MEDICAL SCIENCE MONITOR

ANIMAL STUDY

e-ISSN 1643-3750
© Med Sci Monit, 2020; 26: e922609
DOI: 10.12659/MSM.922609

Received: 2020.01.05
Accepted: 2020.03.02
Available online: 2020.03.09
Published: 2020.03.15

Use of Electrical Impedance Tomography (EIT) to Estimate Global and Regional Lung Recruitment Volume (V_{REC}) Induced by Positive End-Expiratory Pressure (PEEP): An Experiment in Pigs with Lung Injury

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Source of support: The National Natural Science Foundation of China (No: 81871582)

Background: Electrical impedance tomography (EIT) is a real-time tool used to monitor lung volume change at the bedside, which could be used to measure lung recruitment volume (V_{REC}) for setting positive end-expiratory pressure (PEEP). We assessed and compared the agreement in V_{REC} measurement with the EIT method versus the flow-derived method.

Material/Methods: In 12 Bama pigs, lung injury was induced by tracheal instillation of hydrochloric acid and verified by an arterial partial pressure of oxygen to inspired oxygen fraction ratio below 200 mmHg. During the end-expiratory occlusion, an airway release maneuver was conduct at 5 and 15 cmH_2O of PEEP. V_{REC} was measured by flow-integrated PEEP-induced lung volume change (flow-derived method) and end-expiratory lung impedance change (EIT-derived method). Linear regression and Bland-Altman analysis were used to test the correlation and agreement between these 2 measures.

Results: Lung injury was successfully induced in all the animals. EIT-derived V_{REC} was significantly correlated with flow-derived V_{REC} (R^2=0.650, p=0.002). The bias (the lower and upper limits of agreement) was –19 (–182 to 144) ml. The median (interquartile range) of EIT-derived V_{REC} was 322 (218–469) ml, with 110 (59–142) ml and 194 (157–307) ml in dependent and nondependent lung regions, respectively. Global and regional respiratory system compliance increased significantly at high PEEP compared to those at low PEEP.

Conclusions: Close correlation and agreement were found between EIT-derived and flow-derived V_{REC} measurements. The advantages of EIT-derived recruitability assessment included the avoidance of ventilation interruption and the ability to provide regional recruitment information.

MeSH Keywords: Electric Impedance • Positive-Pressure Respiration • Respiration, Artificial • Respiratory Mechanics

Full-text PDF: https://www.medscimonit.com/abstract/index/idArt/922609

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Background

Although the use of positive end-expiratory pressure (PEEP) during mechanical ventilation is a common practice in patients with acute respiratory distress syndrome (ARDS), the setting of the "best" PEEP remains controversial [1]. PEEP can play a beneficial role by recruitment of previously collapsed regions of the lung, but it can cause deleterious effects due to overexpansion of the already inflated regions. The overall effect of PEEP on an individual might depend on recruitability [2]. Because the recruitability of patients with ARDS varies widely and is closely related to the response to PEEP [2], personalized settings for PEEP require an estimation of lung recruitment volume (V_{REC}) [3].

V_{REC} can be measured at the bedside using flow-derived technology [3,4]. Traditionally, a multiple quasi-static respiratory system pressure-volume curve method has been established to measure V_{REC} [5,6]. A simplified method has been introduced to calculate V_{REC} as the difference between the actual and minimal predicted lung volume change induced by PEEP [7,8]. However, this method requires a release maneuver by disconnection of the ventilator, which can enhance lung damage. Recently, Chen et al. introduced a modified single-breath decremental PEEP maneuver that used a prolonged expiration to measure PEEP-induced lung volume change [9,10]. However, measuring exhaled volume during prolonged expiration requires deep sedation and often requires muscle paralysis to eliminate the influence of spontaneous breathing.

Electrical impedance tomography (EIT) is a radiation-free and real-time tool to monitor the change of global and regional lung volume at the bedside [11]. The validity and repeatability of EIT monitoring of lung volume change have been tested with reference techniques such as CT scans [12]. Previous reports have introduced the method of V_{REC} measurement by EIT, which has been validated against the helium-dilution technique [13]. To date, no study has been conducted to compare EIT-derived and flow-derived V_{REC} measurements.

In the present study, we hypothesized that V_{REC} measured by EIT is correlated with the flow-derived approach. The primary objective was to assess the agreement of V_{REC} measurement by these 2 technologies.

Material and Methods

The study protocol was approved by the Experimental Studies Ethical Committee (No. 201803001) at Beijing Neurosurgical Institute, Beijing, China.

Animal preparation and monitoring

Twelve healthy Bama pigs weighing 40–44 kg and 11–14 months old were sedated by intramuscular injection of ketamine hydrochloride (0.3 ml/kg) and xylazine hydrochloride (0.3 ml/kg). Pigs were placed in the supine position on a thermo-controlled surgery table. The rectal temperature of the animals was maintained at approximately 36–38°C. During the experiment, normal saline was intravenously infused at a rate of 100 ml/h. A fluid bolus was given when the heart rate exceeded 120 beats/min. Hypotension persisting despite fluid replacement was treated with intravenous norepinephrine (10 μg bolus or continuous infusion at 0.05 to 0.5 μg/kg/min). The mean arterial pressure was maintained above 65 mmHg.

