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RESEARCH REPORT

Incentive spirometry and positive expiratory pressure improve ventilation and recruitment in postoperative recovery: A randomized crossover study

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ABSTRACT
Introduction: Impairment of global and regional pulmonary ventilations is a well-known consequence of general anesthesia. Positive expiratory pressure (PEP) or incentive spirometry (IS) is commonly prescribed, albeit their efficacy is poorly demonstrated. The aim of this study was to assess the effects of PEP and IS on lung ventilation and recruitment in patients after surgery involving anesthesia using electrical impedance tomography (EIT). **Method**: Ten male subjects (age = 61.2 ± 16.3 years; BMI = 25.3 ± 3.8 kg/m^2), free of pulmonary disease before being anesthetized, were recruited. Two series of manoeuvers (PEP and volume-oriented IS) were randomly performed with quiet breathing interposed between these phases. Pulmonary ventilation (ΔEELVVT ($i - e$)) and recruitment (ΔEELI) were evaluated continuously in a semi-seated position during all phases by EIT. Comparisons between rest and treatment were performed by Wilcoxon signed rank test. Rest phases were compared by a mixed ANOVA. Bonferroni method was used for *post-hoc* comparisons. **Results**: ΔEELVVT ($i - e$) and ΔEELI were significantly increased by both techniques (+422% [$p < 0.001$]; +138% [$p = 0.040$] and +296% [$p < 0.001$]; +638% [$p < 0.001$] for PEP and IS, respectively). No difference was observed between both manoeuvers neither on ventilation nor on recruitment. This positive effect disappeared during the quiet breathing phases. **Conclusion**: IS and PEP improved ventilation and recruitment instantaneously without remnant effect after stopping the exercise.

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Physical therapy modalities; incentive spirometry; positive expiratory pressure; physiotherapy; anesthesia; electrical impedance tomography

Introduction

Global and regional ventilations are impaired in anesthetized patients (Frerichs et al., 1998). Up to 90% of patients undergoing upper abdominal surgery suffer from postoperative pulmonary complications such as atelectasis, pneumonia, mucus hypersecretion, impaired mucociliary clearance, and derecruitment (Overend et al., 2001). These complications are related to mechanical ventilation, anesthesia, pain, and duration of bed rest postsurgery (Frerichs et al., 1998).

Strategies to prevent and/or to treat postoperative pulmonary complications are widely recommended in routine. Techniques promoting lung expansion and ventilation such as positive expiratory pressure (PEP) and incentive spirometry (IS) devices are commonly used in clinical practice during the perioperative period of major surgeries (Carvalho, Paisani, and Lunardi, 2011). Advantages of these techniques are low cost, ease of application in routine, and good adherence of patients (Hristara-Papadopoulou, Tsanakas, Diomou, and Papadopoulou, 2008). However, their immediate physiological responses are poorly studied (Lima et al., 2014; McCarren and Alison, 2006; Pfleger et al., 2015).

Lung function, quality of life, exercise tolerance, gas exchanges, and mucociliary clearance were previously and regularly used as outcome to evaluate the benefit of these techniques. Until now, their effects on ventilation changes have never been measured due to technical or methodological inadaptability of the conventional methods of assessment.

Electrical impedance tomography (EIT) is a noninvasive and radiation-free imaging technique measuring an electrical potential related to the regional ventilation changes (Carvalho, Paisani, and Lunardi, 2011). EIT can be used at the bedside providing new possibilities

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regarding the evaluation of chest physiotherapy techniques and it is a highly reproducible method (Hinz et al., 2003). It measures continuously the local and global changes in volumes and end-expiratory level (Frerichs, Dargaville, Dudykevych, and Rimensberger, 2003; Hinz et al., 2003). It was used to observe the effects of breathing aids on ventilation distribution in healthy adults and cystic fibrosis (CF) patients (Wettstein, Radlinger, and Riedel, 2014). The aim of this study was to assess the effects of PEP and IS on lung ventilation and recruitment in patients after surgery involving anesthesia using EIT.

