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Volume rather than flow incentive spirometry is effective in improving chest wall expansion and abdominal displacement using optoelectronic plethysmography

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Abbreviated title: The effect of incentive spirometry on thoracoabdominal motion

Ethics approval: The Ethics Committee of the School of Medicine approved this study. All participants gave written informed consent before data collection began.

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ABSTRACT

Background: Incentive spirometers (IS) are widely used in clinical practice and classified as flow-oriented (FIS) and volumetric (VIS). Until recently, the respiratory inductive plethysmography used to evaluate the effects of IS on chest wall mechanics presented limitations, which may explain why the impact of VIS and FIS remains poorly known. **Objective**: We compared the effects of the VIS and FIS on thoracoabdominal mechanics and respiratory muscular activity in healthy volunteers. **Methods**: This cross-sectional trial assessed 20 subjects, 60% female, aged between 20 and 40 years and with a body mass index (BMI) between 20 and 30 kg/m^2. All participants performed 8 quiet and 8 deep breaths using both FIS and VIS in a randomized order. The outcomes measured were the thoracoabdominal kinematics (i.e., chest wall, upper and lower ribcage and abdominal volumes), assessed using Optoelectronic Plethysmography, and the muscular activity of the sternocleidomastoid and superior and inferior intercostal muscles, assessed using electromyography. The statistical analysis was performed with one-way repeated measures ANOVA, and the significance level was set to 5%. **Results**: VIS increased the chest wall volume to a greater extent than the FIS (p=0.007) and induced a larger increase in the upper and lower ribcages and abdomen (respectively, 156%, 91% and 151% p<0.001). By contrast, the FIS induced more activity in the accessory muscles of respiration compared to VIS (p<0.001). **Conclusion**: Our results demonstrate that the VIS promotes a greater increase in the chest wall volume with a larger abdominal contribution and lower respiratory muscular activity than the FIS in healthy adults.

Key words: Breathing exercises, Physical therapy modalities, Electromyography, Biomechanics, Incentive spirometry, Chest wall, Respiratory mechanics, Lung volume measurements

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INTRODUCTION

Several clinical situations are often followed by respiratory impairment, particularly in patients undergoing thoracic[1] and abdominal surgeries[2] or during prolonged bed rest[3-4]. In such cases, respiratory impairment includes a reduction in both chest wall volume and bronchial capacity that may result in respiratory infection. Incentive spirometry (IS) can be used to encourage deeper breaths and provide increased respiratory capacity, thus reversing alveolar collapse and improving oxygenation. IS has been used for the prophylaxis and treatment of pulmonary complications during abdominal [5-7], cardiac [8] and thoracic surgeries [9].

There are two types of IS: flow- (FIS) and volumetric-oriented (VIS); both devices provide visual feedback aimed at improving pulmonary expansion, and it seems that the FIS demands higher inspiratory flow than VIS[7]. Despite the widespread use of IS, recent systematic reviews suggest, based on the questionable methodological quality of previous trials, that their benefits are controversial[5]. In addition, few studies have evaluated the effect of the FIS and VIS on thoracoabdominal mechanics, which is necessary to determine the use of these devices based on the therapeutic goals.

Parreira et al (2005)[10] and Tomich et al (2007)[11] showed that the VIS induced a higher pulmonary volume than the FIS, although both devices induced similar displacement of the abdominal and thoracic compartments. In addition, they showed that the FIS induced a higher respiratory rate and accessory respiratory muscle activity compared to the VIS. Nevertheless, subjects in both studies were assessed in a dorsal (supine) position, which restricts chest wall expansion and reduces the diaphragm´s capacity to generate strength[12]. In addition, thoracoabdominal

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mechanics were measured using respiratory inductive plethysmography, a technique that evaluates pulmonary volume using a two-compartment analysis but does not have an accurate calibration method.

Recently, optoelectronic plethysmography (OEP) was developed to analyse chest wall kinematics using a three-compartment analysis that measures pulmonary volume and thoracoabdominal synchrony and makes it possible to evaluate the subject in any position with the simultaneous analysis of respiratory muscle activity by using surface electromyography[12-14]. Our hypothesis is that the similar results between the FIS and VIS observed in previous studies are the result of using an inaccurate instrument to evaluate thoracoabdominal mechanics and an inappropriate subject position. In the present study, we compared the effect of the VIS and FIS on thoracoabdominal mechanics and respiratory muscular activity evaluated by OEP in healthy volunteers in a seated position.