During the experiment, the animals were intubated and ventilated (Evita Infinity V500TM, Dräger, Lübeck, Germany). At baseline, the ventilator was set up in volume-controlled ventilation mode with constant flow, a tidal volume of 6 ml/kg, and respiratory rate 15–25 breaths/min to maintain a partial pressure of carbon dioxide in arterial blood ($PaCO_2$) within a range of 35 to 45 mmHg, a PEEP of 5 cmH_2O, an inspiratory to expiratory ratio (I:E) of 1: 2 with 0.3 s inspiratory pause, and an inspired oxygen fraction (FiO_2) of 0.40.

Propofol (1–5 mg/kg/h) and fentanyl (0.4 μg/kg/h) were infused continuously. Vecuronium (0.3 mg/kg/h) was used to eliminate respiratory efforts, as needed.

The preparation included femoral arterial catheterization, a Swan-Ganz catheterization, and epicystotomy. We inserted a 7.0 Fr flow-directed thermodilution fiberoptic pulmonary artery catheter (Edwards Lifesciences, Irvine, CA, USA) for pulmonary arterial pressure (PAP), pulmonary arterial wedge pressure (PAWP), central venous pressure (CVP), cardiac output (CO) measurements, and mixed venous blood sampling. Femoral artery cannulation was performed with a 7.0 Fr pediatric jugular catheter (ES-04150, Arrow International, Inc., Shanghai, China) for arterial blood sampling and arterial pressure monitoring. Continuous ECG monitoring was performed. For hemodynamic monitoring, a monitor (BeneView T5, Mindray, Shenzhen, China) was used. Cardiac output was measured in triplicate using the pulmonary artery catheter. Arterial and mixed venous blood samples were collected and analyzed.

Airway pressure was measured by pressure transducer (KT 100D-2, Kleis TEK, Italy, range: ±100 cmH_2O). Flow tracing was collected continuously by a heated Fleisch pneumotachograph (Vitalograph, Inc., Lenexa, KS, USA) placed at the end of the endotracheal tube. The signal of pressure and flow was collected continuously (ICU Lab 2.5 Software Package, ICU Lab, Kleis TEK Engineering, Bari, Italy) in a computer for offline analysis with a sample rate of 200 Hz [14].

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EIT monitoring (PulmoVista 500; Dräger, Lübeck, Germany) was performed through a 16-electrode belt positioned under the armpit. One reference electrocardiogram electrode was placed at the right lower extremity [15]. EIT was connected to the ventilator (Evita Infinity V500TM, Dräger, Lübeck, Germany) to collect serial flow, volume, airway pressure, and impedance measurements synchronously. Data were continuously recorded at 40 Hz. A low-pass filter with 50 Hz was used to remove cardiac artifacts. Data were analyzed offline via dedicated software (Dräger EIT Data Analysis Tool 6.3, Lübeck, Germany).

ARDS modeling

After the initial preparation, the ARDS model was induced by instillation of hydrochloric acid (4 mL/kg) into the endotracheal tube [16]. When the ratio of the partial pressure of oxygen in arterial blood (PaO_2) to FiO_2 (PaO_2/FiO_2) remained below 200 mmHg at 5 cmH_2O PEEP for 30 min [17], the ARDS model was considered to be established successfully. An additional 2 ml/kg of hydrochloric acid solution was instilled into the trachea if the criterion was not met.

Study protocol

After the ARDS model was established, low and high PEEP levels (5 and 15 cmH_2O) were applied in random order based on an online random number generator (*http://www.psychicscience.org/random*, accessed on June 1, 2018) and sealed in envelopes. Throughout the study procedure, all the ventilator settings except PEEP were left unchanged from baseline settings. Each PEEP level was maintained for at least 1 h to standardize the lung volume history [18]. At the end of each PEEP level, a procedure was conducted as follows:

1. Arterial and mixed venous blood were sampled. Gas exchange and hemodynamic data were collected.
2. End-inspiratory and end-expiratory airway occlusion were performed, each for 3–5 s, to assess auto-PEEP and calculate respiratory system compliance (Crs) [19].
3. A standard release maneuver was conducted [20]. Briefly, with the end-expiratory occlusion holding, the animal was disconnected from the ventilator with the pneumotachograph remaining on the endotracheal tube, until the flow tracing reached zero.
4. Then, the animal was reconnected to the ventilator. A low-flow inflation pressure-volume curve (constant flow at 6 L/min) was performed at zero PEEP to exclude airway closure [21,22].

