〈Regular Article〉

Effects of mechanical insufflation-exsufflation on compartmental chest wall volume in patients with chronic cervical spinal cord injuries

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ABSTRACT The purpose of this study was to evaluate the effects of mechanical insufflation-exsufflation (MI-E) on volume change of the chest wall and each compartment of the chest wall in patients with cervical spinal cord injury using optoelectronic plethysmography (OEP).

Fourteen male patients with chronic cervical spinal cord injuries were included with the following characteristics: age, 56.2 ± 13.6 years; height, 168.4 ± 5.5 cm; body weight, 62.3 ± 12.7 kg; median number of days after injury, 387 days (range, 200-3575 days). The change of chest wall volume was significantly greater during MI-E of ≥ ±30 cmH_2O than when taking a deep breath. The volume change in the upper and lower thorax compartment was significantly greater during MI-E of ≥ ±30 cmH_2O than when taking a deep breath. However, MI-E made no significant difference to the volume of the upper and lower thorax compartment between pressures of ±30 cmH_2O and ±50 cmH_2O. The volume change in the abdomen compartment was slightly greater during MI-E than when taking a deep breath, but this was not statistically significant.

The findings of this study indicate the possibility of maintenance or improvement of the compliance of the chest wall, especially the rib cage in patients with spinal cord injuries, using MI-E. In turn, these findings could lead to the prevention of pulmonary complications.

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INTRODUCTION

The incidence of respiratory disorders as the cause of death in patients with spinal cord injuries is increasing[1, 2)]. Insufficient airway clearance, which increases the risk of the airway secretion retention, atelectasis, and pneumonia[3-5)], seems largely

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Effective airway clearance requires adequate inspiratory volume and expiratory strength. Forced vital capacity (FVC) standardized with age[6)] and airway clearance capacity are reduced in patients with cervical spinal cord injuries compared with healthy individuals and patients with paraplegia. In addition, decline of pulmonary function with age is faster in this population. Once these functions are compromised, a manual cough assist or mechanically assisted coughing (MAC) is recommended[7)].

MAC, or mechanical insufflation-exsufflation (MI-E), a therapy in which a device gradually inflates the lungs (insufflation) and quickly deflates, producing a rapid exhalation (exsufflation) and generating a maximum of 600 L/min of cough peak flow (CPF), has recently been reintroduced as a method for enhanced expectoration of sputum in patients with respiratory muscle paralysis[8, 9)]. Bach *et al*. evaluated CPF in patients with spinal cord injuries using various procedures and found that MI-E generates the highest CPF[10)].

Maintenance of chest wall compliance is important for effective airway clearance. Patients with cervical spinal cord injury have poor rib cage movements during breathing due to the intercostal muscle paralysis. Occasionally, paradoxical movements are observed in some cases[11)], which may cause rib cage contractures due to reduced rib cage volume during inspiration. Unlike in cervical cord injuries, where the function of the diaphragm is maintained, neuromuscular patients lose both inspiratory and expiratory muscle strength. Therefore, distribution of contracture of the chest wall seems to be different between these two disease groups. For patients with neuromuscular disease, enforcement of air stacking is recommended in order to prevent a decrease in compliance of the chest wall. However, the question arises as to whether a similar procedure to that used in neuromuscular disease patients is effective for cervical spinal cord injuries.

Optoelectronic plethysmography (OEP) enables analysis of compartmental movement of the chest wall[12)]. As chest wall compliance of patients with spinal cord injuries is higher in the abdomen than in the rib cage[13)], we hypothesized that MI-E might be less effective in the rib cage than in the abdomen.

The purpose of this study was to evaluate the effects of MI-E on volume change of the chest wall and each compartment of the chest wall in patients with cervical spinal cord injuries. This will allow us to determine whether rehabilitation for maintaining compliance in these patients requires MI-E only or if additional approaches to facilitate the rib cage are required.