METHODS

Design: This cross-sectional trial was performed in healthy volunteers. The study was approved by the Ethics Committee Hospital (protocol number 150/11), and all subjects provided written informed consent.

Participants: Adults aged 20 to 40 years and with a body mass index (BMI) between 20 and 30 kg/m^2 were evaluated. The exclusion criteria were a deformity of the chest wall or spine, the presence of pulmonary (FEV_1 or FVC <80% predicted or $FEF_{25-75\%}$<60% predicted) or cardiac diseases and current smoking. All participants were unfamiliar with the IS and reported never having used this equipment before.

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Instructions about the use of the devices were given just before the measurements. Subjects were evaluated between April 2011 and January 2012, and 2 subjects were excluded before evaluations due to a diagnosis of asthma.

Study Protocol: After signing the informed consent, subjects performed spirometry according to the European Respiratory Society/American Thoracic Society protocol[15], followed by an analysis using OEP of the thoracoabdominal mechanics at rest and when using FIS and VIS.

The assessment of thoracoabdominal kinematics and inspiratory muscle activity was performed during quiet breathing followed by either VIS or FIS, guided by a Respiratory Therapist. The order of use (VIS or FIS) was randomly determined and placed in sealed envelopes that were numbered sequentially by an independent researcher. All subjects performed 8 quiet breaths followed by 8 deep breaths, using FIS and VIS in the order specified by the randomization, with an interval of at least 2 minutes between the devices. The 8 breaths using IS were performed asking to the patient a slow inhalation to raise the ball (FIS) or the piston-plate (VIS) and sustain the inflation for at least five seconds, followed by a normal exhalation[7,16], and the average of 6 homogeneous respiratory cycles was considered for the data analysis performed by a bioengineer. The chest wall volumes and inspiratory muscular activity outcomes were assessed concurrently.

Respiratory Therapy Resources: Respiron® (NCS, Brazil) and Voldyne 5000® (Hudson RCI, USA) were used to evaluate FIS and VIS, respectively. This choice was influenced by the fact that these devices are commonly used in our country.

Respiron is a flow-oriented incentive spirometer. During inspiration, the patient makes the ball in the column of the instrument rise and keeps it suspended by the sustained inspiratory flow; this serves as visible feedback of the inspiratory flow (Figure 1A).

Voldyne is a volume-oriented incentive spirometer. During inspiration, the patient makes the piston-plate rise and keeps it suspended, serving as visible feedback of the inspiratory volume (Figure 1B).

Insert Figure 1

The subjects were instructed to perform a slow inhalation to raise the ball (FIS) or the piston-plate (VIS) and sustain the inflation for at least five seconds, followed by a normal exhalation[7].

Measurements:

1. <u>Thoracoabdominal Kinematics</u>

Thoracoabdominal kinematics were evaluated using optoelectronic plethysmography (OEP System, BTS, Italy), as previously described[17]. This equipment is based on eight special video cameras (solid-state charge-coupled devices) operating at 100 frames per second and synchronized with an infrared flashing light-emitting diode. Four cameras were positioned in front of the subject and four behind. Eighty-nine retro-reflective markers were placed on the anterior and posterior sides of the trunk, according to the protocol previously described by Aliverti et al (2009)[13]. A three-dimensional calibration of the equipment was performed, based on the manufacturer's recommendation. After that, the assessment was performed with the subject seated on a wheelchair without a back support, so the thoracoabdominal

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kinematics around the chest wall could be evaluated. The following variables were measured:

- *Total chest wall (CW) and compartmental volumes:* The OEP software (SMART) reconstructed the three-dimensional position of each marker during the experiment and computed the chest wall volumes with high accuracy. Algorithms computed the volume variations of the whole chest wall and the thoracic and abdominal compartments: the values for the upper and lower ribcage and abdomen were expressed as absolute values and percentages.

- *Time variables:* The mean values of the inspiratory (Ti) and total times (Ttot) as well as the inspiratory duty cycle (Ti/Ttot) were quantified based on each respiratory cycle.

- *Thoracoabdominal asynchrony (θ):* This value was obtained using a calculation of the upper ribcage to the abdominal phase angle, according to Agostoni et al (1966)[18]. Phase angle was calculated as the lag time between the peaks of the upper ribcage and the abdominal signals divided by the total cycle time times 360 degrees.