Materials and methods

Subjects

Subjects admitted for elective endorological surgical procedure (around 1 h of anesthesia) in Cliniques Universitaires Saint-Luc were consecutively recruited between July and August 2014 by the physicians of the team. This cohort of patients was chosen because their pain level is usually minimal with little variation in intensity and therefore, surgical pain would be expected to minimally perturb the lung ventilation and recruitment data. Inclusion criteria were to be older than 18 years and nonsmoker or non-ex-smoker, absence of pulmonary disease (confirmed by the medical examination and a normal lung function [FEV1/FVC > 0.8 and FVC > 0.85]), having undergone an operation under general anesthesia, naïve for the device, and absence of contraindications related to EIT (pacemaker, automatic implantable cardioverter defibrillator, and implantable pumps). Exclusion criteria were subjects presenting cognitive disorders or inability to perform correctly the techniques. Subjects signed a written informed consent form in accordance with the Declaration of Helsinki and with current guidelines for Clinical Good Practice after approval by the Institutional Medical Ethics Committee (B403201318261) and registration of the trial on clinicaltrial.gov (NCT01932567).

Devices

Two different devices were investigated on the same day in the cohort of recruited patients: (1) a volume-oriented incentive spirometer with a visual feedback on inspiratory flow (VIS) (Coach II, DHD Healthcare, USA) and (2) a PEP mask (Pari PEP-S, Pari, Germany). The diameter of the resistor was determined for each patient by the manometer provided by the manufacturer to give a steady PEP of 10–20 cmH_2O.

Design

It was a crossover study. Patients were included in the protocol within 2 h after surgery and before the first lift of bed. Protocol included the following five phases for each patient (Figure 1): (1) 5 min of quiet breathing (Rest 1), (2) 10 breathes through a device (IS or PEP – Phase 1), (3) 5 min of quiet breathing (Rest 2), (4) 10 breathes through the other device (PEP or IS depending on phase 1 – Phase 2), and finally (5) 10 min of quiet breathing (Rest 3). The order of IS or PEP use was previously randomized by a computer generated random number list (randomizer.org).

During all the protocol, subjects were assessed in a semi-seated position (45°) in bed. They breathed by the nose during each phase of quiet breathing (Rest 1, 2, and 3). During each phase of exercise, 10 breaths were performed. During IS phase, subjects inhaled slowly until maximal inspiratory volume, followed by a breath-hold for 3 s and expired spontaneously. During PEP phase, subjects performed an inspiration until mid-lung volume and exhaled actively to maintain an expiratory pressure between 10 and 20 cm H_2O.

Primary outcomes

EIT measurement

Ventilation defined as lung volume changes and recruitment were continuously assessed as main outcomes by EIT (PulmoVista®500, Dräger Medical, Lübeck, Germany) (Leonhardt and Lachmann, 2012).

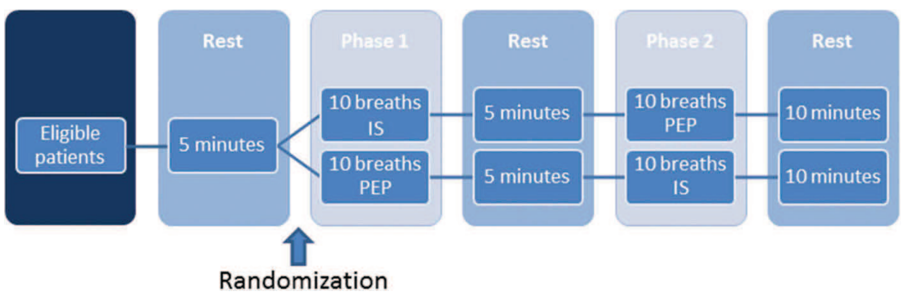

Figure 1. Design of the study.