MATERIALS AND METHODS

Subjects

Patients with chronic cervical spinal cord injuries who did not receive MI-E, had spontaneous respiration, and visited the outpatient clinic of Kibikogen Rehabilitation Center for Employment Injuries on a regular basis between May 2016 and January 2017 were recruited. The inclusion criteria were as follows: (1) patients with cervical spinal cord injuries at ≥ 180 days after injury; (2) patients with an American Spinal Injury Association impairment scale (AIS) classification of A, B, C, or D; and (3) patients in a stable condition without acute respiratory disease or other complications in the 4 weeks preceding enrolment. The exclusion criteria were as follows: (1) patients who were unable to follow the test instructions due to cognitive dysfunction or mental disorders and (2) patients with findings suggesting respiratory complications such as upper airway symptoms, fever, and sputum.

Ethics

This study was approved by the ethics committee of Kibikogen Rehabilitation Center for Employment

Injuries (approval number: 9-1). All subjects gave written informed consent prior to the study.

OEP

Each subject was instructed to lie on a bed in the supine position and 45 reflective markers were placed on predetermined locations on the chest wall (Fig. 1). To determine a reference plane on the bed, 4 markers were placed on the backrest in locations where they would not be covered by the subject's body. The subject's shoulders were slightly abducted so that the markers on the chest could be photographed by the cameras. The respiratory movements were recorded by a 3D optoelectronic motion analysis system (Vicon MX; Vicon Motion Systems, Oxford, UK) with 6 infrared cameras placed around the subject. Virtual markers (i.e., markers on the back inferior to the nipple level in a horizontal cross-section) were defined as the points at which lines dropped perpendicular to the bed from the markers on the anterior and lateral surfaces of the chest wall intersected a reference plane created by four markers placed on the bed (Fig. 2). The 3D coordinates of the infrared reflective markers on

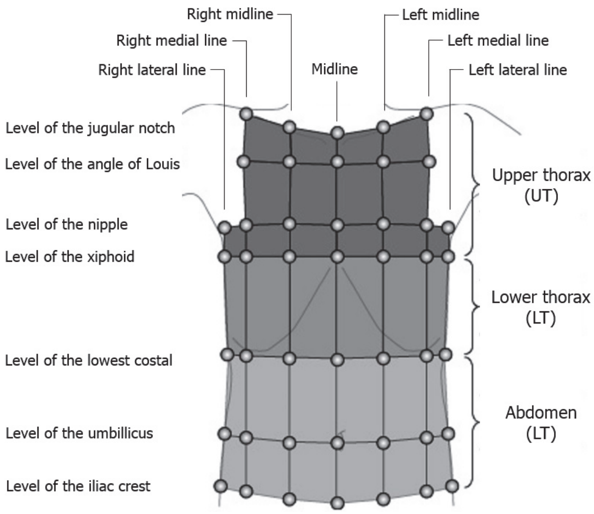

Fig. 1. Positions of the reflective markers on the chest wall.

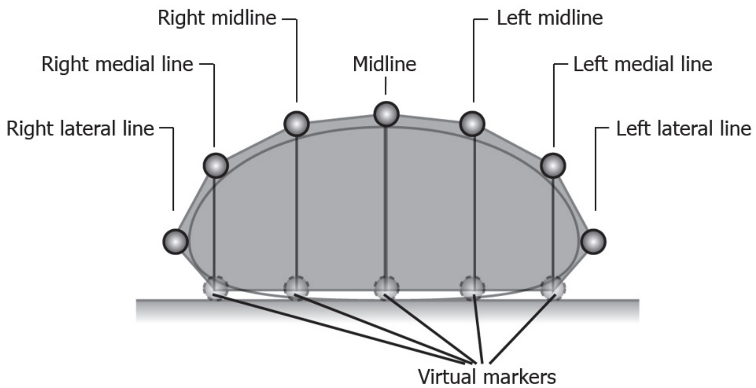

Fig. 2. Positions of virtual markers on the back, inferior to the nipple level, in a horizontal cross section.
Virtual markers were defined as the points at which lines dropped perpendicular to the bed from the markers on the anterior and lateral surfaces of the chest wall intersected a reference plane created by four markers placed on the bed.

the body surface were sampled at 120 Hz and used to calculate the volume of each compartment of the chest wall.