2. <u>Respiratory muscle activity</u>

The activity of the sternocleidomastoid and external superior and inferior intercostal muscles was assessed using electromyography signals (EMG BTS, Italy) obtained simultaneously with the thoracoabdominal kinematics.

a) *Electrode position*: Each probe was attached to two reusable bipolar superficial electrodes consisting of Ag/AgCl material and a conductive adhesive hydrogel (Maxicor®, Brazil). The inter-electrode distance was 20 mm. To place the electrode, the skin was cleaned with an alcohol swab at the sites of attachment to remove oils from the contact surface, thus decreasing the impedance of the skin. Superficial electrodes were fixed on the muscle belly, away from the motor point and parallel to the direction of the muscle fibers, in accordance with the European concerted action on surface EMG for the non-invasive assessment of muscles[19]. The right sternocleidomastoid (RSL) electrode was placed on the muscular body 5 cm from the mastoid process[20]. For the external intercostal muscle of the right upper ribcage (RIC), the electrode was placed on the 2nd anterior intercostal space[21]. For the external intercostal muscle of the left lower ribcage (LIC), the electrode was placed on the 7th and 8th anterior intercostal spaces[21]. All electrode positions were determined in accordance with the best signal capture, and the EMG analyses were carried out as recommended by Hermens et al (2000)[19].

b) Data acquisition and processing: signals were obtained using an eight-channel EMG module with wireless probes that had an acquisition frequency of 1000 Hz. Each probe consists of a mother electrode and a satellite electrode connected via a flexible cable, each fitted with a clip. The mother electrode contains an A/D converter with a resolution of 16 bits, the antenna and the battery. The satellite electrode contains a signal-conditioning low-pass filter with a frequency of 500 Hz and an amplifier with a gain range of ±1.62 mV. All data were processed using dedicated software for acquisition and analysis (SMART).

In the post-processing stage, we applied a Butterworth high-pass filter with a cut-off frequency of 20 Hz; thus, the frequency range of the signal was set at 20-500

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Hz. To detect the linear envelope of the EMG signal, the signal was full-wave rectified and low-pass filtered. The electrical activity of the sternocleidomastoid and the upper and lower intercostal muscles was measured using the root mean square (RMS) values and expressed in 10^{-3}mV.

Data analysis: The sample size calculation was performed by considering the average difference of total chest wall volume generated by the VIS relative to the FIS as 475 ml, with an average standard deviation of 15% (71 ml) and a power of 80% as the primary variable[11]. The sample size estimation was 16 subjects. Data values were presented in mean ±standard deviation. The differences between quiet breathing and breathing using the devices were analyzed using one-way repeated measures ANOVA with a post hoc Dunn's test. The significance level was set to 5%. The statistical analysis was performed using the Sigma Stat software package, version 3.2 (San Jose, EUA).

RESULTS

Twenty-two subjects were screened, and 20 met the eligibility criteria and were evaluated. A total of 12 (60%) subjects were females aged 25.9± 4.3 years, with an average BMI of 23.6± 2.4 kg/m^2. All subjects presented normal lung function, as confirmed by the following parameters: forced vital capacity, 103.6±13.2 %; forced expiratory volume in 1 second, 101.4±12.7% and FEV_1/FVC 83.5± 6.6%.

Thoracoabdominal volumes: Both the FIS (335%) and VIS (400%) increased the chest wall volume compared to quiet breathing ($p<0.001$; Table1). However, the chest wall volume obtained with VIS was 65% greater than that obtained with FIS (p=0.007).

The FIS and VIS induced similar increases in the upper (respectively, 138% and 156%) and lower respiratory compartments (respectively, 80% and 91%) compared to quiet breathing. In addition, the FIS and VIS induced a displacement in the abdominal compartment of 117% and 151%, respectively, compared to quiet breathing (p<0.001; Table 1 and Figure 2). However, the VIS induced a 34% greater displacement compared to FIS (p=0.03).

Insert Table 1 and Figure 2

Time: There was an increase in the inspiratory (Ti) and total time (Ttot) when using the VIS compared to using FIS (Ti: 3.81±3.30 sec vs. 2.17±1.06 sec and Ttot: 7.18±3.98 sec vs. 4.94±2.49 sec, respectively) (p=0.035; Table 1). However, there was no difference in Ti/Ttot between the VIS and FIS (0.42±0.11 vs. 0.44±0.07, respectively) (p=0.636; Table 1).