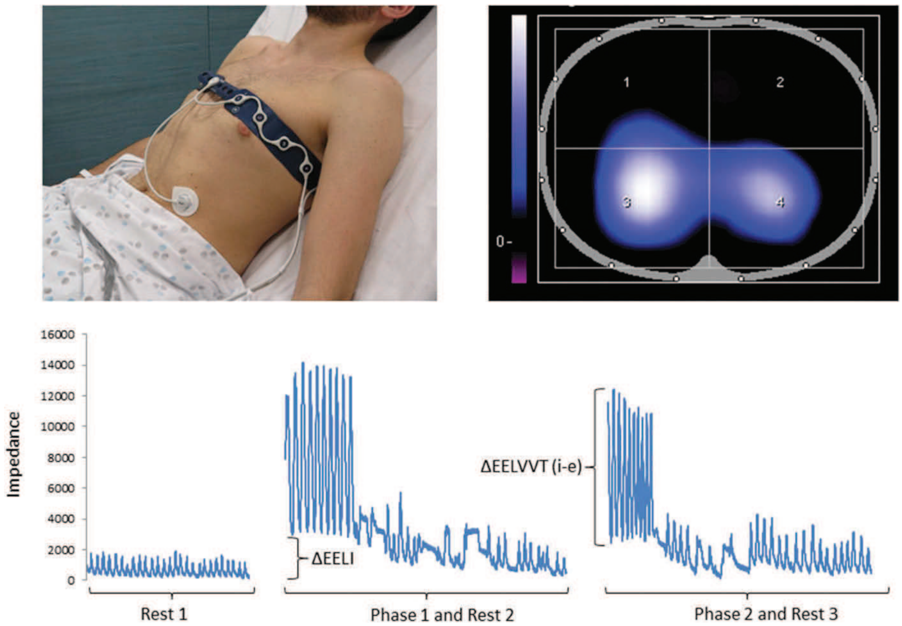

Figure 2. Illustration of EIT: the belt (upper left panel) and a sample of a scan (upper right panel) and a waveform during impedance recording (impedance values are expressed as arbitrary units) (lower panel).

It monitors continuously the lung function by generating cross-sectional images of the lung using a 16-electrode belt (approximately 3 cm between the electrodes) between the 4th and 5th intercostal space which applies an electrical alternating currents (50 kHz, 5 mA peak-to-peak) in a sequential rotating process (Figure 2 – upper left panel).

The resulting surface potential differences were measured between electrode pairs. A reference electrode was placed at the patients' abdomen. Belt size was determined according to the chest circumference of the patient. The contact surface was coated with a conductor spray. The voltage profiles at 16-electrode positions were recorded and compiled into cross-sectional images. A scan was reconstructed continuously at 20 Hz during the whole procedure providing images consisting of 32 × 32 pixels using the software provided with the EIT device (Figure 2 – upper right panel). A digital low-pass filter with a cut-off frequency of 1 Hz is used by EIT to eliminate impedance changes related to heartbeat. The displayed EIT images are from caudal to cranial and the total reconstructed scan can be divided in different regions of interest arranged either as layers, as quadrants, or in a customized way.

Total lung ventilation during a phase was calculated by the mean impedance variation (differences between end-inspiratory and end-expiratory values of impedance (ΔEELVVT ($i - e$)) for the total scan area from the consecutive respiratory cycles of the respective phase (Figure 2 – lower panel). It is defined as the tidal volume used by breath.

The end-expiratory lung impedance variation (ΔEELI) was calculated by the difference between the mean of minimum (end-expiratory) impedance values (representing functional residual capacity) of two consecutive phases. It is defined as the change in end-expiratory lung volume (Figure 2 – lower panel). The reading of the results was performed by a blinded assessor.

Secondary outcomes

Chest expansion

Upper CE was assessed before and at the end of each phase by a cloth tape as it was recently validated (Debouche et al., 2016). The anatomical marks were the third intercostal space, the middle of the clavicular line, and spinous process of the fifth thoracic vertebrae. The cloth tape was held without generation of any deformation or cutaneous folds. Measurement was performed at the end of complete inspiration. Subjects inspired slowly by the nose to push the tape and to swell lungs as much as possible. They were asked "to inspire slowly through the nose and to push against the tape measure to expand lungs as much as you can." CE was calculated by subtracting expiratory diameter of thorax from the same diameter measured at the end of a maximal inspiration.

Cardiorespiratory parameters, fatigue, and pain

At the end of each phase, pulsed oxygen saturation (SpO_2) was assessed by an oximeter (NONIN, Onyx) and perceived exertion was quantified by a Borg scale. Pain was quantified before the experiment by a visual analog scale.

