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ORIGINAL ARTICLE

Neuromuscular electrical stimulation of completely paralyzed abdominal muscles in spinal cord-injured patients: a pilot study

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Study Design: Prospective placebo-controlled.
Objective: The effect of abdominal neuromuscular electrical stimulation (NMES) in patients with spinal cord injury. The principal parameters observed in this study are lung capacity, colonic transit, patient satisfaction of used method and of aesthetics effect on abdominal wall.
Settings: Centre de Traumatologie et de Réadaptation, Brussels, Belgium.
Methods: A total of 10 volunteers participated in this study and were assigned to two groups—the effective electrical stimulation group (ESG) and the placebo-controlled group (PG). NMES of abdominal muscles was performed 25 min per day for 8 weeks.
Results: NMES significantly decreased forced vital capacity (FVC) in ESG but not in PG. In ESG, colonic transit was accelerated in ascending, transverse and descending colon but transit in rectosigmoideum was not affected. In PG, no variations in colonic transit were observed. Satisfaction scale shows a better influence on aesthetics effect in ESG than in PG.
Conclusion: This pilot study shows that NMES of paralyzed abdominal muscles positively affects colonic transit except in rectosigmoideum segment and negatively affects FVC. It could be a simple self-used method to regulate colonic transfer with considerably good cosmetic effect on abdominal wall. However, regular verification of FVC will probably be necessary.
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Keywords: neuromuscular electrical stimulation; spinal cord injury; abdominal muscles; forced vital capacity; colonic transit

Introduction

Spinal cord injury (SCI) results in impairment or abolishment of motor control and sensibility below the level of the spinal lesion including loss of normal bladder and bowel function, disturbed sexual function and impaired function of the sympathetic nervous system. The affected individuals are often no more able to perform sufficient voluntary exercises to maintain a good level of physical fitness.

Neuromuscular electrical stimulation (NMES) refers to the electrical stimulation of an intact motor neuron to activate paralyzed or paretic muscles.[1] This method is used in neurological rehabilitation of SCI for functional or therapeutic benefit. NMES method was applied in upper- or lower-limb neuroprosthesis devices, in control of respiration and bladder function, for enhancement of muscle strength, retardation of muscles atrophy, reducing spasticity, prevention of disuse osteoporosis or deep venous thrombosis.[2] It was described that NMES resistance exercise therapy may reduce the risk of future cardiovascular disease.[3] Intensive regime of electrical stimulation can also result in considerable restitution of mass, excitability and force in denervated muscles more than 20 years after SCI.[4,5] Efficacy of delivered electrical current is dependent on stimulus frequency, amplitude and pulse width. The minimum stimulus frequency that generates a fused muscle response is $\sim$12.5 Hz. Greater muscle force generation is accomplished by increasing the pulse duration (200–300 μs).[1]

Functional abdominal muscles play a role of accessory expiratory muscles. The rectus abdominis is a key postural muscle ensuring a trunk flexion. Functions of the external oblique are rotation and flexion of the trunk that compresses the abdominal cavity and increases the intra-abdominal pressure. Both muscles are innervated by the lower six intercostal nerves (T7–T12).

The purpose of this study was to evaluate the effect of abdominal NMES on lung capacity, colonic transit, individual quality of live, patient satisfaction of used method and of aesthetics effect on abdominal wall, in subjects with complete abdominal muscle paralysis secondary to SCI.

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We hypothesized that 8 weeks of treatment would improve respiratory capacity and colonic transit.

Materials and methods

Participants

The study population consisted of 10 spinal cord injured-patients hospitalized at the Centre de traumatologie et de Réadaptation of Brussels. The study was reviewed and approved by the local ethics committee. Written informed consent was obtained from all subjects. The selection criteria included patients younger then 75 years with complete abdominal muscle paralysis and SCI level at least T10 or higher. Subjects who met any of the following exclusion criteria were excluded from participation: cardiac disease, presence of a pacemaker, metal implants in the area of stimulation (for example, baclofen pump), presence of abdominal hernia and pregnancy. Subjects were asked not to make changes to their physical activity levels, dietary habits or current bowel program (use of laxatives, defecatory maneuvers) during the period of the study.

Seven subjects were randomly assigned to two groups: four subjects to effective electrical stimulation group (ESG) and three subjects to placebo-controlled group (PG). After the end of first stimulation cycle, all three PG subjects decided to continue in ESG for a second cycle. Three new subjects started at the same time in PG. Globally, after two cycles of treatment, ten patients were recruited—seven subjects participated in ESG and six in PG. Three subjects (E, F and G) benefited from both stimulations. The characteristics of the subjects are summarized in Table 1, including sex, age, height, weight, months postinjury, level of injury and severity score according to the American Spinal Injury Association (ASIA) classification.[6] None of the subjects had tracheostomy at the time the experiment was performed.