Flow-derived V_{REC} measurement

For flow-derived V_{REC} measurement, airway pressure and flow signals were collected from the attached pressure transducer and heated Fleisch pneumotachograph mentioned above. During the release maneuver, the expired volume from PEEP to atmospheric pressure was integrated on flow waveform and documented as PEEP-volume. The difference in PEEP-volume between low and high PEEP was documented as the actual PEEP-induced increase in lung volume. Importantly, disconnection of the ventilator can determine the derecruitment effect. The minimal predicted PEEP-induced increase in lung volume was calculated as the product of static Crs at the low PEEP and the change in PEEP (i.e., 10 cmH_2O in the present study). The V_{REC} between the low and high PEEP was derived as the difference between the actual and the minimal predicted increase in lung volume induced by PEEP [7,8].

EIT-derived V_{REC} measurement

For EIT-derived V_{REC} measurement, data on flow, volume, airway pressure, and impedance were downloaded from Evita Infinity V500TM ventilator connected to the EIT monitor. Stable breaths within the last minute of recording at each PEEP level were analyzed to calculate the lung volume parameters previously described by Mauri et al. [13].

The change in end-expiratory lung volume (ΔEELV) between high and low PEEP was calculated as the change in end-expiratory lung impedance (ΔEELI) by multiplying the ratio between tidal volume (ml) measured by ventilator and the corresponding global tidal impedance change (expressed as absolute unit) at the low PEEP level. Mathematically, ΔEELV can be calculated as:

ΔEELV=ΔEELI×(Tidal volume (ml))/(Tidal impedance change (absolute unit)).

The minimal predicted increase in lung volume induced by PEEP was calculated as described in the flow-derived method, but using data collected from the ventilator. EIT-derived V_{REC} was defined as the difference between ΔEELV and minimal predicted increase in lung volume induced by PEEP [13].

In offline EIT analysis, we defined a matrix of 32×32 pixels in the thoracic cross-section as the global region of interest (ROI), which were further evenly divided into the ventral ROI (nondependent lung region) and dorsal ROI (dependent lung region) [15]. V_{REC} in the nondependent and dependent lung regions were calculated accordingly. The regional Crs was also determined. The heterogeneity of the lungs was assessed using the center of ventilation, which was expressed as the percentage of the anteroposterior extension of the certain lung region [23].

Statistical analysis

Data are expressed as the median (interquartile range, IQR). Parameters before and after ARDS modeling, as well as between low and high PEEP, were compared using the Wilcoxon signed rank

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Table 1. Parameters before and after the establishment of lung injury model.

	Before		After		*p*
PaO_2/FiO_2	450	(398–483)	154	(142–158)	<0.001
Mean blood pressure (mmHg)	128	(116–137)	110	(93–121)	0.010
Heart rate (beats/min)	51	(46–59)	85	(45–106)	0.004
Dead space ratio	0.15	(0.10–0.20)	0.25	(0.21–0.29)	0.005
MPAP (mmHg)	20.0	(18.0–21.8)	30.5	(26.8–39.0)	<0.001
PAWP (mmHg)	9.5	(7.0–13.0)	8.5	(5.3–11.0)	0.680
CVP (mmHg)	7.0	(5.3–10.0)	6.5	(4.3–7.8)	0.593
Cardiac output (L/min)	2.6	(2.4–3.2)	2.6	(2.3–3.4)	0.356
Crs (ml/cmH_2O)	45.0	(39.8–55.2)	25.6	(23.5–31.7)	<0.001

Data are shown as median (interquartile range). PaO_2/FiO_2 – the ratio of arterial partial pressure of oxygen to fraction of inspiration oxygen; MPAP – mean pulmonary arterial pressure; PAWP – pulmonary arterial wedge pressure; CVP – central venous pressure; Crs – respiratory system compliance.

test. The parameters for association analyses were checked for normal distribution by the Kolmogorov-Smirnov test. Association between flow-derived and EIT-derived V_{REC} was assessed by linear regression. Bland-Altman analysis was performed to test the agreement between these 2 measures. Mean bias (EIT-derived V_{REC} minus flow-derived V_{REC}) and standard deviation of the mean bias were calculated. Lower and upper limits of agreement were defined as bias ±1.96 standard deviation of the mean bias. Correlations of V_{REC} with the changes in PaO_2/FiO_2 ratio and Crs between low and high PEEP levels were analyzed by linear regression. Analyses were conducted using SPSS 22.0 (SPSS, Chicago, IL, USA). $p<0.05$ was considered statistically significant.

Results

ARDS was successfully induced in all pigs, with median (IQR) PaO_2/FiO_2 decreasing from 450 (398–483) to 154 (142–158). Compared to baseline values, Crs decreased significantly (45.0 [39.8–55.2] *vs*. 25.6 [23.5–31.7] ml/cmH_2O, $p<0.001$) and the dead space ratio increased significantly (0.15 [0.10–0.20] *vs*. 0.25 [0.21–0.29], $p=0.005$) after modeling (Table 1). During the experiment, no auto-PEEP or airway closures were found in any of the experimental animals.

