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ORIGINAL ARTICLE

Comparison of the effects of voluntary and involuntary breath stacking techniques on respiratory mechanics and lung function patterns in tracheostomized patients: a randomized crossover clinical trial

Luciano Matos Chicayban[1,2,3], Alice Campos Hemétrio[3], Liz Tavares Rangel Azevedo[3]

1. Laboratório de Pesquisa em Fisioterapia Pneumofuncional e Intensiva, Institutos Superiores de Ensino do Centro Educacional Nossa Senhora Auxiliadora – ISECENSA – Campos dos Goytacazes (RJ) Brasil.
2. Unidade de Terapia Intensiva, Hospital Geral de Guarus – HGG – Campos dos Goytacazes (RJ) Brasil.
3. Curso de Fisioterapia, Institutos Superiores de Ensino do Centro Educacional Nossa Senhora Auxiliadora – ISECENSA – Campos dos Goytacazes (RJ) Brasil.

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ABSTRACT

Objective: To compare the effects of voluntary breath stacking (VBS) and involuntary breath stacking (IBS) techniques on respiratory mechanics, lung function patterns, and inspiratory capacity in tracheostomized patients. **Methods:** This was a randomized crossover clinical trial involving 20 tracheostomized patients admitted to the ICU and submitted to the VBS and IBS techniques, in random order, with an interval of 5 h between each. Ten cycles of each technique were performed with an interval of 30 s between each cycle. In VBS, patients performed successive inspirations for up to 30 s through a one-way valve, whereas in IBS, successive slow insufflations were performed with a resuscitator bag until the pressure reached 40 cmH_2O. Respiratory mechanics, inspiratory capacity, and the lung function pattern were evaluated before and after the interventions. **Results:** After IBS, there was an increase in static compliance ($p = 0.007$), which was also higher after IBS than after VBS ($p = 0.03$). There was no significant difference between the pre-VBS and post-VBS evaluations in terms of static compliance ($p = 0.42$). Inspiratory capacity was also greater after IBS than after VBS (2,420.7 ± 480.9 mL vs. 1,211.3 ± 562.8 mL; $p < 0.001$), as was airway pressure (38.3 ± 2.6 cmH_2O vs. 25.8 ± 5.5 cmH_2O; $p < 0.001$). There were no changes in resistance or lung function pattern after the application of either technique. **Conclusions:** In comparison with VBS, IBS promoted greater inspiratory capacity and higher airway pressure, resulting in an increase in static compliance.

Keywords: Mucociliary clearance; Respiratory care units; Respiratory mechanics; Physical therapy modalities.

INTRODUCTION

Patients admitted to the ICU show increased mucus production and impaired mucociliary clearance. The deleterious effects of prolonged bed rest, acquired muscle weakness, and advanced age make it difficult to mobilize and eliminate mucus.[1] Acquired respiratory muscle weakness due to long ICU stays reduces lung volume, sighing, and peak cough flow (PCF), resulting in decreased expansion of the lungs and rib cage.[2] The progressive loss of inspiratory muscle strength leads to a restrictive pattern of lung function, causing complications such as atelectasis, pulmonary infection, and gas exchange dysfunction. In addition, deterioration of the expiratory muscles decreases cough effectiveness.[1] The combination of a restrictive pattern of lung function and the inability to adequately clear pulmonary secretions increases the incidence of respiratory complications.[3,4] In patients with neuromuscular disease, increased survival is related to bronchial hygiene measures, such as assisted cough and manual hyperinflation.[4]

Involuntary breath stacking (IBS) can be defined as a technique of pulmonary insufflation through multiple inspiratory efforts achieved with the assistance of a resuscitator bag. IBS is performed with a one-way valve and has the objective of producing volumes greater than the resting inspiratory capacity (IC).[2] The benefits of IBS include increased inspiratory volume, improved thoracic mobility, prevention of atelectasis, and mobilization of secretions. IBS is widely used in order to improve cough effectiveness in patients with neuromuscular diseases, such as Duchenne muscular dystrophy, quadriplegia, and amyotrophic lateral sclerosis, because of the associated respiratory muscle weakness.[2,5]