Study protocol

The subjects were given adequate time to breathe naturally. Then, various parameters of pulmonary function were measured in the supine position. FVC and $FEV_{1.0}$ were measured using standard procedure. Maximal expiratory pressure (PEmax) was measured under the instruction to exhale as hard as possible for more than 1.5 sec at maximum inspiratory level, and maximum inspiratory pressure (PImax) was measured under the instruction to inhale as hard as possible for more than 1.5 sec at maximum expiratory level, using an electrical spirogram (Autospiro AS-507, Minato Medical Science, Osaka, Japan). CPF was then measured by a peak flow meter (ASSESS, Health Scan Products Inc, Cedar Grove, NJ, USA).

Subjects were then instructed to breathe quietly after a deep breath and then repeat the process several times. In other words, they were instructed to perform forced inspiration and expiration at least 3 times before MI-E was applied. After patients breathed quietly several times, mechanical insufflation (+30 cmH_2O) and exsufflation (-30 cmH_2O) were performed using the CoughAssist E70 (Philips Respironics, Inc., Murrysville, PA, USA), and this was repeated several times. Each session was repeated at least 3 times. After a few minutes of rest, similar sessions were performed at ±40 cmH_2O and ±50 cmH_2O. The discontinuation criteria were as follows; (1) the subject requested to discontinue; (2) the subject reported severe fatigue; and (3) the subject complained of respiratory symptom.

Calculation

The following parameters were calculated from the saved 3D coordinate data of the reflective markers.

Chest wall volumes

The total volume of the chest wall (V_{CW}) and the volume of each compartment of the chest wall were calculated from the 3D coordinates of the reflective markers' using the methods of Ferrigno and Carnevali *et al.*[14] and Wang *et al.*[15] V_{CW} was divided into compartments as follows: volume of the upper thorax (V_{UT}), volume of the lower thorax (V_{LT}), and volume of the abdomen (V_{AB}). V_{UT} was the volume superior to the xiphoid process, V_{LT} was the volume from the xiphoid process to the lowest costal level, and V_{AB} was the volume inferior to the lowest costal level (Fig. 1). In other words, $V_{CW} = V_{UT} + V_{LT} + V_{AB}$.

Changes in chest wall volume

Changes in volume during respiration were calculated from variations in the obtained chest wall volumes. ΔV_{CW} was calculated as the volume difference between V_{CW} at maximum inspiratory level and V_{CW} at maximum expiratory level. ΔV_{UT}, ΔV_{LT}, and ΔV_{AB} were calculated in the same way for the compartment volume of the upper thorax, lower thorax, and abdomen, respectively. Three consecutive samples of each deep breath and the respective pressure of MI-E were taken and averaged.

Statistical analysis

ΔV_{CW} and changes in compartment volumes (ΔV_{UT}, ΔV_{LT}, and ΔV_{AB}) during deep breath and MI-E were evaluated by 1-way ANOVA. When a significant difference was obtained, the difference in the average value was further analyzed using the Bonferroni post-hoc comparison. The significance level was set at less than 5%. IBM SPSS® Statistics 21 (IBM Inc., Tokyo, Japan) was used for all analyses.