The V_{REC} data were normally distributed. EIT-derived V_{REC} was significantly correlated with flow-derived V_{REC} ($R^2=0.649$, $p=0.002$, Figure 1A). The bias (the lower and upper limits of agreement) was –19 (–182 to 144) ml (Figure 1B). The median (IQR) EIT-derived V_{REC} between low and high PEEP was 322 (218–469) ml, with 110 (59–142) ml and 194 (157–307) ml in dependent and nondependent lung regions, respectively. The percentage of V_{REC} in the dependent region was 29.5% (25.3–38.3%).

Table 2 shows the Crs and the center of ventilation at the 2 PEEP levels. The global Crs increased significantly at high PEEP compared to that at low PEEP (34.5 [29.1–42.1] *vs*. 24.5 [23.1–28.9] ml/cmH_2O, $p<0.001$). The increase in Crs in the dependent region (98.0% [77.7–1.63%]) was significantly higher than that in the nondependent region (22.5% [9.7–30.6%], $p<0.001$). Tidal volume was distributed more homogenously at high PEEP as shown by the center of ventilation (21.5% [18.5–23.8%] *vs*. 29.5% [25.3–38.3%], $p<0.001$).

Table 3 shows the physiological parameters at the 2 PEEP levels. Compared to low PEEP level, the PaO_2/FiO_2 ratio significantly increased (173 [158–181] *vs*. 254 [223–299], $p<0.001$), and the dead space ratio significantly decreased (0.25 [0.20–0.34] *vs*. 0.20 [0.15–0.23], $p=0.013$) at high PEEP level.

The V_{REC} data, PaO_2/FiO_2 ratio, and global and regional Crs were normally distributed. No significant correlation was found between the change in PaO_2/FiO_2 ratio from low to high PEEP level and global and regional V_{REC} (Figure 2A–2C). The global V_{REC} was directly correlated with the change in global Crs (Figure 2D). A direct correlation was also found between the regional V_{REC} and the changes in Crs in the dependent region (Figure 2E) and nondependent region (Figure 2F).

Discussion

In the present animal experiment, we assessed the correlation and agreement in V_{REC} derived from flow integration and EIT monitoring. The main finding was that EIT appears to be an accurate method to estimate lung recruitability at the bedside. Compared with flow-derived technology, EIT avoids

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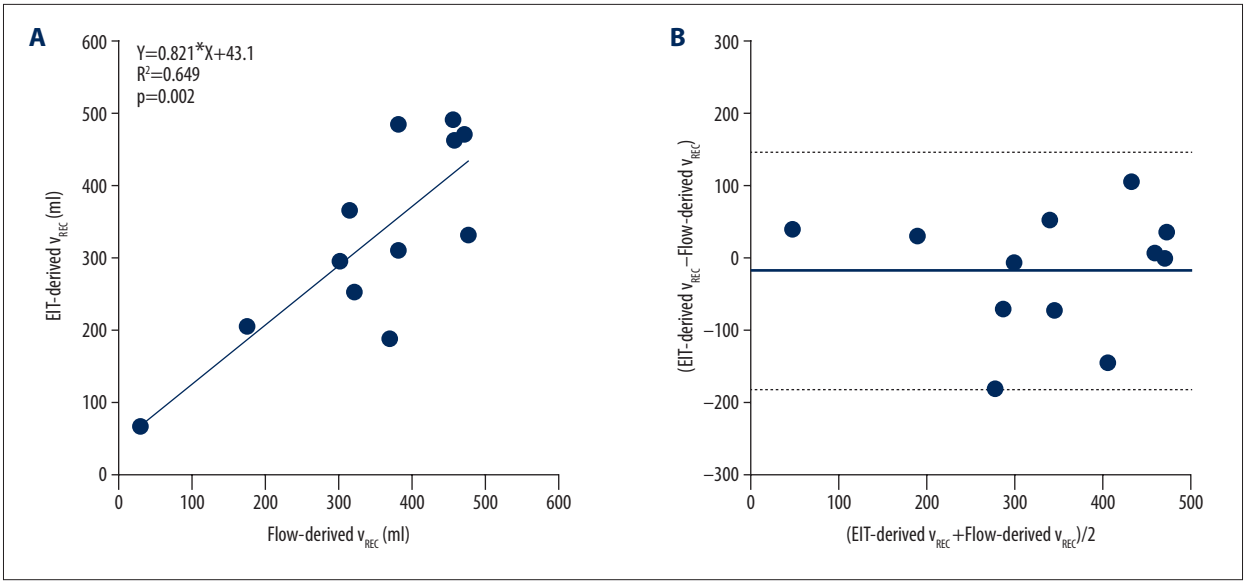

Figure 1. Linear regression (**A**) and Bland-Altman agreement analysis (**B**) for recruitment lung volume (V_{REC}) measured by electrical impedance tomography (EIT) and flow integration. (**A**) A significant linear correlation was found between EIT-derived V_{REC} and flow-derived V_{REC} (R^2=0.649, p=0.002). (**B**) For Bland-Altman agreement analysis, mean bias (EIT-derived V_{REC} minus flow-derived V_{REC}, solid line) and standard deviation of the mean bias were calculated. Lower and upper limits of agreement were defined as bias ±1.96 standard deviation of the mean bias (dashed line).