Training

NMES was delivered via eight round self-adhesive 50 mm surface electrodes (Cefar Saint-Cloud Stimtrode, USA) placed over external oblique muscle and rectus abdominis muscle (bilaterally, two electrodes for each muscle). Stimulation was performed by a neuromuscular stimulator (Cefar Rehab 4 Pro, Cefar Medical AB, Chantonnay Cedex, France) delivered in a case of ESG biphasic square wave pulses of 300 μs duration with variable stimulus frequency 25–40 Hz. The 6 s pulse train was alternated with 6 s rest period for to minimize muscle fatigue effect.[7] The time of stimulation was 25 min per day. Intensity of the current was increased manually by the investigator to supramaximal level, based on visual inspection of the contraction obtained (50–120 mA). For PG we used biphasic square wave pulses of 50 μs duration with variable stimulus frequency 2–5 Hz and the 6 s pulse train alternated with 6 s rest period. Intensity of the current was identical with ESG and the subjects were stimulated also for 25 min per day. The phase duration and frequency used in PG cannot generate a muscle contraction response,[1,8] it is a reason why this type of current was chosen like placebo. Subjects of both groups were treated for 8 weeks (5 days per week).

Measurements

All measurements were done 1 week before beginning of the stimulation and 1 week after the end of the study.

Complete paralysis of abdominal muscles was one of the inclusion criteria for the study. Electromyography (EMG) was performed to evaluate muscle status before start and after the study ends. It consisted in detection of eventually volitional muscle fiber contraction by surface electrodes placed on the eight electrical stimulation points.

Forced vital capacity (FVC) was measured by spirometry (Schiller AT-60, Switzerland). The patients were first instructed about this method and they could do some training exercises before the test. The value of FVC was measured three times and the best result was taken. Predicted values for each subject were based on neurologically intact nonsmoking individuals with no known pulmonary complaints and derived from gender, age, weight and height.

For measurement of colonic transit,[9] patients ingested 20 radiopaque markers (Sims Portex Ltd, UK) and a simple

Table 1 Clinical characteristic of the patients

Subject	*Age (years)*	*Sex (M/F)*	*Height (m)*	*Weight (kg)*	*Months since injury*	*Lesion level*	*ASIA severity score classification*
ESG							
A	23	M	1.90	85	6	C8	C
B	32	M	1.79	80	5	T6	A
C	34	M	1.75	70	8	T5	A
D	71	M	1.73	75	4	C8	B
PG and ESG							
E	24	M	1.84	80	7	C6	B
F	64	F	1.70	60	25	C6	A
G	47	M	1.78	73	7	T4	A
PG							
H	43	M	1.89	87	32	T4	A
I	63	M	1.85	95	528	T10	A
J	25	M	1.73	55	8	C5	B

Abbreviations: ASIA, American Spinal Injury Association; ESG, electrical stimulation group; F, female; M, male; PG, placebo-controlled group.

abdominal X-ray film was realized 120 h after ingestion. Number of remaining markers in different colon segments (ascending colon, transverse colon, descending colon and rectosigmoideum) was measured.

Before and after the study, the functional ability of each participant was evaluated with the Catz–Itzkovich Spinal Cord Independence Measure (SCIM II) scale.[10] After the end of the study, patients completed a questionnaire about their satisfaction. It was a four-points scoring scale (1, dissatisfied; 2, moderately dissatisfied; 3, generally satisfied; 4, very satisfied) and two 'yes/no' questions were asked:

1. Are you satisfied with the method used?
2. Are you satisfied with the aesthetics effect on abdominal wall?

Statistics

Statistical comparison of the parameters before and after training was made using nonparametric Wilcoxon signed-ranks test. The values are described as mean ± standard deviation (s.d.) and levels of significance for test were set at $P \leqslant 0.05$. The software used was IFA Statistics (www.fon.hum.uva.nl/Service/Statistics.html).

We certify that all applicable institutional and governmental regulations concerning the ethical use of human volunteers were followed during the course of this research.

Results

All included subjects finished the whole cycle of NMES. From seven individuals (42 ± 19 years) participating in ESG three were paraplegic and four tetraplegic. Of six PG subjects (44 ± 18 years), three were paraplegic and three tetraplegic. Studied population is described in Table 1. We did not find any secondary effect of the used stimulation current except for a transitional spasticity increase in two ESG patients. This spasticity appeared in second week of stimulation and disappeared within 2 weeks.

