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CLINICAL REPORT

Pulmonary function testing in spinal cord injury: Effects of abdominal muscle stimulation

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Abstract—The purpose of this study was to assess the effects of applying transcutaneous electrical stimulation to paralyzed abdominal muscles during pulmonary function testing (PFT) of individuals with spinal cord injury (SCI). Ten male subjects with anatomical level of SCI between C5–T7 were studied. Subjects performed PFTs with and without electrical stimulation delivered to the abdominal muscles. Subjects with the lowest percentage of predicted expiratory volumes and flows demonstrated the greatest improvement when electrical stimulation was delivered during forced expiration. The overall increases seen in percent of predicted for the study sample were 23 percent for forced vital capacity (FVC), 16 percent for forced expiratory flow in 1 s (FEV_1), and 22 percent for peak expiratory flow rate (PEF). Contractions of paralyzed expiratory muscles in response to electrical stimulation during the performance of PFT maneuvers can significantly improve FVC, FEV_1, and PEF in some individuals with SCI.

Key words: *electrical stimulation, pulmonary function testing, spinal cord injuries.*

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INTRODUCTION

Expiratory muscle weakness or paralysis in individuals with spinal cord injuries (SCI) results in decreases in peak expiratory flow (PEF) rate, forced expiratory volume in 1 s (FEV_1) and forced vital capacity (FVC) (1,2). Moreover, expiratory muscle weakness or paralysis is responsible for decreased cough efficiency and contributes to excess respiratory morbidity in this population (3).

For high-level cervical injuries, the phrenic motoneurons can often be damaged, resulting in ventilator dependence (4). In some cases, phrenic pacing (5) has been suggested as an alternative to a mechanical ventilator. There are also other, noninvasive options available, such as mouth (and possibly nasal) intermittent positive pressure ventilation (6). At lower cervical and thoracic level injuries, individuals can breathe independently, but lung volumes and flows recorded during a pulmonary function test (PFT) are typically well below predicted values. For individuals with C4–8 level injuries, FVC, FEV_1/FVC, and PEF are approximately 58 percent, 83 percent, and 54 percent of predicted, respectively (1). At lumbo-sacral levels, the PFT values of an individual are less affected by SCI (1,2).

Since FVC requires inhalation to total lung capacity followed by exhalation to residual volume, it is thought to be a good test of muscular strength, because it is dependent on both inspiratory and expiratory muscles (1). FVC is reduced in individuals with SCI. It may be at or near normal for the lowest levels of injury but is monotonically reduced along with ascending levels of injury. Although some loss of inspiratory capacity does occur in these patients, the primary contributor to reduced FVC is weakened or paralyzed expiratory muscles. Not surprisingly, these patients have a greater residual volume than controls (1).

The purpose of the present study was to assess the effect of transcutaneous electrical stimulation of upper motor neuron-paralyzed abdominal muscles on expiratory flows and volumes in individuals with SCI. The hypothesis to be tested was that FVC, FEV_1, and PEF could be increased over purely volitional levels by applying electrical stimulation to abdominal muscles during the performance of a standard PFT.

METHODS

Study Subjects

Ten male subjects were recruited from the inpatient and outpatient populations of the SCI Service at Hines Veterans Affairs Hospital. The selection criteria included volitional (unassisted) FVC ±90 percent of predicted, anatomical level of injury between C5–T7, upper motor-neuron paralysis of the abdominal muscles, tolerance of the electrical stimulation, visible abdominal muscle contraction upon application of electrical stimulation, and no current pulmonary complaint. The characteristics of the subjects are summarized in **Table 1**, including subject designator, age, height, weight, level of injury, American Spinal Injury Association (ASIA) classification, and years postinjury. None of the subjects had tracheostomies at the time the experiments were performed. The study was reviewed and approved by the Human Studies Subcommittee of the hospital. Written informed consent was obtained from all subjects.

Study Design

This study used a quasi-experimental, one-group design, with each subject serving as their own control. Each subject performed three PFTs under two conditions: with and without stimulation. Under each condition, subjects were encouraged to exert their maximal voluntary effort. Data were tabulated for each individual subject, and a linear regression approach was applied to the aggregate data.