Table 2. Regional parameters at low and high positive end-expiratory pressure levels.

	Low PEEP		High PEEP		*p*
PEEP (cmH_2O)	4.9	(4.7–5.1)	14.6	(14.4–14.9)	<0.001
Global Crs (ml/cmH_2O)	24.5	(23.1–28.9)	34.5	(29.1–42.1)	<0.001
Dependent regional Crs (ml/cmH_2O)	5.1	(4.4–6.3)	11.0	(8.0–13.3)	<0.001
Nondependent regional Crs (m/cmH_2O)	19.6	(16.1–22.8)	22.1	(17.0–30.4)	0.003
Center of ventilation (%)	21.5	(18.5–23.8)	29.5	(25.3–38.3)	<0.001

Data are shown as median (interquartile range). PEEP – positive end-expiratory pressure; Crs – respiratory system compliance.

airway disconnection and provides regional information on lung volume change.

Recently, the recruitment assessment for PEEP settings to minimize ventilator-induced lung injury has received increasing attention [1]. When higher PEEP is used, non-recruitable lungs may be exposed to harmful overdistension, and when insufficient PEEP is used, recruitable lungs may be exposed to cyclic alveolar opening and closing. Repeated CT scans and gas-dilution techniques have been employed to estimate recruitability. However, due to their complexity, these techniques have been confined to research settings [8]. Several methods have been introduced for the bedside assessment of PEEP-induced alveolar recruitment [4,6]. With passive spirometry, the pressure-volume curve [5,6] and further simplified single-breath decremental PEEP maneuver [7–10] are convenient and repeatable for recruitment measurement, but these methods need deep sedation and muscle paralysis and cannot provide information about overdistension. Recently, the EIT-derived recruitment volume assessment method has been proposed [11] and validated against the helium-dilution method [13]. Mauri et al. conducted a prospectively randomized crossover investigation in 20 adult patients with ARDS or acute hypoxemic respiratory failure, and found a close association in PEEP-induced alveolar recruitment between the helium-dilution and EIT techniques [13]. In the present study, we also demonstrated a direct correlation between EIT-derived and flow-derived V_{REC} in a hydrochloric acid-induced ARDS model (R^2=0.650, p=0.002). Compared to flow-derived measurement, the EIT-derived method slightly underestimated V_{REC}, with a bias of –19 (–182 to 144) ml. This is also in agreement with the results in the comparison of EIT with helium-dilution techniques, in which a –26 ml of bias and limits of agreement of –211 to 160 ml were found [13]. The helium-dilution method and the flow integration during the release

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Table 3. Physiological parameters at the low and high positive end-expiratory pressure levels.

	Low PEEP		High PEEP		*p*
PEEP (cmH_2O)	4.9	(4.7–5.1)	14.6	(14.4–14.9)	<0.001
PaO_2/FiO_2	173	(158–181)	254	(223–299)	<0.001
Mean blood pressure (mmHg)	110	(89–129)	94	(87–110)	0.443
Heart rate (beats/min)	79	(50–106)	81	(59–115)	0.492
Dead space ratio	0.25	(0.20–0.34)	0.20	(0.15–0.23)	0.013
MPAP (mmHg)	30.5	(29.3–37.5)	31.5	(28.3–36.5)	0.632
PAWP (mmHg)	9.0	(6.0–11.0)	12.0	(9.0–14.0)	0.002
CVP (mmHg)	6.5	(4.3–7.0)	9.0	(8.0–10.8)	<0.001
Cardiac output (L/min)	2.8	(2.3–3.1)	1.9	(1.4–2.7)	<0.001
Crs (ml/cmH_2O)	25.3	(23.0–28.8)	–27.5	(24.0–41.4)	<0.001

Data are shown as median (interquartile range). PEEP – positive end-expiratory pressure; PaO_2/FiO_2 – the ratio of arterial partial pressure of oxygen to fraction of inspiration oxygen; MPAP – mean pulmonary arterial pressure; PAWP – pulmonary arterial wedge pressure; CVP – central venous pressure; Crs – respiratory system compliance. Crs data were collected from the attached pressure transducer and heated Fleisch pneumotachograph.

