Critical Care

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Airway opening pressure in mechanically ventilated patients: regional distribution and impact of body position

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Abstract

Background Airway Opening Pressure (AOP) refers to the pressure level needed to reopen previously collapsed airways. Its underlying mechanisms remain debated. This study aimed to assess its regional distribution and the effect of body position.

Methods Global AOP (AOP_{GLOBAL}) was assessed by the low-flow inflation maneuver. Electrical impedance tomography allowed to assess regional AOP (ventral and dorsal). Measurements were performed in the semi-recumbent position (SR30°) in all patients and repeated in supine position (SP0°) in a subgroup of patients to explore the effect of body position. As a proof of concept, AOP was also evaluated in four Thiel cadavers in both SR30° and SP0°, with and without the adjunction of a 3 kg saline bag on the abdomen.

Results 46 mechanically ventilated patients were analyzed. In SR30°, AOP_{GLOBAL} was detected in 10 patients (22%) (median level 8.4 [6.3–12.0] cmH_2O), while $AOP_{VENTRAL}$ and AOP_{DORSAL} occurred in 11 (24%) and 16 (35%) patients, respectively. The lowest regional AOP correlated with the AOP_{GLOBAL} ($r^2 = 0.993$, $p < 0.001$). In the subgroup of 23 patients with position analysis, the highest regional AOP increased from SR30° to SP0°. Cadavers' experiments showed that the increase in end-expiratory esophageal pressure associated with SP0° or increased abdominal pressure correlated with the increase in AOP_{GLOBAL} ($r^2 = 0.908$, $p < 0.001$).

Conclusion Bedside AOP detection based on the low-flow insufflation method may miss regional AOP, leading to an underestimation of the minimal positive end-expiratory pressure which may be required to avoid tidal opening and closing in some lung regions. The level of regional AOP increases in SP0° compared to SR30° position.

Keywords Airway closure, Pressure-volume curve, Esophageal pressure, End-expiratory lung volume, Acute respiratory distress syndrome

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Introduction

Pressure-volume (P-V) curve of the respiratory system analysis is a valuable tool to understand and optimize ventilation in patients with the acute respiratory distress syndrome (ARDS) [1]. Recently, a particular feature has been described: a very low slope in the initial segment followed by an abrupt increase, defined as airway closure [2]. The pressure level measured at the sudden change in slope defines the airway opening pressure (AOP) [2, 3]. This phenomenon has since been reported in 25 to 50% of ARDS patients and appears more frequent in patients with obesity [4–6]. However, the regional distribution of gas flowing and the mechanisms underlying airway closure remain poorly known. Interestingly, body position could affect these mechanisms.

Compared to the semi-recumbent position, strict supine position is associated with increased pleural pressure and decreased end-expiratory lung volume (EELV) due to the inequal gravity distribution between ventral and dorsal part of the lungs, which could favor airway closure and regional AOP [6–9].

Electrical impedance tomography (EIT) is a non-invasive, non-irradiant method allowing to assess gas distribution towards the lungs [10]. Thus, EIT enables the study of lung inflation both globally and regionally with a high temporal resolution [10, 11].

We analyzed with EIT the global and regional P-V curves in semi-recumbent and supine position in critically ill patients and cadavers, (1) to confirm the absence of any gas entry into the lungs below the AOP level and determine whether the AOP identified by EIT matched that measured with the P-V curve method; (2) to explore potential regional heterogeneity in the airway pressure at the onset of inflation; (3) to explore the effect of body position on AOP and gain insights into the mechanisms of airway closure.

Methods

Patient selection

Forty-six adult patients admitted to the Medical Intensive Care Unit of the University Hospital of Angers, France, from October 2018 to September 2021 were enrolled in the study within 72 h from intubation.

Patients were excluded if they had any contra-indication for introduction of the esophageal catheter (e.g. esophageal underlying disease) or for EIT measurements (e.g. severe chest wound or burns). Patients under 18 years old, with legal protection and pregnant women were also excluded.

Forty patients have been included in previously published studies [5, 12, 13]. Measurements in the supine position were performed following an amendment.

Study procedure

Patients were deeply sedated by Midazolam and Fentanyl, then paralyzed by Atracurium or Cisatracurium according to the attending physician's choice.