Statistical analysis

Clinical data were analyzed by SPSS Statistics 24.0 (IBM company). The sample size needed for detecting an impedance improvement of 2000 (corresponding to a 60% improvement of a mean rest impedance value based on preliminary results) with a power of 0.80 was determined (n = 9). The Type I error probability associated with this test is 0.05. Normality of the distributions was verified by Kolmogorov–Smirnov test. Results were expressed as mean ± SD and confidence interval (Campbell and Gardner, 1988), or by median and interquartile range depending on the normality of the distribution.

To compare treatment effects and period effects, treatment effects were computed separately in the two sequence groups. The assumption that washout phase was long enough to avoid relevant carryover effect and then the validity of the procedure were checked by conducting the pre-test of the data as conceived by Wellek and Blettner (2012). For this pretest, the sum of the values from both periods was calculated for each subject. Then, these sums were compared across the two sequence groups by means of an appropriate test of independent samples (Wellek and Blettner, 2012). After confirmation of a negligible carryover effect, a standard Student's t test for independent samples using the intraindividual differences between values was measured in both periods to assess the difference in treatment effects. Rest phases were compared by a mixed analysis of variance. Bonferroni method was used for *post-hoc* comparisons. A p value less than 0.05 was considered as statistically significant. Examiner was blinded.

Results

Ten subjects were recruited in this crossover study (Figure 3). The anthropometric and cardiorespiratory parameters of the subjects measured at rest are presented in Table 1. The duration of the anesthesia was 51.5 ± 9.1 min. Three kinds of surgery were found (i.e., transurethral resection of bladder tumor or of bladder neck (7), hydrocele surgery (2), and transurethral resection of the prostate (1)). The median score of pain was 0 (0–2).

The results of ventilation (ΔEELVVT (i − e)) and recruitment (ΔEELI) for the global lung and of the secondary outcomes at the different phases are represented in Figure 4 and Table 2. No relevant carryover effect was observed for ventilation (p = 0.73), recruitment (p = 0.46), CE (p = 0.74), and pulsed oxygen

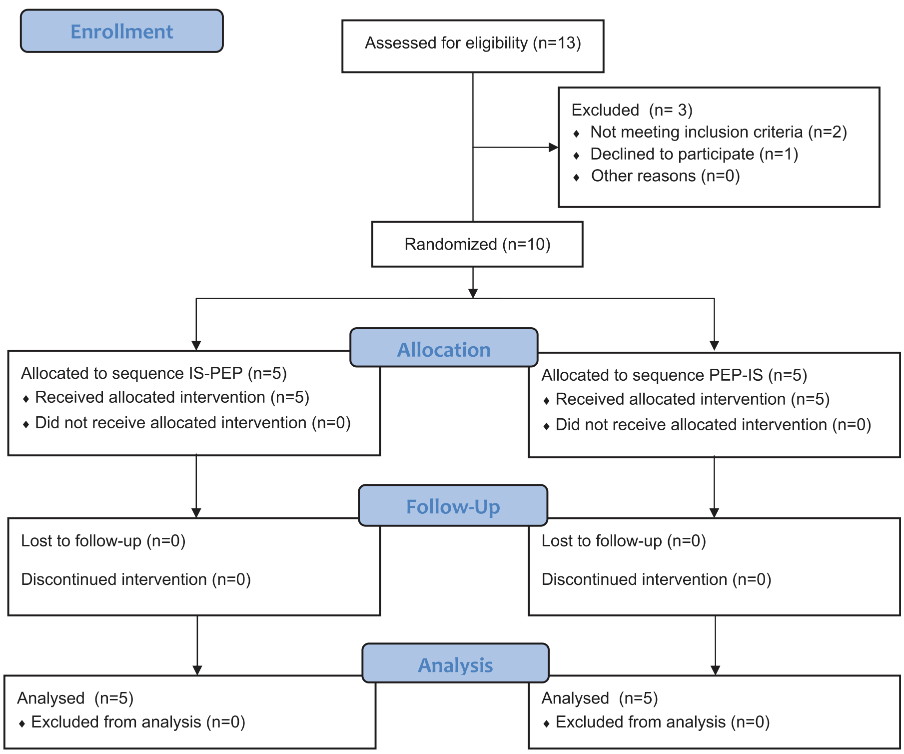

Figure 3. Consort flow chart.