Thoracoabdominal asynchrony: Asynchrony was observed when subjects used the FIS but not when they used the VIS (p=0.026; Table 1 and Figure 3).

Insert Figure 3

Electromyography: The electromyography analysis of the RSL, RIC and LIC showed an increase in electrical activity when using the FIS compared to using the VIS (p<0.001; Table 1)

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DISCUSSION

Our results showed that volume- (VIS) and flow-oriented (FIS) incentive spirometers increase pulmonary volumes in healthy adults; however, the VIS induced a greater total chest wall volume, especially in the abdominal compartment, and lower respiratory muscular activity compared to the FIS. Moreover, we observed that only the FIS promoted thoracoabdominal asynchrony. To the best of our knowledge, this is the first study carried out that compares both types of incentive spirometers and uses accurate equipment that allows chest wall volume assessment in a three-dimensional and three-compartment analysis that also simultaneously quantifies the respiratory muscle activity.

Although the VIS or FIS are widely used and recommended in clinical practice, especially for perioperative care, there is no consensus about their benefits or indications because no previous study has demonstrated which IS is the most effective[22-24]. This is most likely because few studies have assessed the differences in respiratory mechanics between the two devices. Parreira et al[10] and Tomich et al[11] evaluated thoracoabdominal motion when using the FIS and VIS in healthy adults and showed that the VIS induced higher chest wall expansion compared to the FIS. Although these results appear similar to ours, they observed reduced volumes either in the baseline state (subject´s tidal volume of 300 ml) or using FIS (1264 ml) and VIS (1739 ml) compared with our results (respectively, 620 ml, 2000 ml and 2480 ml). There are at least two possible explanations for the discrepancy between our study and previous ones: i) differences in the patient´s position when using the VIS and FIS and ii) differences in the equipment used to evaluate thoracoabdominal mechanics.

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In previous studies[10-11], the use of the FIS and VIS was evaluated in a semi-reclined position (45º); however, several studies showed that chest wall volume and the relative contribution of the ribcage to tidal breathing are higher in spontaneous quiet breathing in the seated compared to the supine position[12, 25]. This is because the geometry of the respiratory muscles is strongly influenced by posture; for instance, the diaphragm has a reduced capacity to generate strength in the supine position[12]. In addition, previous studies have shown that it is possible to generate higher chest wall volumes in the seated position without back support [12], which may explain the higher volumes observed in our study. The use of optoelectronic plethysmography (OEP) in the present study may also explain the higher chest wall volumes obtained in our study using both IS devices because the OEP demonstrates excellent consistency in estimating the lung volumes[26] and allows the evaluation of thoracoabdominal motion in a three-dimensional (3D) analysis[13,17]. At present, it is not possible to determine if either the subject´s position or the use of the more precise technique, the OEP, was the main reason for the increased chest wall volume we observed. However, we believe that our findings are quite relevant because the use of IS devices in the seated position is more common in clinical practice[12].

Interestingly, we also observed that VIS induced a greater abdominal displacement, and we hypothesize that this may have occurred because VIS is performed with lower inspiratory flow, which optimizes diaphragmatic excursion and improves the expansion of the basal area of the chest wall. Our data are supported by results obtained by Chuter et al. (1989), showing that FIS does not increase the abdominal contribution to total chest wall volume in patients who have had abdominal surgery[27].

Our study also showed that FIS promoted thoracoabdominal asynchrony. Although the occurrence of asynchrony may seem unusual in healthy subjects, previous studies have observed thoracoabdominal asynchrony associated with increased respiratory loads in healthy subjects[28]. Previous studies have also suggested that using the FIS requires an increase in the activity of the respiratory muscles compared to VIS[10]. Based on those results, we suggest that the FIS can impose an additional load on the respiratory system, leading to thoracoabdominal asynchrony. We also observed that the VIS induced lower activity of the sternocleidomastoid and intercostal compared to the FIS, suggesting that this lower effort of the inspiratory muscles may be due to increased displacement of the abdominal compartment (described above).

Our study presents some limitations: first, the effect of IS was evaluated in subjects with normal lung function; however, our research group is conducting studies with the same protocol in different populations, including the morbidly obese and elderly to increase the practical applicability of the IS. Second, muscular activity was evaluated using surface electromyography, and there is no consensus about electrode positioning for the respiratory muscles; in our study, the electrodes were located according to previous studies performed by experts in this field[20,21].