All patients were ventilated with a Carescape R860 ventilator (General Electrics Healthcare, Madison, WI, USA) in volume-controlled ventilation (VCV), set as follows: tidal volume (V_T) of 6 $mL.kg^{-1}$ of predicted body weight (PBW), PEEP 5 cmH_2O, inspiratory flow 60 $L.min^{-1}$, respiratory rate (RR) to reach pH above 7.30 and inspired fraction of oxygen (FiO_2) to reach oxygen saturation as measured by pulse oximetry (SpO_2) > 94%.

An esophageal balloon catheter was introduced (Nutrivent, Sidam, San Giacomo Roncole, Italy) and calibrated with the occlusion maneuver as previously described [14]. To avoid an interaction between AOP and esophageal pressure, the occlusion test was performed during end-inspiratory holds [15].

The EIT belt, coupled to a Pulmovista device (Dräger, Lübeck, Germany) was positioned between the 4th and 5th intercostal spaces. To grant the stability of EIT signal, the anti-bedsore mattress was turned off, and fluid boluses or diuretics were avoided along the procedure [10].

EELV was measured by the wash-in wash-out method (E-COVx module sensor, GE Healthcare, Madison, USA) [16].

The study protocol included the following procedures: (1) arterial blood gas; (2) end-expiratory and end-inspiratory occlusions; (3) low-flow insufflation; (4) EELV measurement at PEEP 5 cmH_2O; and (5) pressure decrease from PEEP 5 to PEEP 0 cmH_2O (ZEEP), in order to measure ΔEELV between these pressure levels.

In a subgroup of consecutive patients, the measurements performed at SR30° were also performed in the supine position, with a 0° bed inclination (SP0°).

Measurements and data collection

Main characteristics were collected, including age, body mass index (BMI), *SOFA* score [17], *SAPS II* [18] and the presence of ARDS, defined according to the current definition [19].

Airway flow and pressure and esophageal pressure data were continuously recorded during the whole procedure via the Ohmeda software (GE Healthcare) from the ventilator. EIT files were obtained by using the PV500 Data Analysis software (Dräger). Then, all data were exported and synchronized with a common sample rate of 25 Hz, and analyzed on the Acqknowledge software (Biopac, Goleta, CA, USA). Synchronization was based on the volume and impedance curves, by controlling the inflation starting and ending points.

Complementary study on cadavers

To further explore the mechanisms underlying airway closure and the effect of position, a complementary study was performed on four human cadavers from a specific donation program of the University of Quebec-Trois-Rivières (Quebec, Canada). Cadavers were embalmed according to the "Thiel" process, allowing preservation of tissue elastic properties and airway anatomy. These cadavers have already been described as a good human model of airway closure [20]. All cadavers were mechanically ventilated and equipped with an esophageal balloon and an EIT belt. Further information is available in the Online Supplement.

All procedures were conducted according to local legislation after approval from the local Research Ethics Board (CER-09-148-06.05).

Cadavers were studied in 3 conditions: (1) in SR30° ; (2) in SP0° ; (3) in SP0° with adjunction of external weight (SP0°+3 kg) put on the abdomen to artificially increase pleural pressure. Of note, SR30°+3 kg was also explored. Each condition was maintained during at least 5 min.

Offline global and regional pressure-volume curve reconstruction

Global flow-based P-V curves and EIT-based P-V curves were obtained by low-flow insufflation (start at PEEP 5 cmH_2O, respiratory rate 5 min^{-1}, inspiratory flow 5 $L.min^{-1}$). Global flow-based P-V curves were rebuilt by plotting airway pressure and volume curves. Global EIT-based P-V curves were obtained by associating airway pressure and impedance curves, the impedance values being converted in volume using the ratio between expiratory V_T and global impedance change ($V_T/\Delta Z$) [21].

The same process was applied to the regional impedance tracings in the ventral and dorsal regions of the lungs to obtain regional EIT-based P-V curves, by weighting the $V_T/\Delta Z$ by the fraction of V_T reaching each region of interest (ROI) ($V_{T-ROI\%}$) (Figure S1 in the Online Supplement).

Airway closure detection and AOP measurements

AOP was automatically calculated (method 1) on all curves by detecting two distinct compliance lines using linear regression measured with a dedicated program (Python - Wilmington, NC, USA). AOP was computed as the intersection point of these two lines. AOP_{FLOW} and AOP_{EIT} were obtained from global flow-based P-V curves and global EIT-based P-V curves, respectively.