Voluntary breath stacking (VBS) is based on encouraging inspiration by occluding the expiratory port of the one-way valve and allowing only the inspiratory flow.[6] However, the patient should actively recruit progressively increasing volumes of air, via contraction of respiratory muscles. The VBS technique came to be widely used after it was shown to produce higher vital

Correspondence to:
Luciano Matos Chicayban. Rua Doutor Augusto Bessa, 324, Parque Turf Club, CEP 28015-150, Campos dos Goytacazes, RJ, Brasil.
Tel.: 55 22 99803-0510. E-mail: lucianochicayban@gmail.com
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capacity values than did the conventional method in patients with an obstructive or restrictive pattern of lung function, in those with neuromuscular disease, and in healthy individuals.[7]

We have found no studies that compared the therapeutic effects of the VBS and IBS techniques or analyzed the volumes recruited and pressures achieved by the two techniques in tracheostomized patients admitted to the ICU. The hypothesis of the present study was that IBS would increase IC, with clinically relevant effects on lung compliance. Therefore, the objective of the present study was to compare the effects of VBS and IBS on respiratory mechanics, lung function patterns, and IC in tracheostomized patients admitted to the ICU.

METHODS

This was a randomized crossover clinical trial involving 20 tracheostomized adults admitted to the ICU of the Guarus General Hospital, in the city of Campos dos Goytacazes, Brazil, all of whom had been breathing spontaneously, with no need for ventilatory support, for at least 96 h. Patients with undrained pleural effusion or undrained pneumothorax were excluded from the study, as were those with static compliance values less than 25 mL/cmH_2O and those who were unable to undergo measurement of respiratory mechanics (Figure 1). The study was approved by the Research Ethics Committee of the Institutes of Higher Education of the Our Lady of Perpetual Help Education Center (Reference no. 93156718.0.0.0000.5524), in the city of Campos dos Goytacazes. Written informed consent was obtained from the legal guardians of all participating patients.

Intervention

All patients were submitted to the VBS and IBS techniques with an interval of 5 h between each. The order in which the two techniques were applied was determined by using a computer-generated random permutation, and the results were placed into envelopes numbered from 1 to 10, totaling 20 envelopes. The envelopes were opened sequentially at the time of data collection. The randomization process was performed by a second investigator, and the principal investigator was blinded to the order in which the two techniques were applied.

To perform the interventions, we placed the patients in the supine position with the head of the bed elevated 45°, and cuff pressure was increased to prevent leaks. Before the interventions, patients underwent endotracheal suctioning, in accordance with the recommendations of the American Association for Respiratory Care.[8] The protocol for the VBS and IBS techniques consisted of a series of ten cycles of each with an interval of at least 30 s between each cycle. For VBS and IBS, the system was connected to the tracheostomy tube at basal end expiration (i.e., at functional residual capacity). As shown in Figure 2, the system (for both techniques) consisted of a one-way valve, a manometer, and a digital respirometer, connected to a bacterial filter for the purpose of being coupled to the tracheostomy tube.