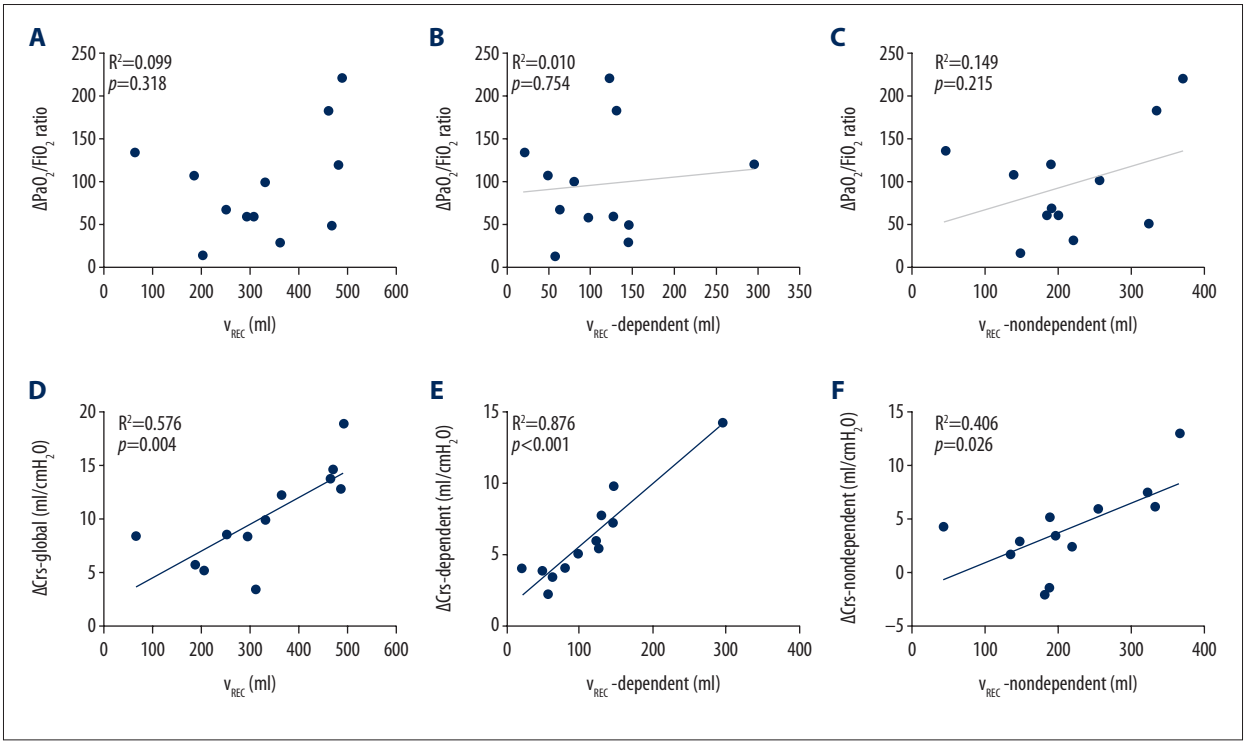

Figure 2. Correlation between global recruitment lung volume (V_{REC}) versus change in the ratio of the partial pressure of oxygen in arterial blood to inspired oxygen fraction ($\Delta PaO_2/FiO_2$) (**A**), between V_{REC} in the dependent lung region (V_{REC}-dependent) versus $\Delta PaO_2/FiO_2$ (**B**), between V_{REC} in the nondependent lung region (V_{REC}-nondependent) versus $\Delta PaO_2/FiO_2$ (**C**), between global V_{REC} versus change in global respiratory system compliance (ΔCrs-global) (**D**), between V_{REC}-dependent versus change in Crs in the dependent lung region (ΔCrs-dependent) (**E**), and between V_{REC}-nondependent versus change in Crs in the nondependent lung region (ΔCrs-nondependent) (**F**). For regional electrical impedance tomography analysis, the lung images were divided horizontally into 2 equal sizes from ventral to dorsal, as the nondependent lung region and the dependent lung region. The regional V_{REC} and Crs were determined by assessing the V_{REC} and tidal volume into these 2 regions.

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maneuver measure all lung regions accessible to ventilation, while the EIT only measures a portion of the lungs, representing approximately half of the whole lung size [11]. However, our data and previously reported results [11,24] indicate that the V_{REC} is underestimated by about 10% by the EIT method, which seems to be within a clinically acceptable range. Compared to the flow-derived method, the main advantage of EIT-derived V_{REC} measurement lies in the avoidance of interruption of mechanical ventilation and the need for deep sedation and paralysis.

EIT can also provide information on regional ventilation, which is valuable for assessment of local recruitment and overdistension [11]. Recently, Scaramuzzo et al. analyzed regional slow-inflation pressure-volume curves from 12 mechanically ventilated patients [25]. The study showed high variable regional lower and upper inflection points, which highlighted the ability of EIT to detect the lung heterogeneity. In a prospective interventional study, Spadaro et al. introduced a new EIT-derived index, the dependent silent spaces, that is a dynamic indicator of regional recruitment [23]. The regional information provided by the EIT allows careful respiratory monitoring of well-designed interventions [26]. In our animals, 30% of PEEP-induced V_{REC} was distributed to the dependent lung area, which is comparable to previous results in acute respiratory failure patients [13]. We also found that global and regional Crs increased significantly at high PEEP, with ventilation distributing more evenly across dependent and nondependent lung regions (Table 2). Meanwhile, gas exchange was improved after the elevation of PEEP. However, these changes in both gas exchange and respiratory mechanics were not found in a previous clinical study by Mauri et al. [13]. There are 3 factors that might contribute to this discrepancy. First, the difference in low and high PEEP levels was 5 cmH_2O in Mauri's study, whereas it was 10 cmH_2O in our study. Second, the measurements were performed in patients at a mean (±standard deviation) of 2±1 days after intubation in the clinical study, but our study was conducted immediately after establishment of the ARDS model, which might have represented more recruitable lungs in the very early stage of ARDS [27]. Third, due to their small sample size, Mauri et al. also hypothesized that the risk of hyperinflation in the nondependent regions was lower and recruitment might be greater at higher PEEP levels in ARDS patients compared to non-ARDS respiratory failure patients. The ability to assess regional ventilation distribution might allow the EIT to be used as effective monitoring in clinical PEEP settings.