Table 1. Anthropometric and cardiorespiratory parameters of the 10 subjects.

Age (years)	61.2 ± 16.3 [56.1; 66.4]
Height (cm)	176.6 ± 8.4 [174.0; 179.3]
Weight (kg)	78.8 ± 12.3 [75.0; 82.7]
BMI (kg/m^2)	25.3 ± 3.8 [24.1; 26.5]
CE (cm)	7.1 ± 2.4 [6.4; 7.9]
SpO_2 (%)	97.8 ± 1.9 [97.2; 98.4]

BMI: Body mass index; CE: chest expansion; SpO_2: pulsed oxygen saturation.
Data are expressed by mean ± SD and 95% interval confidence in brackets.

saturation (p = 0.16). We found no difference between IS and PEP neither in ventilation (p = 0.17), nor in recruitment (p = 0.81), nor in CE (p = 0.76), nor in pulsed oxygen saturation (p = 0.97), nor in fatigue (p = 0.87). ΔEELVVT ($i - e$) and ΔEELI were significantly increased by both techniques (+422% [$p < 0.001$]; +138% [$p = 0.040$] and +296% [$p < 0.001$]; +638% [$p < 0.001$] for PEP and IS, respectively). No difference was observed between rest phases for ventilation (p = 0.60) and for recruitment (p = 0.37).

Discussion

This study highlights that PEP and IS improve equally ventilation and recruitment after surgery in patients without pulmonary disease. Although both techniques gave a similar benefit, the effect was only related to the duration of the phase of exercise.

IS has been used historically to prevent or treat postoperative complications after abdominal or cardiac surgery (Stock et al., 1985). However, the use of this techniques is supported by a low level of evidence due to inconsistent results in the literature (Carvalho, Paisani, and Lunardi, 2011; Do Nascimento Junior et al., 2014; Freitas, Soares, Cardoso, and Atallah, 2012; Gosselink et al., 2000). IS devices aim to stimulate deep and slow breaths to increase lung inflation, to improve sputum expectoration avoiding lung infection, especially after surgery (Hristara-Papadopoulou, Tsanakas, Diomou, and Papadopoulou, 2008). We highlighted that IS increases instantaneously ventilation and recruitment, in line with this expected effect. Previous studies focused mainly on the effects of IS on respiratory motion and showed comparable results based on different criteria (Kotani et al., 2015; Lima et al., 2014; Lunardi et al., 2014; Parreira, Tomich, Britto, and Sampaio, 2005; Tomich et al., 2007). Indeed, IS demonstrated an improvement in respiratory motion in young healthy subjects after 2 weeks of training with IS (Kotani et al., 2015). Flow IS (FIS) and volume-oriented IS (VIS) were also compared by this way. Rib cage motion contributions to tidal volume were showed to be different between FIS and VIS in young healthy subjects (Parreira, Tomich, Britto, and Sampaio, 2005) contrarily to elderly people (Lunardi et al., 2014). Improvement of chest wall mobility related to IS was also observed in patients after a stroke as asymmetry of right and left pulmonary rib cage expansion was decreased (Lima et al., 2014).

Our results demonstrated only a very short-term effect of our IS protocol on ventilation and recruitment.