FVC values in ESG and PG are shown in Table 2. In ESG, all patients had a decrease of their FVC after 8 weeks of electrical stimulation. The most important decreases were observed in patient B (15%), C (11%) and F (14%). Subjects B and C had highest FVC before experiment, 93 and 97%, respectively. Decrease of FVC mean was 0.33 l, which is statistically significant result for the Wilcoxon signed-ranks test (0.016). In PG, two subjects had a decreased FVC (33%), two had an increased FVC (33%) and two had unchanged FVC (33%). Decrease of FVC mean was 0.04 l, which was not a statistically significant result. Individual changes of FVC are shown in Figure 1a (ESG) and Figure 1b (PG). Comparing results of subjects E, F and G that participated firstly in PG and secondarily in ESF, we found small decrease of FVC after PG for subjects E and F (3 and 4%) but a 1% FVC increase for subject G. After the stimulation in ESG, subjects E and F further decreased FVC and also subject G developed a decrease of FVC to return to his basis level.

Number of remaining radiopaque markers 120 h after ingestion in all colonic segments and in three segments (ascending, transverse and descending colon) before and after study is displayed in Table 3. Comparison of the three segments markers quantity mean results in ESG and PG is shown in Figure 2. There was a decrease of total markers quantity in three colonic compartments (ascending, transverse and descending colon) for all patients in the ESG after the completion of the treatment, but not in PG. This result was no statistically significant for the Wilcoxon test ($P = 0.063$). In five of seven subjects of ESG (71%), reduced quantity of remaining markers in all segments was identified after NMES. In PG, the same result was observed only in one subject (17%). However, neither in ESG nor in PG any statistically significant result, after a statistical comparison of the means of total markers in all compartments (including rectosigmoideum), was calculated. Subjects E, F and G who participated in both groups showed, after PG stimulation, a decrease of remaining markers in all segments in one case (E), patient F had no change and patient G had an increased number of markers. After ESG stimulation, all three subjects decreased remaining markers quantity. Similar result of subjects E, F and G was described for the three compartments (excepting rectosigmoideum). Subjective evaluation of the colonic transit showed an improvement of bowel evacuation in six patients out of seven of the ESG (excepting subject D), but no subjective changes for PG subjects were observed.

Table 4 describes the satisfaction evaluation. We observed a good satisfaction of the used method in both groups with a score 3.71 on four in ESG and 3.00 on four in PG. Regarding aesthetics effect, the PG can be considered as not satisfactory with a score of 1.33 on four but the ESG with a 3.71 on four

Table 2 Forced vital capacity

Subject	FVC (l) (% pred)		Δ FVC (l) (% pred)
	Before NMES	After NMES	
ESG			
1st Cycle of NMES			
A	3.98 (66)	3.73 (62)	0.25 (4)
B	5.03 (93)	4.24 (78)	0.79 (15)
C	4.97 (97)	4.39 (86)	0.58 (11)
D	2.34 (55)	2.21 (52)	0.13 (3)
2nd Cycle of NMES			
E	3.72 (66)	3.29 (58)	0.43 (8)
F	1.70 (52)	1.59 (38)	0.11 (14)
G	3.83 (76)	3.78 (75)	0.05 (1)
Mean ± s.d.	3.65 ± 1.25	3.32 ± 1.05 *$P = 0.016$	
PG			
1st Cycle of NMES			
E	3.99 (69)	3.72 (66)	0.27 (3)
F	1.84 (56)	1.70 (52)	0.14 (4)
G	3.78 (75)	3.83 (76)	(−)0.05 (−1)
2nd Cycle of NMES			
H	4.31 (75)	4,33 (75)	(−)0.02 (0)
I	4.11 (81)	4.21 (83)	(−)0.10 (−2)
J	1.28 (25)	1.30 (25)	(−)0.02 (0)
Mean ± s.d.	3.22 ± 1.31	3.18 ± 1.33 *$P = 1.000$	

Abbreviations: ESG, electrical stimulation group; FVC, forced vital capacity; NMES, neuromuscular electrical stimulation; PG, placebo-controlled group; s.d., standard deviation; % pred, percent of predicted value; *P, P-value of Wilcoxon signed-ranks test.