Although improvements in oxygenation and Crs were found at high PEEP levels, V_{REC} was only correlated with Crs but not with oxygenation (Figure 2). A secondary analysis of 2 randomized controlled trials showed that the oxygenation response to PEEP varied widely among individual patients because oxygenation is determined by several factors apart from recruitment [28]. However, improvement in Crs mainly suggests recruitment of the lungs and avoidance of overdistention. Although a recent randomized controlled trial demonstrated no beneficial effect of Crs-guided PEEP setting on clinical outcomes [29], further clinical studies are needed to clarify the use of Crs, especially regional Crs, to titrate PEEP in potentially recruitable patients.

There are several limitations to our study. First, CT is the criterion standard for lung volume measurement. The agreement of V_{REC} measured by flow integration and CT scan has been validated in previous studies [7,8]. In the present study, we mainly proposed to test the agreement between the newly introduced EIT-derived V_{REC} measurement and the traditional flow-derived technique, without performing a triple comparison of CT scans. Therefore, we performed an agreement test between the newly introduced EIT-derived V_{REC} measurement and traditional flow-derived technique without a repeat of the CT scan in our study. Second, the EIT imaging is related to the EIT belt location, and approximately half of the lung area is covered [11]. However, the characteristics of continuous ventilation, non-radiation, non-invasiveness, bedside performance, and the ability to obtain regional information make up for this limitation. The EIT is a potentially useful technique for lung volume monitoring in mechanically ventilated patients. Third, although recent studies have shown that airway closure is common in ARDS patients [21,22], no auto-PEEP and airway closure were found in our experimental ARDS pig model. This may be due to the specific model of tracheal instillation of hydrochloric acid we used. However, because airway closure can result in incorrect calculation of V_{REC}, airway closure and airway opening pressure should be determined before respiratory mechanics measurements [10]. Fourth, the release maneuver during flow-derived V_{REC} measurement can result in derecruitment of the lungs. A single-breath maneuver with prolonged expiration was recently introduced to measure V_{REC} [9,10]. Derecruitment can be avoided with this method for clinical monitoring. Fifth, we did not create a low-flow inflation pressure-volume curve at low and high PEEP levels. Thus, the influence of PEEP on poorly ventilated and overinflated lung areas cannot be analyzed using the methods introduced by Spadaro et al. [23] and Scaramuzzo et al. [25]. Sixth, our study was performed in an ARDS animal model. Further studies are necessary to translate the animal findings to clinical practice.

Conclusions

In this study using an ARDS animal model, we found a close correlation and a clinically acceptable agreement in V_{REC} measurement between EIT-derived and traditional flow-derived techniques. The main advantages of EIT-derived recruitability assessment include the ability to avoid ventilation interruptions and to provide regional ventilation information.

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Conflict of interest

None.

References:

1. Sahetya SK, Goligher EC, Brower RG: Fifty years of research in ARDS. Setting positive end-expiratory pressure in acute respiratory distress syndrome. Am J Respir Crit Care Med, 2017; 195: 1429–38
2. Gattinoni L, Caironi P, Cressoni M et al: Lung recruitment in patients with the acute respiratory distress syndrome. N Engl J Med, 2006; 354: 1775–86
3. Chen L, Brochard L: Lung volume assessment in acute respiratory distress syndrome. Curr Opin Crit Care, 2015; 21: 259–64
4. Lu Q: How to assess positive end-expiratory pressure-induced alveolar recruitment? Minerva Anestesiol, 2013; 79: 83–91
5. Ranieri VM, Giuliani R, Fiore T et al: Volume-pressure curve of the respiratory system predicts effects of PEEP in ARDS: "Occlusion" versus "constant flow" technique. Am J Respir Crit Care Med, 1994; 149: 19–27
6. Lu Q, Constantin JM, Nieszkowska A et al: Measurement of alveolar derecruitment in patients with acute lung injury: Computerized tomography versus pressure-volume curve. Crit Care, 2006; 10: R95
7. Dellamonica J, Lerolle N, Sargentini C et al: Accuracy and precision of end-expiratory lung-volume measurements by automated nitrogen washout/washin technique in patients with acute respiratory distress syndrome. Crit Care, 2011; 15: R294
8. Chiumello D, Marino A, Brioni M et al: Lung recruitment assessed by respiratory mechanics and computed tomography in patients with acute respiratory distress syndrome. What is the relationship? Am J Respir Crit Care Med, 2016; 193: 1254–63
9. Chen L, Chen GQ, Shore K et al: Implementing a bedside assessment of respiratory mechanics in patients with acute respiratory distress syndrome. Crit Care, 2017; 21: 84
10. Chen L, Del Sorbo L, Grieco DL et al: Potential for lung recruitment estimated by the recruitment-to-inflation ratio in acute respiratory distress syndrome. A clinical trial. Am J Respir Crit Care Med, 2020; 201: 178–87
11. Frerichs I, Amato MB, van Kaam AH et al: Chest electrical impedance tomography examination, data analysis, terminology, clinical use and recommendations: Consensus statement of the TRanslational EIT developmeNt stuDy group. Thorax, 2017; 72: 83–93
12. Frerichs I, Hinz J, Herrmann P et al: Detection of local lung air content by electrical impedance tomography compared with electron beam CT. J Appl Physiol, 2002; 93: 660–66
13. Mauri T, Eronia N, Turrini C et al: Bedside assessment of the effects of positive end-expiratory pressure on lung inflation and recruitment by the helium dilution technique and electrical impedance tomography. Intensive Care Med, 2016; 42: 1576–87
14. Sun XM, Chen GQ, Huang HW et al: Use of esophageal balloon pressure-volume curve analysis to determine esophageal wall elastance and calibrate raw esophageal pressure: a bench experiment and clinical study. BMC Anesthesiol, 2018; 18: 21
15. Chen GQ, Sun XM, Wang YM et al: Additional expiratory resistance elevates airway pressure and lung volume during high-flow tracheal oxygen via tracheostomy. Sci Rep, 2019; 9: 14542
16. Smith KM, Mrozek JD, Simonton SC et al: Prolonged partial liquid ventilation using conventional and high-frequency ventilatory techniques: Gas exchange and lung pathology in an animal model of respiratory distress syndrome. Crit Care Med, 1997; 25: 1888–97
17. Ranieri VM, Rubenfeld GD, Thompson BT et al: Acute respiratory distress syndrome: the Berlin Definition. JAMA, 2012: 307: 2526–33
18. Chiumello D, Coppola S, Froio S et al: Time to reach a new steady state after changes of positive end expiratory pressure. Intensive Care Med, 2013; 39: 1377–85
19. Brochard L, Martin GS, Blanch L et al: Clinical review: Respiratory monitoring in the ICU – A consensus of 16. Crit Care, 2012; 16: 219
20. Chiumello D, Cressoni M, Colombo A et al: The assessment of transpulmonary pressure in mechanically ventilated ARDS patients. Intensive Care Med, 2014; 40: 1670–78
21. Chen L, Del Sorbo L, Grieco DL et al: Airway closure in acute respiratory distress syndrome: An underestimated and misinterpreted phenomenon. Am J Respir Crit Care Med, 2018; 197: 132–36
22. Sun XM, Chen GQ, Zhou YM et al: Airway closure could be confirmed by electrical impedance tomography. Am J Respir Crit Care Med, 2018; 197: 138–41
23. Spadaro S, Mauri T, Bohm SH et al: Variation of poorly ventilated lung units (silent spaces) measured by electrical impedance tomography to dynamically assess recruitment. Crit Care, 2018; 22: 26
24. van der Burg PS, Miedema M, de Jongh FH et al: Cross-sectional changes in lung volume measured by electrical impedance tomography are representative for the whole lung in venti- lated preterm infants. Crit Care Med, 2014; 42: 1524–30
25. Scaramuzzo G, Spadaro S, Waldmann AD et al: Heterogeneity of regional inflection points from pressure-volume curves assessed by electrical impedance tomography. Crit Care, 2019; 23: 119
26. Spinelli E, Mauri T, Fogagnolo A et al: Electrical impedance tomography in perioperative medicine: Careful respiratory monitoring for tailored interventions. BMC Anesthesiol, 2019; 19: 140
27. de Matos GF, Stanzani F, Passos RH et al: How large is the lung recruitability in early acute respiratory distress syndrome: A prospective case series of patients monitored by computed tomography. Crit Care, 2012; 16: R4
28. Goligher EC, Kavanagh BP, Rubenfeld GD et al: Oxygenation response to positive end-expiratory pressure predicts mortality in acute respiratory distress syndrome. A secondary analysis of the LOVS and ExPress trials. Am J Respir Crit Care Med, 2014; 190: 70–76
29. Writing Group for the Alveolar Recruitment for Acute Respiratory Distress Syndrome Trial (ART) Investigators, Cavalcanti AB, Suzumura ÉA, Laranjeira LN et al: Effect of lung recruitment and titrated positive end-expiratory pressure (PEEP) *vs*. low PEEP on mortality in patients with acute respiratory distress syndrome: A randomized clinical trial. JAMA, 2017; 318: 1335–45

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