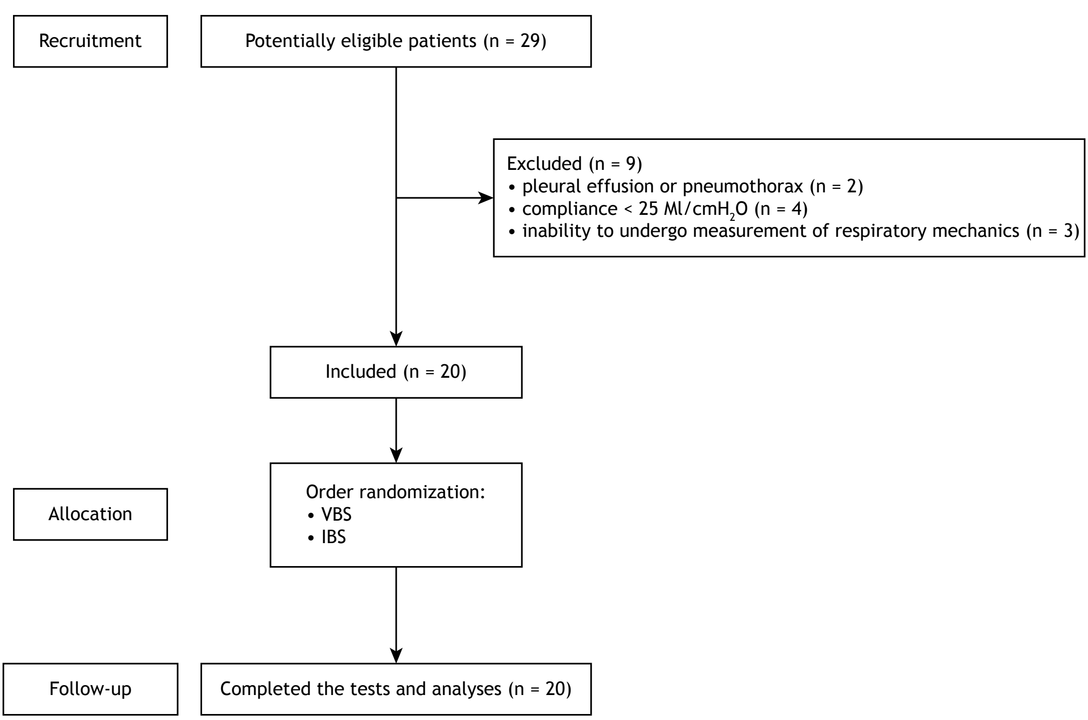

Figure 1. Study patient flowchart. VBS: voluntary breath stacking; and IBS: involuntary breath stacking.

Figure 2. Experimental setup used for voluntary breath stacking. The monitoring system, based on inspiratory capacity (measured with a respirometer), was coupled to a one-way valve connected to an analog manometer. A bacterial filter was used for patient coupling. For involuntary breath stacking, a resuscitator bag was connected to the respirometer outlet.

In VBS, patients took successive inspirations for up to 30 s or until no one-way valve opening or inspiratory volume increase (measured with a respirometer) was observed over two consecutive efforts. In IBS, a resuscitator bag (RWR, São Paulo, Brazil) was connected to the respirometer. Successive slow insufflations were performed, by slowly compressing the resuscitator bag, until the MIP reached 40 cmH_2O.

Evaluation

Before and after the interventions, respiratory mechanics, lung function patterns, IC, and airway pressure were evaluated.

Respiratory mechanics

Respiratory mechanics were assessed with a Vela ventilator (Bird Products Corp., Palm Springs, CA, USA), by using the end-inspiratory occlusion maneuver. The maneuver was performed in volume-controlled ventilation, at a constant flow rate of 40 L/min with an inspiratory pause of 3 s. Prior to the maneuver, all patients underwent 30 s of hyperventilation, which was achieved by increasing the RR to 35 breaths/min. The ventilator screen was "frozen" so that MIP, plateau pressure, and positive end-expiratory pressure could be recorded, making it possible to calculate static respiratory system compliance (C_{st},rs) and total respiratory system resistance (R,rs). Three consecutive, acceptable measurements were made at each time point, and we used the mean of the two measurements with the lowest standard deviations. Measurements were considered acceptable if we detected no deflections in the flow or pressure curves and no plateau during the inspiratory pause, because such changes would suggest patient interference and the presence of leaks, respectively.[9-12]

IC

The maximum volume recruited during VBS and IBS was measured from functional residual capacity, determining IC. In VBS, IC was measured at 30 s of expiratory port occlusion or at the time point when the patient had not recruited volume over two consecutive cycles. In IBS, IC was recorded when the airway pressure reached 40 cmH_2O. IC was measured with a digital respirometer (Ohmeda, Oxnard, CA, USA), in three cycles, and the highest value was used.[5,6,13]

Airway pressure

In VBS and IBS, airway pressure was measured at IC, in the absence of respiratory muscle effort. In VBS, airway pressure was recorded after 30 s of expiratory port occlusion or when the patient had not recruited any volume over two consecutive cycles.