Methods and Apparatus

Evaluation of Pulmonary Function

Lung volumes and PEF were measured by timed spirometry (P.K. Morgan Spiroflow, Gillingham, Kent, UK). Predicted values for each subject were based on neurologically intact nonsmoking individuals with no known pulmonary complaints and derived from gender, age, or height (7,8).

Electrical Stimulation

Electrical stimulation was delivered via eight surface electrodes (Unipatch Encore Plus Silver, 7.5 cm in diameter, Wabasha, MN). Two pairs of electrodes were placed on the lower abdomen, near the midline, and just

Table 1.
Characteristics of subjects.

Subject	Age (yr)	Height (m)	Weight (kg)	Level of injury	ASIA classification	Years post injury
A	75	1.73	70.3	C5	D	12
B	61	1.85	81.6	C7	D	8
C	41	1.73	85.0	C5	A	18
D	30	1.88	73.0	C6	A	2
E	64	1.80	81.0	T7	A	22
F	59	1.73	72.1	C6	B	24
G	46	1.85	69.3	C6	B	3
H	29	1.83	73.3	C5	B	1
I	49	1.88	69.8	C6	B	21
J	50	1.78	93.0	T6	A	12

above the iliac crest. Two other pairs of electrodes were placed on the upper abdomen near the midline, just below the ribs. Spacing between the electrode edges was approximately 3 cm. Two standard commercial neuromuscular stimulators (EMPI Focus, St. Paul, MN) delivered a pulse train of 8-s duration. The pulse train was manually triggered by the investigator, as close in time as possible to the onset of the forceful voluntary exhalation of the subject. The 8-s duration of the pulse train was controlled by a commercially available timed latch switch (Ablenet SLAT, Minneapolis, MN). The pulse amplitude was set manually by the investigator, based on visual inspection of the contraction obtained (up to a maximum of approximately 100 mA) and was constant throughout the pulse train. Pulse repetition rate and width were fixed at 50 pulses/s and 250 μs, respectively.

Protocol

Subjects were studied while seated in their personal wheelchairs. Six PFTs were obtained from each subject, alternating methods (volitional only or volitional with electrical stimulation). The maximum FVC, FEV_1, and PEF chosen from among the three trials under each condition were retained for analysis. In addition, the two best measurements of each variable under each condition had to be within 5 percent of each other to be accepted for analysis. It has been reported that although spirometry in individuals with SCI frequently does not meet American Thoracic Society (ATS) acceptability criteria, it is reproducible and valid for use in epidemiological studies (9).

Data Analysis

Data were tabulated to examine the differences between volitional and stimulated conditions for individual subjects. The measured and tabulated values for the ten patients included volitional and stimulated FVC, FEV_1, and PEF; corresponding percent of predicted values; and change observed between volitional and stimulated PFT. The results are presented in descending order of improvement seen in FVC with electrical stimulation.

After examining the data on an individual case basis, data from all subjects were analyzed with least squares linear regression, as described below. Individuals undergoing PFT will sometimes achieve greater than 100 percent predicted, while other individuals will achieve less than 100 percent predicted. When a sample population with no pulmonary problems is examined in aggregate, the distribution will be approximately normal, and the average will tend to the expected value of 100 percent predicted for any PFT parameter. In this study, when a subject's volitional effort approached 100 percent of the predicted value for any of the selected PFT parameters, the magnitude of the potential improvement with electrical stimulation would be reduced. A sample of individuals with SCI is likely to have a broad range of PFT values that are below 100 percent of predicted. Consequently, it is unlikely that observed individual changes in PFT values with or without stimulation, across all subjects in such a sample, will be normally distributed. Therefore, the classic paired-experimental design (e.g., compute and contrast means between volitional and stimulated) would not be appropriate. For this reason, linear regression procedures were used to determine if there was an effect of stimulation in this sample of subjects.