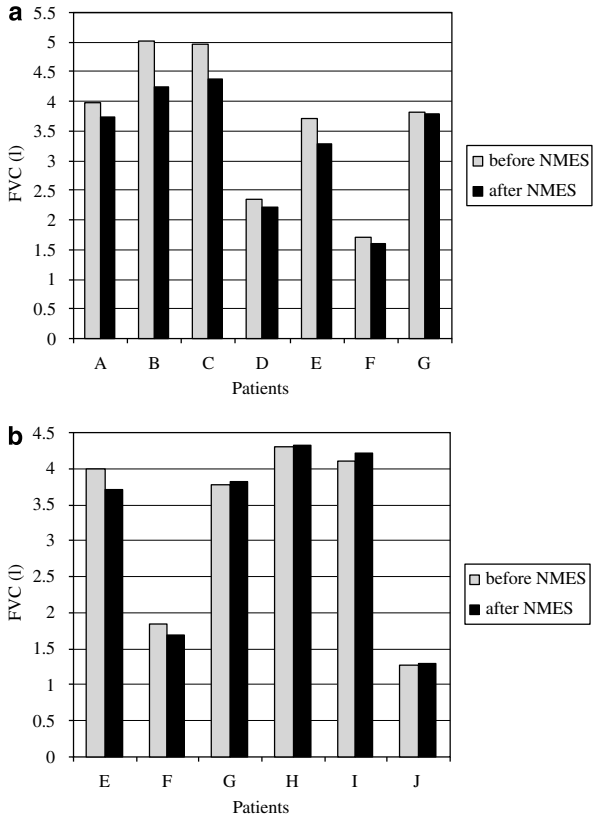

Figure 1 (**a**) Individual forced vital capacity (FVC) before and after abdominal neuromuscular electrical stimulation (NMES) in seven subjects of effective electrical stimulation group (ESG). (**b**) Individual FVC before and after abdominal NMES in six subjects of placebo group.

score can be considered as efficacious subjectively. Comparing aesthetics effect satisfaction of subjects E, F and G, they had a non-satisfactory score after PG but a perceived improvement after ESG.

Individual independence evaluation (SCIM II scale) was done before and after study, results are shown in Table 5. No significant changes were seen in ESG or PG.

Comparing results before and after study of both investigated groups, no significant variations of lesion level were observed. In subject A, functional muscles activity in right external oblique and right rectus abdominis muscle was found by EMG performed after the end of treatment.

Patient A is level C8 tetraplegia classified as ASIA C because of volitional lower-limb muscle activity. However, before the study he had complete paralysis of abdominal muscles by EMG. The volitional abdominal muscles activity after the end of the study was considered as spontaneous evolution of his SCI.

Table 3 Total number of radiopaque markers in all segments and in first three compartments (ascending, transverse and descending colon)

Subject	*Total number of markers (%)*		*Number of markers (%) A+T+D*	
	Before NMES	*After NMES*	*Before NMES*	*After NMES*
ESG				
1st Cycle of NMES				
A	2 (10)	10 (50)	0 (0)	0 (0)
B	20 (100)	15 (75)	19 (95)	12 (60)
C	20 (100)	14 (70)	20 (100)	13 (65)
D	5 (25)	16 (80	2 (10)	0 (0)
2nd Cycle of NMES				
E	2 (10)	0 (0)	0 (0)	0 (0)
F	20 (100	17 (85)	8 (40)	7 (35)
G	15 (75)	13 (65)	13 (65)	0 (0)
Mean ± s.d.	12.00 ± 8.66	12.14 ± 5.81 *P = 0.938	8.86 ± 8.65	4.57 ± 5.99 *P = 0.063
PG				
1st Cycle of NMES				
E	7 (35)	2 (10)	1 (5)	0 (0)
F	20 (100)	20 (100)	10 (50)	8 (40)
G	9 (45)	15 (75)	6 (30)	13 (65)
2nd Cycle of NMES				
H	20 (100)	20 (100)	9 (45)	11 (55)
I	20 (100)	20 (100)	19 (95)	14 (70)
J	20 (100)	20 (100)	10 (50)	9 (45)
Mean ± s.d.	16.00 ± 6.23	16.17 ± 7.22 *P = 1.000	9.17 ± 5.91	9.17 ± 5.04 *P = 0.844

Abbreviations: A+T+D, ascending+transverse+descending colon; ESG, electrical stimulation group; NMES, neuromuscular electrical stimulation; PG, placebo-controlled group; s.d., standard deviation; %, percent of 20 markers; *P, P-value of Wilcoxon signed-ranks test.