In IBS, airway pressure was recorded at the time point when MIP reached 40 cmH_2O. The maximum pressures achieved by VBS and IBS were recorded in three cycles, and we used the arithmetic mean of the two measurements with the lowest standard deviations.[14]

Lung function pattern

Minute volume (V_E) and RR were measured before and after the interventions. The digital respirometer was coupled to the tracheostomy tube, and the volume of air exhaled in 60 s (V_E) was recorded. The mean basal tidal volume (V_T) was calculated as the ratio of V_E to RR (V_E/RR), making it possible to calculate the rapid shallow breathing index (defined as the RR/V_T ratio).[15]

Statistical analysis

The data obtained were organized and reviewed in Microsoft Excel® spreadsheets, making it possible to calculate the mean and standard deviation for each variable. Results were analyzed and graphs were created using SigmaPlot software, version 12.01 (Systat Software Inc., Richmond, CA, USA). When the results of the pre- and post-intervention measurements of respiratory mechanics (C_{st},rs and R,rs) and lung function pattern (V_T, V_E, RR, and RR/V_T ratio) showed normal distribution or homogeneity of variances, as determined by the Shapiro-Wilk test and Levene's test, respectively, they were analyzed by two-way repeated-measures ANOVA with Tukey's post-test. When they showed non-normal distribution, the Friedman test was used. The pre- and post-intervention IC values were compared by using a paired t-test, as were the pre- and post-intervention changes (absolute and relative) in respiratory mechanics and lung function pattern variables. The level of significance was set at 5% for all tests. The clinical effects of VBS and IBS were compared on the basis of the effect size, as determined by calculating Cohen's d. The effect size was calculated on the basis of the difference in absolute and relative changes between pre- and post-intervention measurements.

RESULTS

A total of 20 tracheostomized patients were evaluated between August of 2018 and March of 2019. On the day of the interventions, all of the patients were breathing spontaneously with the aid of nebulization of oxygen. The characteristics of the sample are presented in Table 1. Analysis of the respiratory mechanics showed that only IBS increased C_{st},rs relative to the pre-intervention value ($p = 0.007$), and there was a significant difference between post-VBS and post-IBS values for C_{st},rs ($p = 0.03$; $d = 0.11$). Relative changes in C_{st},rs were greater after IBS than after VBS (13.1 ± 11.9% vs. 1.3 ± 8.8%; $p = 0.008$; $d = 0.49$), as were absolute changes (4.6 ± 4.8 mL/cmH_2O vs. 0.3 ± 4.0 mL / cmH_2O; $p = 0.043$; $d = 0.44$).

No significant differences were observed between pre-VBS and pre-IBS values for C_{st},rs or R,rs or between post-VBS and pre-VBS values for C_{st},rs ($p = 0.85$). Neither technique produced changes in R,rs—there were no significant differences between pre-VBS and pre-IBS values ($p = 0.69$) or between post-VBS and post-IBS values ($p = 0.30$; $d = 0.14$), nor were there significant differences in absolute changes between post-VBS and post-IBS measurements ($p = 0.41$; $d = 0.17$) or in relative changes between post-VBS and post-IBS measurements ($p = 0.16$; $d = 0.01$). Results for respiratory mechanics are presented in Table 2.

IC was greater after IBS than after VBS (2,420.7 ± 480.9 mL vs. 1,211.3 ± 562.8 mL; $p < 0.001$; $d = 0.76$). Inspiratory volume, relative to V_T, increased from 396.1 ± 94.5 mL to 2,420.7 ± 480.9 mL after IBS ($p < 0.001$) and from 398.0 ± 83.3 mL to 1,211.3 ± 562.8 mL after VBS (Figure 3). The difference in recruited volume was 2,024.6 ± 445.1 mL for IBS, compared with 813.3 ± 530.9 mL for VBS ($p < 0.001$). At IC, IBS promoted higher airway pressure than did VBS (38.3 ± 2.6 cmH_2O vs. 25.8 ± 5.5 cmH_2O; $p < 0.001$). No significant difference was observed in the number of cycles required to reach IC ($p = 0.36$). To achieve an inspiratory pressure of approximately 40 cmH_2O, IBS required 4.8 ± 0.9 cycles of insufflation with the resuscitator bag, whereas VBS required 5.0 ± 2.3 cycles.

Regarding the lung function pattern, no significant changes were observed between pre- and post-intervention values for V_E, RR, V_T, or the RR/V_T ratio. The lung function pattern was assessed by comparing pre-VBS with post-VBS values and pre-IBS with post-IBS values, by comparing pre-VBS with pre-IBS values and post-VBS with post-IBS values, and by comparing absolute and relative changes in values between post-VBS and post-IBS measurements. Those data are presented in Table 3.