The presence of a global and regional airway closure was confirmed by visual inspection of P-V and P-Impedance curves during a dedicated meeting by four experienced investigators (BP, AL, AM and FB), blinded to the AOP computation results, clinical characteristics of the patients and the significance of the y axis (volume or impedance).

Regional airway closure (in the ventral or dorsal region) was defined as the existence of an abrupt change in regional compliance, allowing the detection of two compliance lines. The critical pressure marked by the intersection point of these two lines was called regional AOP ($AOP_{VENTRAL}$ and AOP_{DORSAL} in the ventral and dorsal regions defined with EIT, respectively).

Global and regional AOP measurements were also evaluated by the circuit compliance method (method 2), as described in the Online Supplement (Figure S2).

Statistical analysis

All data are expressed in number (percentage) or median [first-third quartile].

Normal distribution was assessed for each variable with a Shapiro-Wilk test.

Patients were pooled in two groups, according to the detection of any regional AOP (ventral or dorsal) or not.

Statistical comparisons were performed using a Student's t-test or a Wilcoxon signed-rank test for paired data and unpaired t-test or Mann-Whitney U test for unpaired data, as appropriate according to variables distributions. When multiple conditions were compared, overall p value was computed by a Friedman test.

A multiple logistic regression was also performed to assess variables independently associated with the presence of a regional AOP in patients evaluated in the SR30°. Clinically relevant variables were selected: BMI, total PEEP (PEEPtot), plateau pressure (Pplat), end-expiratory esophageal pressure (Pes,e) and EELV.

All correlations were computed with a simple linear regression. Data from the SR30° and SP0° positions were gathered to provide correlations between different AOP measurement methods.

All analyses were performed with a type 1 error set at 0.05; results were considered significant with a bilateral p value < 0.05. All tests were conducted using Prism (GraphPad software v10.0, La Jolla, CA, USA) and R software version 4.0.5 (http://www.R-project.org/).

Results

Study population

Forty-six patients were enrolled in the study. The main characteristics of the patients are described in Table 1.

Measurements in SP 0° were performed in 23 (50%) of these 46 patients. Their main characteristics are presented in Table S1 of the Online supplement.

Detection of complete airway closure and AOP measurement

A complete airway closure was detected with both the flow- and EIT-based methods in 10 patients (22%)

Table 1 Main characteristics of patients

	All patients ($n=46$)
Age (years)	65 [56 ; 76]
Male gender, n (%)	26 (57)
BMI ($kg.m^{-2}$)	27.5 [23.7 ; 31.3]
SOFA score	7 [4 ; 10]
SAPS II	49 [38 ; 62]
Delay from intubation (hours)	14 [8 ; 26]
Patients with ARDS (%)	40 (87)
Pneumonia	12 (26)
COVID	19 (41)
Cardiac arrest-related	6 (13)
Others	3 (7)
Days from ARDS diagnosis (days)	0.5 [0-1.75]

ARDS: acute respiratory distress syndrome, BMI: body mass index, COVID-19: SARS-Cov-2 induced pneumonia, SAPS II: simplified acute physiology score II, SOFA: sequential organ failure assessment

ventilated in SR30°. Median AOP_{FLOW} was 8.4 [6.3–12.0] cmH_2O. Examples of three representative patients from this cohort with and without airway closure are depicted in the Fig. 1.

By gathering P-V curves obtained from 5 cmH_2O in SR30° and SP0°, AOP levels were very similar between investigations using flow and EIT-based P-V curves (8.7 [6.8–11.1] cmH_2O and 8.7 [6.9–11.1] cmH_2O, respectively, $p>0.999$) with a strong correlation ($r^2>0.996$, $p<0.001$, Figure S3).

Both method 1 and method 2 of the curves analysis yielded similar results for AOP measurements (Figure S4).

Regional analysis in the semi-recumbent position

A regional AOP was observed in 17 (37%) patients. It was found in both ventral and dorsal regions in 10 (22%) patients and only in dorsal or ventral regions in 6 (13%) patients and 1 (2%) patient, respectively ($p=0.049$).

Individual results from each patient are reported in Table S2 of the Online Supplement. All patients with complete airway closure had both ventral and dorsal AOP.