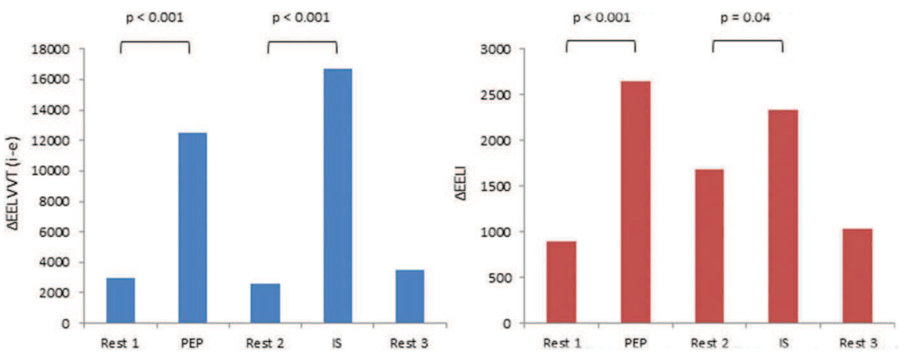

Figure 4. Results of ventilation (ΔEELVVT ($i - e$)) (left panel) and recruitment (ΔEELI) (right panel) expressed by mean impedance for each phases (impedance values are expressed as arbitrary units). IS: Incentive spirometry; PEP: positive expiratory pressure.

Table 2. Pulsed oxygen saturation, CE, and fatigue during the five phases of the protocol.

	Rest 1	PEP	Rest 2	IS	Rest 3
CE (cm)	6 (1) [6; 12]	7 (4) [5; 10]	6 (2) [5; 7]	6 (2) [5; 8]	6.5 (4) [5; 10.5]
SpO_2 (%)	98 (4) [92; 100]	100 (1) [98; 100]	97 (4) [94; 99]	100 (1) [99; 100]	97 (4) [94; 100]
Borg (pts)	1 (3) [0; 4]	1 (4) [0; 4]	0.5 (3) [0; 3]	0 (3) [0; 4]	0.5 (3) [0; 4]

PEP: Positive expiratory pressure; IS: incentive spirometry; SpO_2: pulsed oxygen saturation; CE: upper chest expansion.
Impedance values are expressed as arbitrary units. Data are expressed by median (IQR) and 95% interval confidence in brackets.

To our knowledge, it has never been explored before. Indeed, these two parameters returned to the basal values within 5 min after stopping the manoeuver. This lack of remnant effect could partly explain the negative conclusions of systematic reviews and guidelines regarding the use of IS in postoperative population (Carvalho, Paisani, and Lunardi, 2011; Do Nascimento Junior et al., 2014; Freitas, Soares, Cardoso, and Atallah, 2012) even if it can be related to the short duration of our protocol. Based on our results, the absence of benefits on pulmonary complication after abdominal surgery (Lunardi et al., 2015) seems logical because ventilation and recruitment changes are only observed during the phases of exercise. The cumulative effect of the sessions should be further investigated.

Similar benefits to IS were observed with PEP in our study. PEP devices provide a continuous back pressure at the mouth during the expiration which acts to prevent airway closure (Groth et al., 1985), to increase collateral ventilation (Menkes and Traystman, 1977), and to promote mucus mobilization (Darbee, Ohtake, Grant, and Cerny, 2004). In addition, PEP appeared to counteract inhomogeneity of spatial ventilation distribution in healthy adults and CF patients (Groth et al., 1985; Wettstein, Radlinger, and Riedel, 2014), even if it was recently discussed (Osadnik et al., 2014). Our results are in line with the improved homogenization of the ventilation, even if the protocols were not comparable. This effect was influenced by the lung disease and the kind of positive pressure device. Indeed, continuous positive airway pressure enhances the gravity effect on spatial ventilation distribution in lateral position while PEP counteracted its influence (Wettstein, Radlinger, and Riedel, 2014).

We postulate that EIT might help to better define the airway clearance technique and limit the well-demonstrated intra- and intervariability related to the use of chest physiotherapy (Gregson et al., 2007; Shannon et al., 2009), and to further individualize chest physiotherapy and monitor the physiological effects of the techniques. Indeed, this study highlights the interest of EIT as a noninvasive tool to evaluate physiological effects of chest physiotherapy and offer a way of comparison between different techniques. This tool can be used with limited experience on a daily basis at bedside to observe the regional and global distribution of ventilation and changes in end-expiratory lung volume. As illustration of its interest, we observed the absence of remnant benefit which could imply to prolong the duration of the IS or PEP session or the repetition of the sessions when used in this indication. Even if it was not the objective of the study, that confirmed the validity of EIT to evaluate chest physiotherapy effect. If the changes in impedance values can be translated in an effect on ventilation due to the correlation observed between these parameters (Leonhardt and Lachmann, 2012), to our knowledge, there is no minimal clinically important difference for the different parameters related to EIT. In our study, it was not a problem to interpret the effect of both manoeuver due to the huge difference (more than 300% of improvement due to the manoeuvers) in the EIT outcomes between the different phases but it is necessary to determine the Minimal clinically important difference (MCID) for its use in clinical studies or in the daily follow-up.