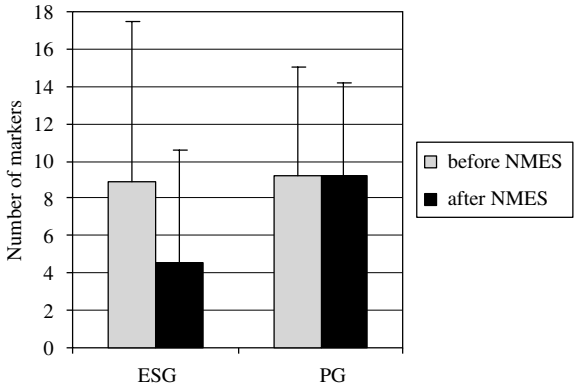

Figure 2 Total quantity of radiopaque markers in ascending, transverse and descending colon (A + T + D) before and after abdominal neuromuscular electrical stimulation (NMES), comparison of effective electrical stimulation group (ESG) and placebo group (PG). Values reported as means ± s.d..

Discussion and conclusion

Respiratory capacity

Our results show the negative influence of NMES on FVC. These data are discordant with some published studies. It was described that contraction of paralyzed expiratory muscles in response to electrical stimulation during the performance of pulmonary testing maneuvers can significantly improve FVC in some individuals with SCI.[11] It has been observed that lower thoracic spinal cord stimulation, which generates contraction of the obliques and transversus abdominis muscles, contributes largely to changes in

Table 4 Satisfaction scale

Subject	*Satisfaction of used method (score 1–4)*	*Aesthetics effect (score 1–4)*
ESG		
A	4	4
B	4	4
C	4	4
D	2	3
E	4	3
F	4	4
G	4	4
Mean ± s.d.	3.71 ± 0.76	3.71 ± 0.49
PG		
E	3	1
F	3	1
G	4	1
H	3	2
I	2	1
J	3	2
Mean ± s.d.	3.00 ± 0.63	1.33 ± 0.52

Abbreviations: ESG, electrical stimulation group; PG, placebo-controlled group; s.d., standard deviation.

Table 5 Independence scale

Subject	*SCIM II Scale (total of 100)*	
	Before NMES	*After NMES*
ESG		
A	69	69
B	67	67
C	67	67
D	34	34
E	22	22
F	13	13
G	28	45
PG		
E	16	22
F	13	13
G	26	28
H	49	49
I	51	51
J	17	17

Abbreviations: ESG, electrical stimulation group; NMES, neuromuscular electrical stimulation; PG, placebo-controlled group; SCIM, Spinal Cord Independence Measure.

positive airway pressures in anesthetized dogs.[12] One recent study showed promotion of respiration and cough by applying electrical simulation to abdominal muscles assisted by EMG. But there were no significant changes or even reduced FVC when the technique was used without EMG assistance.[13] For discussion about these contradictory results, it is necessary to underline that our FVC measurements were realized after 8 weeks' durable NMES and this test was not linked to any simultaneous stimulation. All cited studies tried to show effect of muscles stimulation synchronized with respiration parameters measurement. Decrease of FVC in our study could be interpreted by abdominal muscle mass restitution with increase of abdominal wall pressure. Seeing that this mass is completely inactive, it could have paradoxically negative effect on diaphragm within inspiration with decrease of inspiratory capacity.

Colonic transit

As shown in previously published studies, SCI is associated with bowel function abnormalities and clinical complaints.[14] Investigation of abdominal massage effect on colonic function parameters in spinal cord injured-patients showed some positive clinical aspects of bowel dysfunction. However, abdominal massage did not change colonic transit in constipated group without SCI.[15] It has been demonstrated that direct electrical stimulation of the colon following SCI improved colonic transit in adult male cats.[16] Our study observed a positive effect of NMES on colonic transit activity. Means of remaining markers show accelerated transit in all segments except rectosigmoideum. This result is statistically not significant for nonparametric Wilcoxon test. Total transit time was improved individually in 71% of ESG subjects, but there was no variation in the mean result before and after study completion. The bowel function was subjectively improved in 86% of ESG subjects and in 0% of PG subjects.

The present research demonstrated that NMES of paralyzed abdominal muscles by SCI could not only accelerate colonic transit, except in rectosigmoideum, but also decrease lung capacity. This is the first evaluation study that tries to show the global impingement of abdominal NMES on spinal cord injured-patients. Obviously, the small size of the study groups does not allow significant conclusions. Further studies of larger patient groups are required to develop this method. It could be also interesting to compare different parameters of delivered stimulation current. In case of confirmation of our results, we suggest to apply this method as a long-term home treatment considering the easy self-application of the electrodes and also accessibility of stimulation devices. However, it would be probably necessary to control regularly the FVC of stimulated subjects.

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