Practical implication: Our findings showing the acute effects of lung expansion using two types of IS devices on healthy subjects, however, this suggest the need for a large, randomized controlled trial using IS in the clinical populations and the evaluation of long term effects of IS on postoperative complications and hospital stay.

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Another important fact that must be considered in clinical practice is the difference in the cost of IS (US$ 80 for VIS and US$ 20 for FIS).

Conclusion: The VIS promotes a greater chest wall volume with a higher abdominal contribution and lower muscular activity without inducing thoracoabdominal asynchrony compared to FIS in healthy subjects.

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FIGURE LEGENDS

Figure 1. Types of studied devices: A) FIS (Respiron®) and B) VIS (Voldyne®).

Figure 2: The contribution of the upper and lower ribcages and abdominal motion to the pulmonary volume at rest and during the VIS and FIS. URC=upper rib cage; LRC=lower rib cage; ABD=abdomen; QB=quiet breath; FIS=flow-oriented incentive spirometry; VIS=volume-oriented incentive spirometry; *$p<0.05$ comparing FIS to VIS.

Figure 3: Representation of thoracoabdominal asynchrony when using the FIS (A) and VIS (B). LT= lag time between the end-inspiratory volume of the upper ribcage signal and the abdomen signal. Continuous line: end-inspiratory volume of the upper ribcage signal. Dotted line: end-inspiratory volume of the abdomen signal.

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Table 1: Respiratory data and muscular activity during quiet breathing, FIS and VIS.

	QB	FIS	VIS
VOLUME (*L*)			
CW	0.62±0.18	2.08±0.99*	2.48±1.22* †
URC	0.22±0.11	0.86±0.39*	0.97±0.57*
LRC	0.12±0.07	0.50±0.25*	0.57±0.36*
ABD	0.28±0.09	0.73±0.53*	0.94±0.55* †
TIME (*s*)			
Inspiratory	2.00±0.81	2.17±1.06	3.81±3.30* †
Total	4.68±1.22	4.94±2.49	7.18±3.98* †
Inspiratory/Total (%)	0.43±0.10	0.44±0.07	0.42±0.11
ASYNCHRONY (*θ*)			
URC x ABD	7.08±9.28	33.38±32.58	14.48±14.70
MUSCULAR ACTIVITY (RMS) (10^{-3}*mV*)			
RSL	6.5±3.8	22.8±20.4* †	18.1±21.5*
RIC	6.5±1.6	38.4±29.2* †	27.0±24.1*
LIC	6.4±2.9	16.4±9.8*	13.9±7.7*

Legend: Data are presented as the mean±standard deviation; QB=quiet breath; FIS=flow oriented incentive spirometry; VIS=volumetric oriented incentive spirometry; CW=chest wall; URC=upper rib cage; LRC=lower rib cage; ABD=abdomen; s=seconds; θ=phase angle; RSL=right sternocleidomastoid; RIC=right intercostal; LIC=left intercostal; RMS=root mean square; *p<0.05 compared with quiet breath; † p<0.05 compared between devices.

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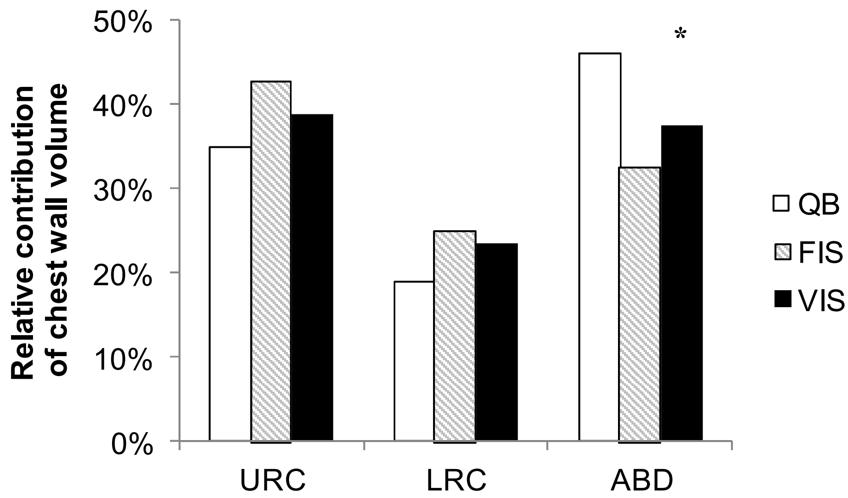

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