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Effects of unilateral PEEP on biomechanics of both lungs during independent lung ventilation in patients anaesthetised for thoracic surgery

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Abstract

Background: Synchronous independent lung ventilation (ILV) is the treatment of choice for unilateral pathology of lung parenchyma. Numerous studies have documented the improved blood oxygenation and clinical efficacy of this procedure. The aim of the present study was to evaluate the effects of ILV on the selected biomechanical parameters of the lungs.

Method: The study involved ASA I-II patients undergoing thoracic surgery in the lateral decubitus position under the standard conditions of general anaesthesia with the thoracic cavity closed. ILV with equal separation of the tidal volume was performed with a prototype volume separator, using incremental a PEEP of 0–15 cm H_2O in the dependent lung. Peak pressures, dynamic compliance and airway resistance of both lungs were evaluated.

Results: The study included 36 patients. In all of the patients, a PEEP of 5–15 cm H_2O in one lung increased its peak pressures, dynamic compliance and resistances, and variably affected the biomechanical parameters of the other lung. Irrespective of patient positioning on the right or left side, the highest compliance was recorded at a PEEP of 10 cm H_2O.

Conclusions: In ILV, peak pressures and airway resistances are higher in the dependent lung compared to compliances in the non-dependent lung. ILV with a PEEP of 5–15 cm H_2O increases the biomechanical parameters of the dependent lung while variably influencing the parameters in the non-dependent lung.

Key words: lung ventilation, independent, biomechanics; lung ventilation, independent, PEEP; anaesthesia, thoracic surgery

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In many cases, artificial lung ventilation is an essential life-saving form of treatment. Despite its undeniable benefits, this procedure can induce many adverse side effects that can lead to both systemic and local–pulmonary challenges [1, 2].

One of the local effects of improperly tailored artificial ventilation is atelectasis, which is a common and harmful phenomenon that can develop in patients undergoing anaesthesia or patients requiring intensive care [1, 3–6]. Treatment methods, such as popular recruitment manoeuvres using PEEP, increase FRC, aerate the collapsed alveoli and beneficially affect gas exchange in the lungs to improve blood oxygenation. The PEEP, per se, prevents numerous adverse reactions triggered by alveolar atelectasis.

Atelectasis is not always symmetrical; in some cases, the pathology impacts only one lung or part of the lung, as observed in ARDS, lung cancer, unilateral thoracic trauma or bronchopleural fistula. Moreover, atelectasis almost always develops during anaesthetic procedures for thoracic surgery, leading to functional and morphological heterogeneity of the respiratory system. Lateralisation of the pulmonary parenchymal injury results in altered compliance and varied airway resistance of both lungs. In such cases, the distribution of respiratory gases is asymmetrical and conventional ventilation cannot distend the atelectatic areas, thus leading to overdistension of the intact parenchymal fragment and its injury, ultimately resulting in impaired gas exchange in the lungs [7]. Additionally, altered gas flow results in less effective turbulent flow [7, 8]. The difference between retraction forces and those maintaining aeration of the pulmonary alveoli increases, which exerts unfavourable effects on the formation of surfactant by type II pneumocytes.

A recumbent position deteriorates the flow of respiratory gases, increasing atelectasis by adversely affecting intra-abdominal pressure or gravitational forces of the individual spheres of the lung parenchyma [9, 10].

Cases such as those above can be treated with independent lung ventilation (ILV), which involves separate aeration of each lung with respiratory parameters titrated to their current condition. ILV requires endobronchial intubation, usually with two ventilators working synchronously or asynchronously.

Another method of treatment consists of the use of one ventilator and a tidal volume separator. The stream of tidal volume reaches the lungs through two separate respiratory systems and expiratory gases are evaluated via two independent expiratory systems. The separator is equipped with PEEP valves, which enables the use of various end-expiratory pressures for each lung [11–13].

Improved blood oxygenation during ILV with PEEP has been well documented in numerous studies, while analyses evaluating its influence on the biomechanics of the respiratory system are lacking. The present study aimed to determine the effects of synchronous ILV using incremental values of PEEP in the non-operated lung on the selected lung parameters in patients undergoing thoracic surgery.

METHODS

The study design was approved by the Bioethics Committee of the Medical University of Lublin. Patients scheduled for lung surgical procedures under bronchial general anaesthesia were included. The exclusion criteria included cardiovascular diseases, COPD, particularly with coexisting emphysema after earlier thoracotomy, and impossible or anticipated difficult distribution of ventilation.