Some limitations need to be addressed. Even if we observed an improvement of ventilation and recruitment related to these two techniques, it was not confirmed by blood gas analysis not allowing an explanation of the underlying mechanism. Moreover, we included only patients with healthy lungs limiting extrapolation of our results to patients with lung disease. Similarly, comparison between these two devices could be different depending on the pathophysiological conditions in other populations. Furthermore, participants were naïve for both techniques even if it seems not influent on the results of our study. In the future, it could be useful to evaluate the cumulative effect of repeated or longer sessions with the attempt to verify a potential remnant effect. The lack of preoperative data on ventilation and recruitment is also a limitation even if we postulate that the absence of lung disease reduces the risk of impairment.

To our knowledge, this is the first study assessing short-term effects of the physiotherapy techniques on ventilation and recruitment within postoperative period. We showed that IS and PEP improved ventilation and recruitment instantaneously without remnant effect after the phases of exercise. It suggests a change in the use of these manoeuvers in postoperative period by repeating regularly the manoeuver.

Declaration of Interest

No conflict of interest is reported.

References

Campbell MJ, Gardner MJ 1988 Calculating confidence intervals for some non-parametric analyses. British Medical Journal 296(6634): 1454–1456.

Carvalho CR, Paisani DM, Lunardi AC 2011 Incentive spirometry in major surgeries: A systematic review. Revista Brasileira De Fisioterapia 15: 343–350.

Darbee JC, Ohtake PJ, Grant BJ, Cerny FJ 2004 Physiologic evidence for the efficacy of positive expiratory pressure as an airway clearance technique in patients with cystic fibrosis. Physical Therapy 84: 524–537.

Debouche S, Pitance L, Robert A, Liistro G, Reychler G 2016 Reliability and reproducibility of chest wall expansion measurement in young healthy adults. Journal of Manipulative and Physiological Therapeutics 39: 443–449.

Do Nascimento Junior P, Modolo NS, Andrade S, Guimaraes MM, Braz LG, El Dib R 2014 Incentive spirometry for prevention of postoperative pulmonary complications in upper abdominal surgery. Cochrane Database Systematic Review 2: CD006058.

Freitas ER, Soares BG, Cardoso JR, Atallah AN 2012 Incentive spirometry for preventing pulmonary complications after coronary artery bypass graft. Cochrane Database Systematic Review 9: CD004466.

Frerichs I, Dargaville PA, Dudykevych T, Rimensberger PC 2003 Electrical impedance tomography: A method for monitoring regional lung aeration and tidal volume distribution? Intensive Care Medicine 29: 2312–2316.

Frerichs I, Hahn G, Golisch W, Kurpitz M, Burchardi H, Hellige G 1998 Monitoring perioperative changes in distribution of pulmonary ventilation by functional electrical impedance tomography. Acta Anaesthesiologica Scandinavia 42: 721–726.

Gosselink R, Schrever K, Cops P, Witvrouwen H, De LP, Troosters T, Lerut A, Deneffe G, Decramer M 2000 Incentive spirometry does not enhance recovery after thoracic surgery. Critical Care Medicine 28: 679–683.

Gregson RK, Stocks J, Petley GW, Shannon H, Warner JO, Jagannathan R, Main E 2007 Simultaneous measurement of force and respiratory profiles during chest physiotherapy in ventilated children. Physiological Measurement 28: 1017–1028.

Groth S, Stafanger G, Dirksen H, Andersen JB, Falk M, Kelstrup M 1985 Positive expiratory pressure (PEP-mask) physiotherapy improves ventilation and reduces volume of trapped gas in cystic fibrosis. Bulletin Européen De Physiopathologie Respiratoire 21: 339–343.

Hinz J, Hahn G, Neumann P, Sydow M, Mohrenweiser P, Hellige G, Burchardi H 2003 End-expiratory lung impedance change enables bedside monitoring of end-expiratory lung volume change. Intensive Care Medicine 29: 37–43.