A scatterplot of "increase/decrease of percent of predicted, with stimulation" on "percent of predicted, volitional effort" was prepared for each PFT parameter. If no change was observed when electrical stimulation was applied, an individual's data point would lie along the horizontal line of zero change in percent predicted. If the stimulation were successful in restoring PFT function to what it would have been if there was no SCI, the data points would be expected to be distributed along a line with a slope of −1.0 passing through the point defined by (100 percent, 0 percent). Some of the individuals would achieve more than 100 percent predicted, others would achieve less than 100 percent predicted, but this line would represent the average restoration across all subjects. Finally, if electrical stimulation resulted in a decrease in the measured parameter, the data point would lie below the line of no effect.

With the use of the least-squares methods, a line of "best fit to the data points" was computed, to assess the overall effect of electrical stimulation on all subjects in the entire sample. A statistical test for nonzero slope of this regression line was used to determine if the effect of stimulation was statistically significant. Because of the use of percent of predicted values, the slope of this line could be interpreted as a measure of the change in percent of predicted associated with stimulation in the sample. Ninety-five-percent confidence intervals were computed for the regression line; these graphically illustrate the confidence interval for the improvement in the sample. If the confidence intervals did not include the horizontal line of zero effect, then a statistically significant change ($p<0.05$) occurred as a result of the stimulation, and the null hypothesis (i.e., that the stimulation had no effect) was rejected.

The paired t-test was used to evaluate the mean difference between measurements of FVC, FEV_1, and PEF for the entire sample of subjects in this study under the two experimental conditions. Because the potential existed that the data may not have been normally distributed, the nonparametric Wilcoxon signed-rank test was also used to test the equality of the medians of FVC, FEV_1, and PEF. In these analyses, an alpha of 0.05 was required for statistical significance.

RESULTS

All subjects tolerated the procedure well. There were no local or systemic adverse effects of electrical stimulation. All subjects produced data adequate for interpretation, and no data were excluded from the analyses. With stimulation, nine of the ten subjects demonstrated an increase in expiratory volumes and seven of the ten subjects demonstrated an increase in expiratory flow rate (i.e., as compared to volitional PFT). Special conditions were noted in two subjects: the first had a colostomy, which made electrode placement difficult and appeared to result in an asymmetry between right and left sides with respect to the resulting muscle contractions (subject E); the second reported discomfort with the stimulation during the PFTs, so that maximal intensity could not be used (subject H). This discomfort was not reported during the initial screening of this subject.

Raw volitional and stimulated values, corresponding percent predicted values, and the change between stimulation and volitional are presented in **Table 2**. Subjects are ordered by change in percent of predicted FVC, from a maximum change of 22 percent to a subject that showed no change (0 percent).

Composite scatterplots of increase/decrease in percent of predicted on percent of predicted for volitional, for FVC, FEV_1, and PEF, are shown in **Figure 1**. Note that with only two exceptions, all data points fall on or above the horizontal line of no effect. The slopes of the regression lines were negative and significantly different from zero, indicating that greater improvements tended to be seen for individuals with smaller percentages of the predicted values under volitional conditions. The slopes were FVC (−0.23), FEV_1 (−0.16), and PEF (−0.22). In **Figure 1**, the shaded areas illustrate the 95-percent confidence intervals for the regression line. On all three plots, the confidence intervals do not include the horizontal line of no effect. Therefore, there is a statistically significant difference in all three PFT values in the population because of stimulation.

Table 2.
"Best" volume and flow measures and percent predicted values (italicized values) for pulmonary function testing volitionally and with electrical stimulation of the abdominal muscles. Changes (△) are presented in **bold** and are result of subtracting volitional from stimulated values (shaded columns). Bottom two rows contain a summary of column data including mean±1 SD and median values. In addition, results of parametric (paired t-test) and nonparametric (Wilcoxon signed-rank test) analysis are presented following each of pairwise comparisons.