Table 1. Demographic data of subjects

	Age (years)	Height (cm)	Weight (kg)	Days from injury (days)	Neurological Level	AIS	FVC (L)	%FVC (%)	$FEV_{1.0}$ (L)	$FEV_{1.0\%}$ (%)	PEmax (cmH_20)	PImax (cmH_20)	CPF (L/min)
Subject 1	61	165	50	280	C4	D	2.39	63.6	2.41	85.8	36.4	53.6	230
Subject 2	55	170	66.7	475	C5	C	2.4	58.1	1.80	73.5	12.7	13.4	180
Subject 3	54	169	99	423	C7	B	3.33	75.2	2.43	79.7	14.2	6.4	150
Subject 4	42	169	58.5	217	C6	D	1.65	37.7	1.37	90.7	20.5	16.1	270
Subject 5	62	167	72	457	C5	D	2.82	75.4	2.37	84.0	54.8	68.2	420
Subject 6	60	167	64.6	1952	C4	D	1.57	41.7	1.04	66.2	29.8	10	180
Subject 7	51	171	65	474	C4	D	3.22	75.6	2.78	92.8	45.2	50.8	380
Subject 8	69	168	68	744	C4	B	1.93	53.4	1.33	68.9	64.1	52.7	250
Subject 9	39	160	49	327	C5	B	3.09	76.5	2.81	92.2	39.4	91.9	320
Subject 10	52	168	55.2	350	C6	D	2.77	67.7	1.99	82.6	39.1	37.6	390
Subject 11	49	172	62	310	C4	D	3.58	82.2	3.03	83.2	60.4	55.4	470
Subject 12	73	168	55.5	3575	C4	D	1.87	52.9	1.87	94.9	25.4	28.3	290
Subject 13	18	183	73	200	C4	D	2.9	52.1	2.43	88.4	19.2	50	250
Subject 14	52	160	60	200	C5	B	2.18	58.1	1.38	95.7	35.2	34.3	210

Fourteen male patients with chronic cervical spinal cord injuries were included in this study. AIS indicates the degree in the American Spinal Injury Association scale.

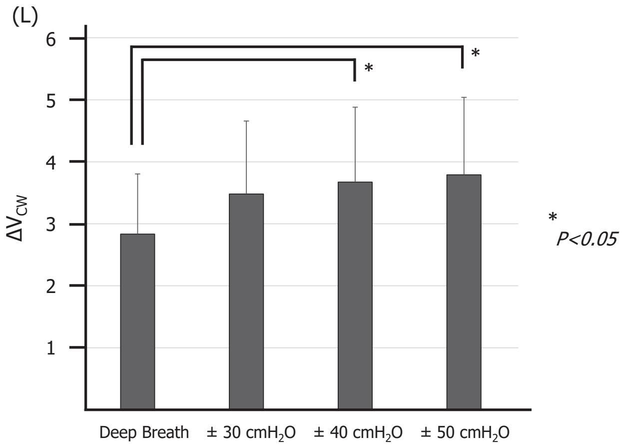

Fig. 3. ΔV_{CW} during MI-E and deep breath.
The change in volume of the chest wall (ΔV_{CW}) was significantly greater during MI-E of ≥ ± 40 cmH_2O than during deep breath.

RESULTS

Subjects

Fourteen male patients with chronic cervical spinal cord injuries were included in this study with the following characteristics: age, 56.2 ± 13.6 years; height, 168.4 ± 5.5 cm; body weight, 62.3 ± 12.7 kg; the median number of days after injury, 387 days (range, 200-3,575 days). Neurological levels as defined by AIS were as follows: AIS B: 4 patients, AIS C: 1 patient, and AIS D: 9 patients. All experimental processes were performed safely; there were no side effects and or dropouts. The subject's demographic data are shown in Table 1.

Changes in the volume of the chest wall

ΔV_{CW} was significantly greater during MI-E of ≥ ± 40 cmH_2O than during deep breath (Fig. 3).

ΔV_{UT} and ΔV_{LT} was significantly greater during MI-E of ≥ ± 30 cmH_2O than during deep breath. There was no significant difference in the volume