All patients were pre-medicated with oral diazepam in a dose of 10 mg one hour before surgery. Prior to the induction of anaesthesia, pre-oxygenation was used, 5 μg kg^{-1} of fentanyl and 0.5 mg atropine. Anaesthesia was induced with propofol, 1 mg kg^{-1}, and suxamethonium, 1 mg kg^{-1}; subsequently, the trachea was intubated with Robertshaw double-lumen endotracheal tubes, appropriately opposing the operated side. Proper location of the endotracheal tubes was verified with a fibrescope.

Lung ventilation was carried out using the IPPV method in a volume-controlled mode, with the Primus anaesthetic device (Dräger, Germany). The following ventilation parameters were used: VT 6–8 mL kg^{-1}, f 12–15 min^{-1} and F_IO_2, 0.35. Anaesthesia was maintained with fractionated doses of fentanyl, 0.001 mg kg^{-1}, and sevoflurane at the concentration of 1–2 vol%; muscle relaxation was maintained with vecuronium, 0.1 mg kg^{-1}.

Intraoperatively, ECG, HR, SpO_2, $ETCO_2$ were monitored continuously and SAP, DAP every 5 minutes (measured non-invasively).

Synchronous independent lung ventilation with equal distribution of tidal volume in a ratio 1:1 was carried out using a volume separator devised in the Institute of Biocybernetics and Biomedical Engineering (IBBE) of the Polish Academy of Sciences (PAS).

Sequential measurements were performed prior to the surgical procedure with the thoracic cavity closed. The data were recorded in patients on the left or right side when the lower lung (non-operated), i.e., the one in which the PEEP was used, was the dependent lung.

According to the accepted algorithm, measurements were started during ventilation without PEEP and then with PEEP at 5, 10, 15 cm H_2O. Peak pressures, dynamic compliance and resistances in both lungs were evaluated. Data were recorded using the Florian analyser (Acutronic, Germany) 10 minutes after the institution of the next study stage.

Results were statistically analysed. Biomechanical parameters were characterised using the median, mean, upper and lower quartile, range of variability and standard deviation. Due to the skewed distribution of data, confirmed by the Shapiro-Wilk test, and heterogeneity of variances assessed by the Fisher`s F test, the intergroup differences were analysed using non-parametric tests. The Mann-Whitney *U* test was used to compare two independent groups and the Wilcoxon matched-pairs signed-ranks test to compare two dependent groups. The 5% deduction error was assumed; hence, $P < 0.05$ was considered as significant.

RESULTS

The study involved 36 patients (7 women and 29 men). The mean patient age was 50.2 ± 12.9 years, body weight was 79.5 ± 11.2 kg, height was 168.8 ± 12.5 cm, and BMI was 27.8 ± 0.75 kg m^{-2}. According to the pre-anaesthesia clinical assessment, there were 11 ASA I, and 25 ASA II patients.

The respiratory system assessment was based on the parameters of the acid-base balance of arterial blood performed during spontaneous breathing with atmospheric air on the day preceding surgery, which demonstrated the following: pO_2 — 80.0 ± 15.0 mm Hg, pCO_2 —35.2 ± 3.7 mm Hg. The basic spirometric parameters were as follows: FVC — 3970 ± 858 mL, constituting 108.1 ± 11.9% of the norm and FEV_1 — 2980 ± 715 mL s^{-1}, i.e., 82.6 ± 6.4% of normal value.

In the study population of 36 patients, 18 were qualified for left lung surgery and 18 for left-sided thoracotomy. The following double-lumen endotracheal tubes were used: no. 37 in 11 patients, no. 39 in 17 and no. 41 in 11 patients.

The most common surgical procedure was lobectomy (16 cases) followed by wedge resection of a tumour (6), exploratory thoracotomy (5), pneumonectomy (5), and video-assisted thoracoscopy (4 cases). In all patients, the course of anaesthesia and surgery were uneventful. After the completion of surgery and routine recovery from anaesthesia, the patients were transported to the postoperative care unit for further treatment.

Examinations revealed that during the independent lung ventilation in the lateral decubitus position, peak pressures and airway resistances were higher while dynamic compliance was lower in the dependent lung. The application of a PEEP of 5–10–15 cm H_2O in one lung resulted in its increased peak pressures, compliance and resistances, while variably affecting the biomechanical parameters of the other lung. Irrespective of patient positioning on the right or left side, the highest values of dynamic compliance in the dependent lung were recorded at a PEEP of 10 cm H_2O. Compared to the other lung, the values of airway resistance in the dependent lung were increasingly high, which was particularly spectacular when the right lung was dependent. Detailed data regarding the biomechanical parameters of the lungs were listed in Tables 1 and 2.