	FVC(L)		△ FVC(L)	FEV_1(L)		△ FEV_1(L)	PEF(L/s)		△ PEF(L/s)
Subject	Volitional	Stimulation	***(% pred)***	Volitional	Stimulation	***(% pred)***	Volitional	Stimulation	***(% pred)***
C	1.63 *(35%)*	2.62 *(57%)*	**0.99 *(22%)***	1.55 *(41%)*	2.20 *(57%)*	**0.65 *(16%)***	4.23 *(48%)*	5.83 *(66%)*	**1.60 *(18%)***
J	1.91 *(40%)*	2.89 *(61%)*	**0.98 *(21%)***	1.36 *(35%)*	2.21 *(57%)*	**0.85 *(22%)***	5.00 *(56%)*	6.71 *(75%)*	**1.71 *(19%)***
F	2.43 *(59%)*	3.05 *(74%)*	**0.62 *(15%)***	2.06 *(62%)*	2.25 *(68%)*	**0.19 *(8%)***	4.08 *(49%)*	4.92 *(60%)*	**0.84 *(11%)***
H	4.48 *(77%)*	5.05 *(87%)*	**0.57 *(10%)***	4.01 *(83%)*	4.31 *(90%)*	**0.30 *(7%)***	7.72 *(76%)*	8.98 *(88%)*	**1.26 *(12%)***
E	3.04 *(67%)*	3.24 *(72%)*	**0.20 *(7%)***	1.35 *(37%)*	1.33 *(37%)*	**-0.02 *(0%)***	3.83 *(44%)*	3.48 *(40%)*	**-0.35 *(-4%)***
G	4.10 *(83%)*	4.27 *(86%)*	**0.17 *(5%)***	3.61 *(90%)*	3.73 *(93%)*	**0.12 *(3%)***	6.99 *(76%)*	6.73 *(73%)*	**-0.26 *(-3%)***
I	2.29 *(41%)*	2.56 *(45%)*	**0.27 *(4%)***	1.91 *(42%)*	2.12 *(46%)*	**0.21 *(4%)***	3.98 *(40%)*	4.46 *(45%)*	**0.48 *(5%)***
B	2.67 *(50%)*	2.79 *(53%)*	**0.12 *(3%)***	1.97 *(46%)*	2.08 *(49%)*	**0.11 *(3%)***	5.43 *(57%)*	5.92 *(62%)*	**0.49 *(5%)***
A	2.80 *(77%)*	2.91 *(80%)*	**0.11 *(3%)***	2.19 *(77%)*	2.42 *(85%)*	**0.23 *(8%)***	4.11 *(53%)*	6.26 *(82%)*	**2.15 *(29%)***
D	5.45 *(88%)*	5.51 *(88%)*	**0.06 *(0%)***	4.69 *(91%)*	4.63 *(90%)*	**-0.06 *(-1%)***	8.92 *(84%)*	9.07 *(85%)*	**0.15 *(1%)***
Mean±SD	3.08±1.22	3.49±1.06	*P=0.006	2.47±1.19	2.73±1.09	*P=0.019	5.43±1.82	6.24±1.79	****P=0.015***
Median	2.74	2.98	‡P=0.005	2.02	2.23	‡P=0.012	4.62	6.09	‡***P=0.022***

FVC=forced vital capacity; FEV_1=forced expiratory volume in one second; PEF=peak expiratory flow rate; ***% pred***=percent of predicted value; ‡statistically significant result of paired t-test; *statistically significant result of Wilcoxon Signed-Rank Test