Hristara-Papadopoulou A, Tsanakas J, Diomou G, Papadopoulou O 2008 Current devices of respiratory physiotherapy. Hippokratia 12: 211–220.

Kotani T, Akazawa T, Sakuma T, Nagaya S, Sonoda M, Tanaka Y, Katogi T, Nemoto T, Minami S 2015 Effects of incentive spirometry on respiratory motion in healthy subjects using Cine breathing magnetic resonance imaging. Annals of Physical and Rehabilitation Medicine 39: 360–365.

Leonhardt S, Lachmann B 2012 Electrical impedance tomography: The holy grail of ventilation and perfusion monitoring? Intensive Care Medicine 38: 1917–1929.

Lima IN, Fregonezi GA, Melo R, Cabral EE, Aliverti A, Campos TF, Ferreira GM 2014 Acute effects of volume-oriented incentive spirometry on chest wall volumes in patients after a stroke. Respiratory Care 59: 1101–1107.

Lunardi AC, Paisani DM, Marques Da Silva CC, Cano DP, Tanaka C, Carvalho CR 2015 Comparison of lung expansion techniques on thoracoabdominal mechanics and incidence of pulmonary complications after upper abdominal surgery: A randomized and controlled trial. Chest 148: 1003–1010.

Lunardi AC, Porras DC, Barbosa RC, Paisani DM, Marques Da Silva CC, Tanaka C, Carvalho CR 2014 Effect of volume-oriented versus flow-oriented incentive spirometry on chest wall volumes, inspiratory muscle activity, and thoracoabdominal synchrony in the elderly. Respiratory Care 59: 420–426.

McCarren B, Alison JA 2006 Physiological effects of vibration in subjects with cystic fibrosis. European Respiratory Journal 27: 1204–1209.

Menkes HA, Traystman RJ 1977 Collateral ventilation. American Review Respiratory Disease 116: 287–309.

Osadnik C, Stuart-Andrews C, Ellis S, Thompson B, McDonald CF, Holland AE 2014 Positive expiratory pressure via mask does not improve ventilation inhomogeneity more than huffing and coughing in individuals with stable chronic obstructive pulmonary disease and chronic sputum expectoration. Respiration 87: 38–44.

Overend TJ, Anderson CM, Lucy SD, Bhatia C, Jonsson BI, Timmermans C 2001 The effect of incentive spirometry on postoperative pulmonary complications: A systematic review. Chest 120: 971–978.

Parreira VF, Tomich GM, Britto RR, Sampaio RF 2005 Assessment of tidal volume and thoracoabdominal motion using volume and flow-oriented incentive spirometers in healthy subjects. Brazilian Journal of Medical and Biological Research 38: 1105–1112.

Pfleger A, Steinbacher M, Schwantzer G, Weinhandl E, Wagner M, Eber E 2015 Short-term effects of physiotherapy on ventilation inhomogeneity in cystic fibrosis patients with a wide range of lung disease severity. Journal of Cystic Fibrosis 14: 627–631.

Shannon H, Gregson R, Stocks J, Cole TJ, Main E 2009 Repeatability of physiotherapy chest wall vibrations applied to spontaneously breathing adults. Physiotherapy 95: 36–42.

Stock MC, Downs JB, Gauer PK, Alster JM, Imrey PB 1985 Prevention of postoperative pulmonary complications with CPAP, incentive spirometry, and conservative therapy. Chest 87: 151–157.

Tomich GM, Franca DC, Diorio AC, Britto RR, Sampaio RF, Parreira VF 2007 Breathing pattern, thoracoabdominal motion and muscular activity during three breathing exercises. Brazilian Journal of Medical and Biological Research 40: 1409–1417.

Wellek S, Blettner M 2012 On the proper use of the crossover design in clinical trials: Part 18 of a series on evaluation of scientific publications. Deutsches Ärzteblatt International 109: 276–281.

Wettstein M, Radlinger L, Riedel T 2014 Effect of different breathing aids on ventilation distribution in adults with cystic fibrosis. PLoS One 9: e106591.