DISCUSSION

Pulmonary complications resulting from the use of various modes of conventional ventilation are often associated with the relatively well-known respiratory mechanics specific to each method. However, knowledge regarding independent lung ventilation is limited; therefore, we decided to conduct this study due to the potential usefulness of this management method during general anaesthesia for thoracic surgery in patients in the lateral decubitus position with the thoracic cavity closed.

There are few reports available in literature in which the impact of patient positioning on selected parameters of respiratory mechanics have been analysed. The publications cited are inconsistent, their results inexplicit, and sometimes contradictory [14, 15].

Lung ventilation in the lateral decubitus position is a complex issue. The lower lung exposed to gravitation is characterised by better perfusion yet worse ventilation, which causes the leak of deoxygenated blood [1, 2]. Independent lung ventilation can eliminate this phenomenon, contributing to better aeration of the lower lung.

Under such conditions, our findings demonstrated higher values of peak pressures in the dependent lung. Moreover, a PEEP of 5–15 cm H_2O in this lung caused an increase in its peak pressures, which generated a significant difference in the parameter studied between the two lungs. Different observations were presented in the publication from 2010, where decreased peak pressures in the dependent lung with incremental increases in PEEP were found. The authors compare their results with pressure-controlled one-lung ventilation [16].

Our observations confirm that PEEP significantly contributes to improved compliance of the pulmonary parenchyma [17]. According to recent studies, the use of a PEEP at even 5 cm H_2O increases compliance by 20%; the PEEP recommended by Wallet and co-workers in patients with ARDS is 15 cm H_2O [18]. In cases of pulmonary pathology with coexisting intra-abdominal hypertension, the beneficial effects of PEEP are observed, irrespective of the method of PEEP application [19]. In patients with intra-abdominal hypertension induced by pneumoperitoneum for laparoscopic procedures, even low values of PEEP contribute to better lung elastance, and thus better compliance [20]. Comparable observations pertaining to individuals undergoing thoracic surgery with ventilation involving only one lung have been conducted [21, 22].

The application of PEEP during artificial ventilation increases the end-expiratory lung volume proportionally to the values of the pressures, both in healthy and injured lungs, which can result in their improved compliance [23]. A study in patients during general anaesthesia for thoracic surgery using sparing one-lung ventilation, tidal volumes of 6 mL kg^{-1} and a PEEP of 5 cm H_2O, revealed significantly improved compliance of this lung, compared to traditional ventilation with tidal volumes of 10 mL kg^{-1} when PEEP was not used [24]. Therefore, single reports of better lung compliance when using traditional high tidal volumes without positive end-expiratory pressure under identical clinical circumstances should be considered controversial and require additional assessment [25].

Furthermore, our study findings confirm an increase in compliance of the dependent lung with incremental values of PEEP, regardless of patient side and position. The highest compliance was noted at a PEEP of 10 cm H_2O, which is comparable to the data presented by Schumann and colleagues [17]. In our study, dynamic compliance of the lung deteriorated at 15 cm H_2O PEEP, which contradicts the findings published by Kingstedt and co-workers, who used a PEEP of 16 cm H_2O [12]. Based on the available literature, it can be assumed that decreased compliance of the dependent lung at a PEEP of 15 cm H_2O resulted from over-distension [26, 27] because increases in functional residual capacity with increases in PEEP have their limits [28]. For the above reasons, a PEEP of 5–10 cm H_2O is considered the best to maintain optimal lung compliance favouring aeration of the lungs without the risk of over-distension [29].

Table 1. Values of lung biomechanical parameters in patients positioned on the right side

PEEP ($cm\ H_2O$)		Median	25%	75%	Range	*P-value*
Peak pressure ($cm\ H_2O$)						
0	D	15,5	15	16	14–19	0.0117
	ND	15	15	16	13–17	
5	D	16	16	17	15–18	0.0006
	ND	15	15	16	13–17	
10	D	18	17	20	16–24	0.0001
	ND	15	15	16	13–17	
15	D	20	19	10	17–27	0.0001
	ND	15	15	16	13–17	
Dynamic compliance ($mL\ cm\ H_2O^{-1}$)						
0	D	23	22	25.2	19–32.2	0.0030
	ND	24.5	23.6	25.9	20.5–33.2	
5	D	23.6	22.6	26	20–33.2	0.0069
	ND	24.85	23.6	26.7	20.5–40.0	
10	D	26.35	21.9	35	23.1–28	0.0428
	ND	24.7	23.6	26.7	20.9–33.4	
15	D	24	23.1	28.1	20.8–36.2	0.6359
	ND	24.45	22.8	25.9	20–33.4	
Resistance ($cm\ H_2O\ L^{-1}\ sec^{-1}$)						
0	D	42.5	40	45	30–68	0.0009
	ND	40	35	43	30–59	
5	D	43.5	41	46	31–70	0.0001
	ND	40	36	43	30–60	
10	D	44.5	42	45	30–70	0.0010
	ND	40.5	38	43	30–60	
15	D	45	43	48	31–70	0.0009
	ND	40.5	38	43	21–60	