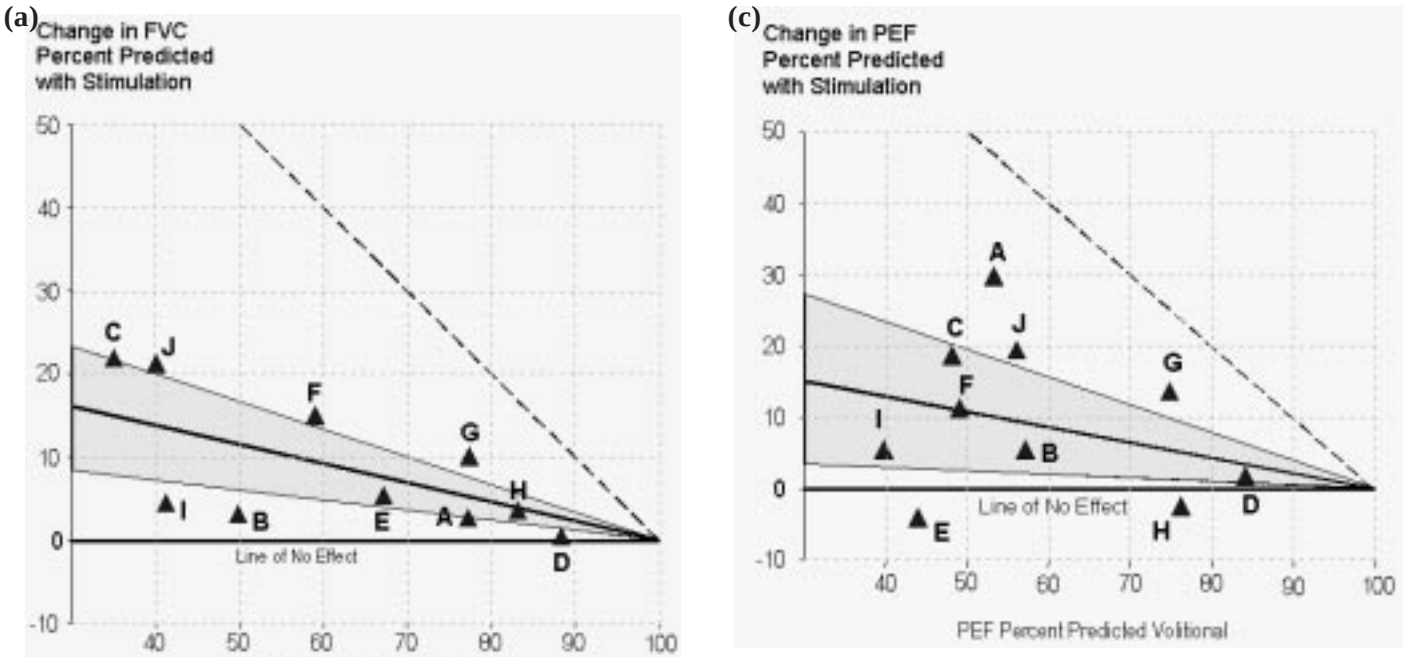

Figure 1
Composite plots for (a) forced vital capacity (FVC), (b) forced expiratory volume in 1 s (FEV_1, and (c) peak expiratory flow (PEF) for all subjects. Horizontal axis is percent of predicted for pure volitional effort with no assistance and represents line of no effect. Dashed line with a slope of −1.0 delineates restoration to 100 percent of predicted. Vertical axis is change in percent of predicted when electrical stimulation was delivered during PFT, and also represents line of no effect. Heavy solid line is a regression line forced through point {100 percent, 0 percent}. Shaded area shows 95 percent confidence intervals. Data for each subject are represented by individual data points labeled with subject letter identifier (see **Table 1**).

The greatest variation in the data around the regression lines was seen in the PEF data, which concomitantly showed the greatest width of confidence intervals. One possible explanation for this observation is that PEF occurs very soon after onset of stimulation and might be most affected by slight differences in timing between the subject's volitional effort and the delivery of stimulation. It is likely that FEV_1 and FVC would be less subject to this potential source of variability.

The results of the paired t-test and Wilcoxon signed-rank test showed a statistically significant difference ($p<0.05$) between the two experimental conditions for all pairwise comparisons of FVC, FEV_1, and PEF (see **Table 2**). To assure the reader that the sample size was sufficiently large to find statistical

significance in the presence of actual differences, a *post hoc* power analysis was performed. Under the conditions of these analyses, i.e., alpha=0.05 and a two-tailed t-test, the power for FVC, FEV_1, and PEF was determined to be 0.90, 0.72, and 0.76, respectively.

DISCUSSION

The present study demonstrated that electrical stimulation of the abdominal muscles could improve expiratory volumes and flows in some subjects with SCI. The results show that the larger the disparity between achieved and predicted values for the expiratory flows and volumes during the volitional effort, the greater the gain in the measured PFT value when electrical stimulation was applied. The results of the present study contribute to the growing body of knowledge on the use of electrical stimulation of paralyzed respiratory muscles to assist individuals with SCI who have pulmonary or ventilatory problems. These include phrenic stimulation of the diaphragm for inspiration, and stimulation of the abdominal muscles for cough and ventilation assist.