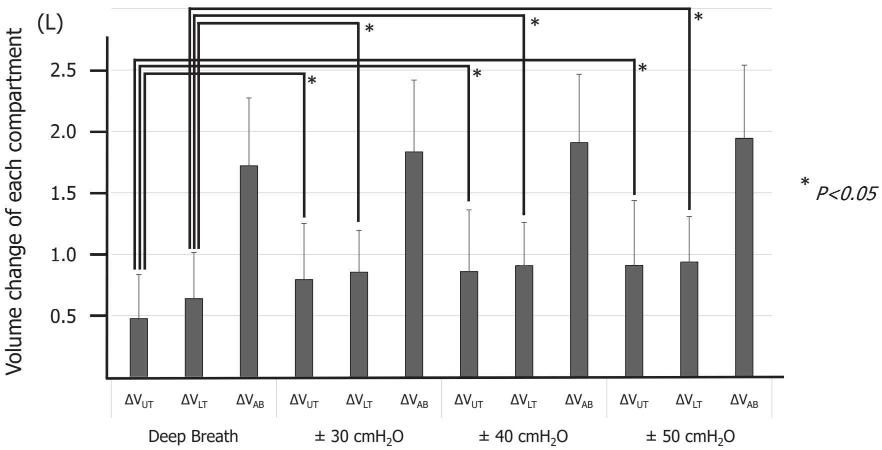

Fig. 4. Volume change of each compartment of the chest wall during MI-E and deep breath.
The change in the volume of the upper thorax (ΔV_{UT}) and lower thorax (ΔV_{LT}) was significantly greater in all inspiratory and expiratory pressures during MI-E of $\geq \pm 30$ cmH_2O than during deep breath. The changes in the volume of abdomen (ΔV_{AB}) during deep breath and MI-E were not significantly different.

change of the upper and lower thorax between MI-E at pressures of ± 30 cmH_2O and ± 50 cmH_2O. ΔV_{AB} was slightly greater during MI-E than during deep breath, but this was not statistically significant (Fig. 4). Moreover, regarding the increase from deep breathing when using MI-E at pressure of $\pm$ 50 cmH_2O, the proportion of each compartment of the chest wall in the total volume increase was as follows: upper thorax 46%, the lower thorax 31% and the abdomen 23%.

DISCUSSION

We commonly evaluate compliance of the chest wall using maximum insufflation capacity (MIC), which is measured using the same maneuver as for vital capacity followed by full insufflation using a resuscitation bag, MI-E, glossopharyngeal breathing, and so on. Although it is a widely used and simple method for monitoring compliance, we could not determine which part contributes to the expansion of the chest wall. In the current study, Δ VCW by insufflation/exsufflation of ± 50 cmH_2O was 34% higher than that achieved by deep breath, which would produce a more effective cough. However, in the evaluation of each compartment of the chest wall, compartment expansion due to insufflation by MI-E was observed in the upper and lower thorax, but not in the abdomen. Additionally, we observed that the upper thorax contributed the most to the increase in chest wall volume. Goldman *et al.*[13] found that the abdominal wall in patients with quadriplegia had 2 times greater compliance than that of normal subjects. Nevertheless, the reason for the greater change in the rib cage was that the compliance of the rib cage may have decreased. However, the relatively small voluntary movement of this compartment led to a significant volume increase by MI-E. In addition, it seems that the severe contracture of the rib cage had not yet developed in the current subjects.

To the best of our knowledge, this study is the first to attempt compartmental chest wall analysis following MI-E application in patients with spinal cord injuries. MI-E seems to be effective for the maintenance or improvement of compliance of the rib cage, even in chronic patients. Prevention of pulmonary complications can be expected with appropriate introduction of MI-E in patients with cervical spinal cord injuries.

The limitation of this study is that virtual markers must be used because subjects with cervical spinal cord injury were evaluated in the supine posture. 89 markers were applied in the original OEP method[12]. However, we placed 45 markers on the anterior and lateral surface of the chest wall of the subjects and the rest of the marker that should be placed on the back were virtual which derived from calculation of the other markers. Therefore, the volume error due to sinking into the bed cannot be evaluated, even if the estimate suggests it to be minimal. In a report on healthy subjects in the sitting position with and without backrest, OEP with a backrest showed that friction between the back of the subject and the backrest limited chest wall movement[16].

CONCLUSION

We evaluated the volume change of the chest wall when we applied MI-E for patients with cervical spinal cord injury using OEP. The change in volume of the chest wall was significantly greater during MI-E of ≥ ±30 cmH_2O than during deep breath. The volume of the upper and lower thorax within the chest wall compartment was significantly increased following MI-E compared to deep breathing; this, however, was not observed in the abdomen compartment. This study indicates the possibility of maintenance or improvement in rib cage compliance in patients with spinal cord injuries using MI-E, which may lead to the prevention of pulmonary complications.

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CONFLICTS OF INTEREST

The authors have no conflicts of interest to disclose.

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