DISCUSSION

The major findings of the present study were that IBS increased C_{st},rs, as well as promoting greater IC

Table 1. Characteristics of the sample (N = 20).[a]

Characteristic	Result
Age, years	62.5 ± 14.3
Male gender	10 (50)
Duration of mechanical ventilation, days	26.9 ± 4.8
C_{st},rs, mL/cmH_2O	40.2 ± 14.9
R,rs, $cmH_2O/L.s^{-1}$	12.3 ± 3.3
Diagnosis	
Pulmonary sepsis	8 (40)
Stroke	6 (30)
Postoperative abdominal surgery	8 (40)
Pneumonia	8 (40)
Acute renal failure	2 (10)

C_{st},rs: static respiratory system compliance; and R,rs: total respiratory system resistance. [a]Values expressed as mean ± SD or as n (%).

Table 2. Results for the effects of voluntary breath stacking and involuntary breath stacking on respiratory mechanics.[a]

Variable	Pre-intervention	Post-intervention	p	Absolute change	Relative change
C_{st},rs, mL/cmH_2O					
Voluntary breath stacking	40.2 ± 14.9	40.4 ± 14.0	0.85	0.3 ± 4.0	1.3 ± 8.6
Involuntary breath stacking	38.8 ± 14.0	43.4 ± 13.6	0.007	4.6 ± 4.8	13.1 ± 11.9
p	0.27	0.03	-	0.043	0.008
Effect size	-	0.11	-	0.44	0.49
R,rs, cmH_2O/L.s^{-1}					
Voluntary breath stacking	12.9 ± 4.1	12.7 ± 4.1	0.37	−0.3 ± 0.9	−2.2 ± 6.7
Involuntary breath stacking	13.8 ± 5.9	14.0 ± 5.3	0.73	0.1 ± 1.3	2.8 ± 8.5
p	0.69	0.30	-	0.41	0.16
Effect size	-	0.14	-	0.17	0.01

C_{st},rs: static respiratory system compliance; and R,rs: total respiratory system resistance. [a]Values expressed as mean ± SD.

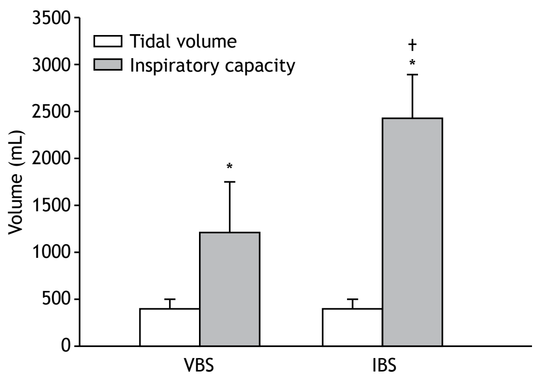

Figure 3. Basal tidal volume (white bar) and the inspiratory capacity (gray bar) obtained by voluntary breath stacking (VBS) and involuntary breath stacking (IBS). *$p < 0.001$ vs. basal tidal volume. †$p < 0.001$ vs. inspiratory capacity in the voluntary breath stacking group.

and higher airway pressure than did VBS. Neither technique produced changes in R,rs or in the pattern of lung function.

Bronchial hygiene techniques that recruit higher lung volumes have a greater potential for eliminating secretions. Higher inspiratory volume translates to higher elastic recoil pressure, higher PEF, and lower R,rs. Therefore, inspiratory volume appears to be the main factor in determining exhaled volume and PCF.[16] Achieving maximum insufflation capacity can confer some benefits, such as increased cough effectiveness, decreased atelectasis, increased compliance, and increased amplitude of chest movement,[17] as well as delaying mechanical ventilation or reducing the time on mechanical ventilation.[18] The two techniques studied here make it possible to maintain lung expansion longer, allowing additional time for the forces of interdependence to recruit volume, a process that does not usually take place during a single inspiratory effort.[19]