The feasibility of using abdominal muscle stimulation to improve cough in subjects with SCI has been demonstrated (10–13). Researchers employing surface electrodes in subjects with SCI have reported that maximum expiratory pressure can be increased over volitional when either manually assisted cough or electrically assisted cough are used (10). Investigators measuring PEF during cough have reported similar improvements over volitional for manually assisted or electrically assisted cough (11). The use of electromagnetic stimulation has also been studied with human subjects, showing increases in cough peak flow rate (12,13).

Phrenic pacing is another example of electrical stimulation that, for some individuals with SCI, can provide independence from mechanical ventilation. One recent study of approximately 700 individuals ranging in age from 2 mo to 89 y has demonstrated the potential for successful phrenic pacing (5). Some of these individuals have been followed for over 20 y. Phrenic pacing utilizes only the diaphragm, the major muscle of inspiration, to achieve ventilation. Electrical stimulation of accessory muscles of inspiration, such as the intercostals (14), has also been studied for the potential to assist or maintain ventilation. With the use of a concept similar to the proven electromechanical "pneumobelt" device (15,16) (which can produce ventilation in individuals with high-level cervical injuries, using an inflatable rubber corset), electrical stimulation of abdominal muscles to produce ventilation has been investigated (17), with promising results.

The best responses were seen for subjects C and J. Two of the subjects in this study had PFT values that could be considered within normal limits (subjects D and H) and showed no or minimal improvement over volitional with electrical stimulation. This may indicate that subjects with percent predicted values of approximately 80 percent or above are not likely to benefit from this technique. The notion that electrical stimulation of abdominal muscles might produce supramaximal results is not supported by the data from these two subjects.

In some subjects, there was either no improvement or a decrement in PFT values. Subject E, the one with the colostomy, for whom electrode placement was difficult, showed a resultant asymmetry between right and left sides with respect to the resulting muscle contractions. The contractions were minimal on the colostomy side. This may indicate that a colostomy is a contraindication for this procedure; however, this subject was the only one whose volitional PFT indicated an airflow obstruction (FEV_1/FVC=0.44). Thus, the obstructive condition could have also been a contributing factor to the ineffectiveness of the stimulation in this subject. This suggests further study may be needed of the effects of electrical stimulation on PFT in individuals with SCI who also have airway obstruction. It is likely that electrical stimulation will be ineffective in improving cough in individuals with airway obstruction.

Subject H reported discomfort with the stimulation during the PFTs, negating use of maximal stimulation intensity. However, this discomfort was not reported during the initial screening of this subject. This may indicate a more rigorous screening procedure for sensation should be developed for future studies.

Subject I did not show a significant improvement in PFT, despite having low percent predicted values for volitional PFT. Based on our subjective assessments, this subject had the weakest abdominal muscle response to the stimulation among all subjects studied. There are several possible explanations for this. The subject may have had a mixed upper and lower motor neuron paralysis of the abdominal muscles, which would have decreased the responsiveness to electrical stimulation. A more likely explanation is that muscle atrophy may account for the failure of stimulation to improve cough in this subject. This suggests a muscle restrengthening program might have some value, as discussed in the following paragraph.

Among all the studies of human subjects with SCI that involved the expiratory muscles discussed previously (10–14,17) as well as the present study, none has attempted to assess the state of the upper motor neuron-paralyzed abdominal muscles, with respect to atrophy. It is likely that these muscles had undergone varying degrees of disuse atrophy in most subjects. Thus, it is reasonable to assume that the immediate increases over volitional obtained with electrical stimulation in the present study are "worst case" values. These values might be improved, if the abdominal muscles were given a reconditioning or exercise program by electrical stimulation. Chronic electrical stimulation of upper motor neuron-paralyzed skeletal muscle has been shown to increase the strength of stimulated contractions, as well as improve fatigue resistance. Chronic stimulation in phrenic pacing has been shown to strengthen the diaphragm, and improve fatigue resistance (5).

In the present study, electrical stimulation of abdominal muscles was used successfully in some subjects with SCI to improve performance during standard clinical PFT. The challenge of the future is to expand on previous successful applications of electrical stimulation to improve pulmonary function, reduce pulmonary complications, and increase the quality of life for individuals with SCI. The results of the present study indicate the potential of using abdominal muscle stimulation in meeting this challenge, particularly in selected individuals with the most severe impairments.

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