed to patient fatigue after the unassisted and the assisted breathing. For standardization purposes, the tests were performed in all patients in the same sequence, with FES tested last, assuming that the rest periods between tests were sufficient to prevent fatigue. But it is possible that random sequencing of tests would have avoided the effect of one method on the next and would have enabled better performance.

Another factor that could have affected the results is the position of the patients during the tests. Patients were examined in the supine position to achieve optimal respiratory outcome, because best spirometric measurements have been demonstrated in this position in tetraplegia patients.[17,18] But in certain patients with tetraplegia, FVC decrease was described from the 35° to the 60° head-up position, and no changes in FVC occurred between the horizontal and 35° head-up positions. In these patients maximum oxygenation and patency of alveoli were achieved in the 60–90° head-up positions, and the optimum position recommended for them, for deep breathing and coughing, was the horizontal or 35° head-up position.[19] Therefore, performing the tests at a 35° head-up tilt could be considered, but it is doubtful that this position would have changed the outcomes of the various methods of respiratory care.

Problems with the FES technique could also have affected findings. The response to abdominal FES may be very weak in some patients. In one study no significant abdominal muscle contraction could be elicited in more than 20% of patients. In particular, abdominal FES is not likely to be successful in patients with significant adipose tissue because of the added electrical resistance of fatty tissue.[20]

Abdominal FES may cause problems, especially in long-term use, including skin irritation with high stimulus currents of 90–100 mA, and the need for tedious and cumbersome repeated application of devices to the appropriate skin surface.[20] Long-term use of FES for walking was associated with a significant decrease in leg muscle stiffness.[21] A similar decrease in abdominal muscle stiffness may reduce the intra-abdominal pressure and the expiratory capacity during quiet respiration.

Despite the disappointing results and potential problems, the findings support the advantage of the newly introduced therapeutic method, showing that PEF values, which reflect cough efficacy,[2] and FVC values, which reflect the efficacy of forced expiration, were significantly higher when induced by EMG-activated FES than when induced by patient-activated FES. The new method protected patients from the negative effect of switch-activated FES, and may contribute to better coughing and breathing if the FES application is improved.

The small size of the study group in this preliminary research does not allow robust conclusions. But the new method may prove successful with potential improvements of the technique. Improvements may include different EMG signal delays, different placing of electrodes, and different abdominal stimulus amplitudes, frequencies, train durations, and pulse waveforms. A combination of EMG-activated abdominal FES with respiratory training and abdominal binder may also improve respiratory function, as suggested in previous publications.[10,22]

Further studies of a larger patient group, with improved technique, are required to develop this method. Success would enable caregiver-free improved cough and respiratory capacity and the prevention of respiratory complications in patients with tetraplegia.

In conclusion, although abdominal FES failed to improve respiratory functions in this study, activation of FES applied to abdominal muscles by EMG from the patient's muscle may promote caregiver-free respiration and coughing in persons with cervical SCL.

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