D — dependent lung; ND — non-dependent lung

Moreover, the documented correlation between positive end-expiratory pressure and compliance favours research on PEEP optimisation based on lung compliance. Animal experiments demonstrated an explicit relationship between dynamic compliance versus the extent of atelectasis and inability to titrate PEEP to ensure optimal recruitment [30]. Considering that increasing numbers of modern ventilators enable a bedside assessment of lung compliance, this type of management can be of significant clinical value and is likely to replace routine determinations of lung ventilation parameters based on arterial blood gasometry with non-invasive assessments of lung biomechanical parameters [28].

Under the specific conditions of anaesthesia for thoracic surgery, both lung compliance and airway resistance change. As a relevant factor, determining proper lung ventilation undergoes significant changes due to anaesthesia, airway instrumentation or patient positioning. The adverse effects are well known of increasing airway resistance during general anaesthesia, which result from a decrease in all components of lung volume, subsequently leading to decreases in the airway diameter. In the light of the laws of physics, specifically the Hagen-Poiseuille equation, the adverse effects of endotracheal intubation or intubation of main bronchi on airway resistance are unquestionable.

Our findings disclosed that in patients in the lateral decubitus position, undergoing independent lung ventilation with uniform distribution of tidal volume, airway resistance is higher in the lung where a PEEP of 5–15 cm H_2O was used, compared to the non-dependent lung. Interpretation of the above changes based on the available literature is not easy, as it was demonstrated that under the conditions of general anaesthesia and endotracheal intubation, PEEP

Table 2. Values of selected biomechanical parameters of lungs in patients positioned on the left side

PEEP ($cm H_2O$)		Median	25%	75%	Range	*P-value*
Peak pressure ($cm H_2O$)						
0	D	16	15	18	14–19	0.0431
	ND	15	14	18	13–18	
5	D	17	16	18	15–20	0.0184
	ND	16	14	18	13–18	
10	D	19	18	20	16–28	0.0002
	ND	15	15	18	13–19	
15	D	20	19	24	17–33	0.0001
	ND	16	15	18	13–19	
Dynamic compliance ($mL\ cm\ H_2O^{-1}$)						
0	D	25	21	27	14–29	0.0079
	ND	26.1	21	27.2	16.4–30.4	
5	D	26.1	23	28	15–32	0.5712
	ND	26.1	20.5	27.2	16.5–30.4	
10	D	29.9	25.8	32.3	16.9–36.1	0.0005
	ND	26.1	20.5	27.4	17–30.4	
15	D	28.2	24.1	30.2	16.4–36.3	0.0235
	ND	26.2	20.5	27.2	17–30.4	
Resistance ($cm\ H_2O\ L^{-1}\ sec^{-1}$)						
0	D	40	39	42	29–59	0.0013
	ND	40	36	40	27–49	
5	D	41	40	43	32–59	0.0011
	ND	40	36	40	27–49	
10	D	40	39	44	30–62	0.0053
	ND	40	37	40	27–49	
15	D	41	39	44	31–63	0.0032
	ND	40	37	41	28–49	

D — dependent lung; ND — non-dependent lung

favours a decrease in airway resistance by improving lung compliance, irrespective of the type of surgery [32–35]. The values of resistances observed might have been associated with the use of double-lumen tubes of narrower diameters than in endotracheal tubes and with secretion accumulation in the tubes [36].

The usefulness of independent lung ventilation is documented in case reports and collective studies [37–41]. Almost all of them are based on clinical observations of patients and do not take into account complex and still unknown problems of lung biomechanics in this model. In this regard, our study is original not only on the national scale, which does not facilitate the interpretation of results.

Future studies should explain the mechanism responsible for the changes in biomechanical parameters of the non-dependent lung during ventilation with PEEP in the dependent lung. A working hypothesis accepted for future research assumes such an effect and is confirmed by our results.

CONCLUSIONS

During synchronous independent lung ventilation in patients undergoing general anaesthesia in the lateral decubitus position, peak pressures and airway resistances are higher in the dependent lung while dynamic compliance is higher in the non-dependent lung.

Under the conditions of synchronous independent lung ventilation with positive end-expiratory pressure in the dependent lung, biomechanical parameter values of this lung increase and are higher compared to those in the other lung, where their changes are varied.

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2. The authors declare no conflict of interest.

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