Increases in PCF during IBS can be obtained in various populations, including healthy individuals, individuals with respiratory muscle weakness, and patients with an obstructive pattern of lung function.[20] The patients who benefit most from IBS are those with a restrictive pattern of lung function, as well as those with neuromuscular disease, such as Duchenne muscular dystrophy,[21] spinal muscular atrophy,[22] congenital muscular dystrophy,[22] and amyotrophic lateral sclerosis.[5,23,24] Other indications include the postoperative period after cardiac surgery[25] and Parkinson's disease.[26]

In a study of 61 patients with Duchenne muscular dystrophy, PCF was compared among four conditions: during unassisted coughing; during IBS alone; with abdominal thrusts; and during IBS combined with abdominal thrusts. IBS promoted PCF values higher than those obtained during unassisted cough or with abdominal thrusts. However, IBS combined with abdominal thrusts was the most effective technique in increasing PCF.[21] Although the present study did not assess PCF, the larger increase in lung volume achieved by IBS appears to have been crucial for the increase in lung compliance and in the prevalence of productive cough. One study involving healthy individuals demonstrated that insufflations from a resuscitator bag promoted a mean increase in IC of 599 mL (20.4%) relative to the resting IC.[5] In the present study, VBS increased mean basal inspiratory volume by 813 mL, totaling a mean resting IC of 1,211 mL, whereas IBS increased mean basal inspiratory volume by 2,024 mL, resulting in a mean resting IC of 2,420 mL. Because our sample consisted of patients with respiratory muscle weakness due to prolonged hospitalization and mechanical ventilation, the resting IC was considerably smaller than that reported for healthy young adults. The improvements in volume and pressure obtained through the use of breath stacking techniques have been associated with increased PCF, greater mobilization of secretions, and increased cough effectiveness.[2,5]

In addition to producing higher lung volumes, IBS has the advantage of not requiring great muscle effort to achieve maximum IC, because it is a passive/assisted pulmonary insufflation technique. However, insufflation from a resuscitator bag should be performed in synchrony with inspiratory muscle contractions. Insufflations during the expiratory phase cause asynchrony and spikes in airway pressure. However, complications such as barotrauma

Table 3. Results for the effects of voluntary breath stacking and involuntary breath stacking on respiratory patterns.[a]

Variable	Pre-intervention	Post-intervention	p	Absolute change	Relative change
V_E, L					
Voluntary breath stacking	9.0 ± 1.9	8.5 ± 2.8	0.43	−0.5 ± 1.7	−6.2 ± 21.1
Involuntary breath stacking	9.5 ± 3.0	9.1 ± 3.0	0.43	−0.5 ± 1.9	−3.8 ± 16.4
p	0.39	0.39	-	0.99	0.39
Effect size	-	0.10	-	0.00	0.06
V_T, mL					
Voluntary breath stacking	398.0 ± 83.3	388.0 ± 84.2	0.61	−10.1 ± 71.7	−1.5 ± 16.5
Involuntary breath stacking	396.1 ± 94.5	378.2 ± 91.8	0.36	−17.9 ± 47.0	−4.2 ± 11.4
p	0.94	0.69	-	0.78	0.34
Effect size	-	0.05	-	0.06	0.09
RR, breaths/min					
Voluntary breath stacking	23.1 ± 5.4	22.4 ± 7.4	0.55	−0.7 ± 3.9	−3.4 ± 18.5
Involuntary breath stacking	24.1 ± 6.2	25.2 ± 7.2	0.32	1.1 ± 2.7	4.8 ± 12.1
p	0.53	0.10	-	0.26	0.13
Effect size	-	0.19	-	0.26	0.25
RR/V_T ratio, breaths/min/L					
Voluntary breath stacking	62.3 ± 23.4	62.4 ± 30.9	0.98	0.1 ± 17.6	1.9 ± 29.8
Involuntary breath stacking	64.0 ± 23.8	69.1 ± 24.9	0.29	5.1 ± 11.6	9.0 ± 20.3
p	0.81	0.34	-	0.46	0.27
Effect size	-	0.12	-	0.16	0.14

V_E: minute volume; and V_T: tidal volume. [a]Values expressed as mean ± SD.

have not been observed in neuromuscular patients after IBS.[2] The same is true for the use of IBS in healthy individuals with no primary intrinsic lung disease. One study reported that the resuscitator bag was well calibrated and that the safety valve opened automatically when the pressure reached 40 cmH_2O.[5] In the present study, in addition to the use of a safety valve, pressure was monitored by a manometer incorporated into the system, and the slow manual insufflations were stopped when the pressure reached 40 cmH_2O. Nevertheless, pressure spikes were observed during cough in patients who mobilized secretions, especially after IBS. Of the 20 patients evaluated, 17 (85%) coughed and required suctioning during IBS, compared with only 2 (10%) during VBS.

Another benefit of IBS is that it can be performed by the patients themselves through self-insufflation from a resuscitator bag. It is indicated for patients with reduced vital capacity, reduced PCF, secretion retention, or difficulty in eliminating secretions, as well as for those who are at high risk for atelectasis.[17] In one study, 18 patients with spinal muscular atrophy or congenital muscular dystrophy engaged in daily IBS training and were followed at home for 4-6 months to assess the effects.[22] The prescribed daily regimen was 10 series of 3-4 insufflations. There were increases in assisted and unassisted PCF, although the increases were less pronounced in the patients with associated scoliosis. In addition, FVC was found to have increased in the patients without scoliosis.[22]

IBS consists of consecutive insufflations from a resuscitator bag and consequent stacking of breaths. In contrast, manual hyperinflation consists of a single slow insufflation from a resuscitator bag, followed by an inspiratory pause.[27] Therefore, the volume recruited during IBS is probably higher than that recruited during manual hyperinflation. Several authors have used manual hyperinflation in mechanically ventilated patients, assessing its therapeutic effects or comparing its therapeutic effects with those of ventilator hyperinflation. Studies[10,28-30] have demonstrated that manual hyperinflation improves respiratory mechanics, without causing hemodynamic changes, and have used C_{st},rs to assess therapeutic effects, as in the present study. The mobilization of secretions leads to expansion/recruitment of collapsed lung units or lung units with high time constants, resulting in an increase in C_{st},rs. That effect is due to increases in collateral ventilation, elastic recoil pressure, and expiratory flow, resulting in an increase in gas-liquid interaction.[28]

During VBS, occlusion of the airways in the expiratory phase triggers compensatory mechanisms by progressively increasing central drive. The airflow resulting from each inspiratory effort increases the lung volume and stacks breaths. Over the course of successive inspiratory efforts, the volume increments tend to decrease, because the respiratory muscles are placed at a biomechanical disadvantage and compliance decreases. The inspiratory flow continues until the inspiratory effort becomes insufficient to open the one-way valve. At this point, the lung volume is close to total lung capacity.[7,19] One study compared the resting IC, the resting IC with a breath hold, and VBS in 26 cooperative patients in whom pain or muscle weakness resulted in impaired ability to achieve or sustain deep inspiration. VBS increased inspiratory volume, indicating that the addition of a one-way valve is effective in increasing IC.[13] One other study compared the effects of incentive spirometry and VBS on FVC and recruited volume in 35 patients in the first five days after cardiac surgery. The authors reported that VBS completely restored inspiratory volume by postoperative day 2, in addition to having promoted greater lung volume recruitment over the five days of treatment, although they did not observe differences between the two techniques in terms of the FVC.[6]

The one-way valve allows the patient to relax the inspiratory muscles without exhaling and allows volume to increase during successive breaths. Two mechanisms can help to explain volume recruitment during VBS: increased neural stimulation and increased lung recruitment. In most patients, relatively high inspiratory volumes can be achieved with moderate pressures. However, patients whose respiratory mechanics are impaired by dyspnea or pain are unable to sustain the effort needed to achieve maximum volume recruitment.[13] The volume recruited during VBS depends exclusively on respiratory muscle contraction, and that dependency is a limiting factor for volume recruitment and the consequent therapeutic efficacy. Respiratory muscle weakness reduces the effectiveness of the inspiratory phase of cough, there being a direct relationship between MIP and cough flow, which emphasizes the need to strengthen the respiratory muscles.[17] In the present study, we observed that some patients were able to open the inspiratory valve after 30 s of occlusion. Those patients might have achieved greater IC.

IBS promoted greater IC and higher airway pressure than did VBS, resulting in an increase in C_{st},rs. However, neither technique had any effect on the lung function pattern.

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