Global and regional P-V curves of representative patients from this cohort are depicted in Fig. 1.

There was a significant correlation between the lowest regional AOP and the global AOP_{FLOW} value ($r^2=0.993$, $p<0.001$, Fig. 2). In patients with complete airway closure, the median difference between the highest regional AOP and the AOP_{FLOW} was 1.3 [0.1–2.7] cmH_2O.

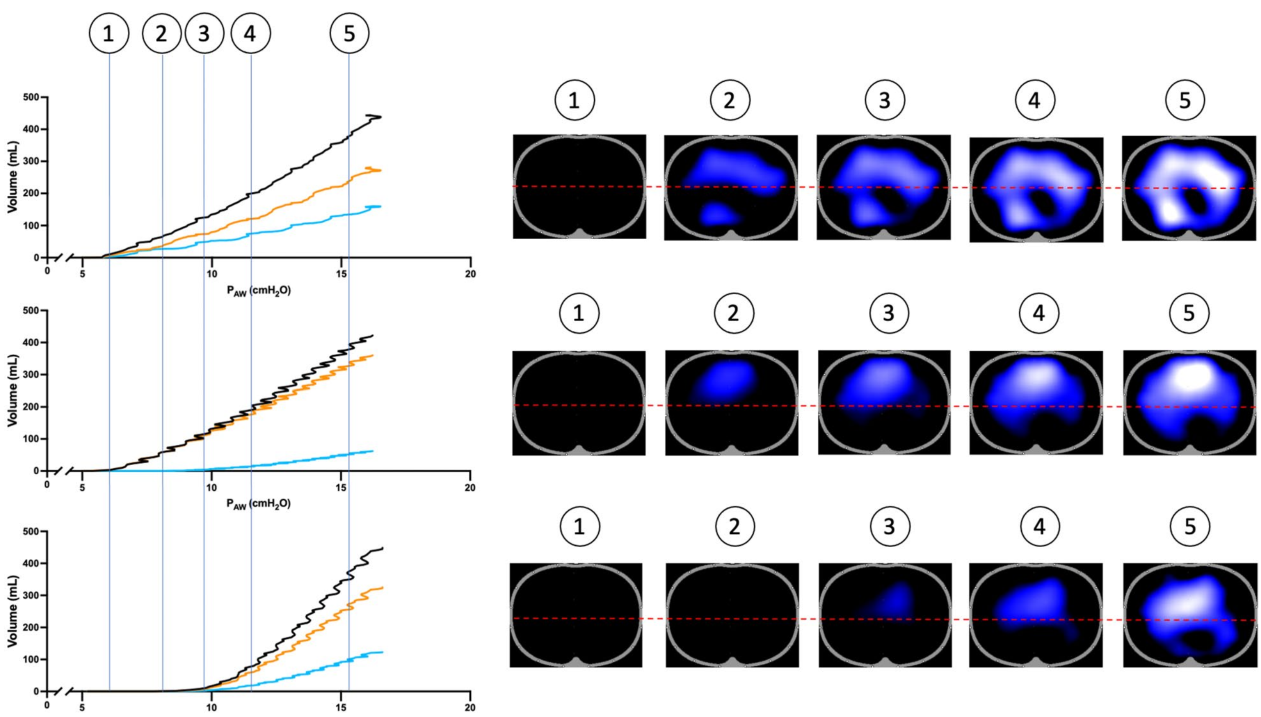

Fig. 1 Pressure-volume (P-V) curves and Electrical Impedance Tomography (EIT) imaging of three representative patients of the study. Global (black lines) and regional (ventral, orange lines and dorsal, blue lines) P-V curves are presented in the left part of the figure: in a patient without airway opening pressure (AOP) (upper panel), with only dorsal AOP (middle panel) and with a global AOP (lower panel). EIT tidal impedance mapping is presented in the right part of the figure at five timepoints: (1) 1 cmH_2O above insufflation start, (2) 3 cmH_2O above insufflation start, (3) below the airway opening pressure (AOP) detected in the patient with airway closure, (4) above AOP in the patient with airway closure, (5) at the end of insufflation in the patient without airway closure. Gas flowing into the thorax appears in blue. Note the absence of gas flowing below the AOP value in the patient with airway closure

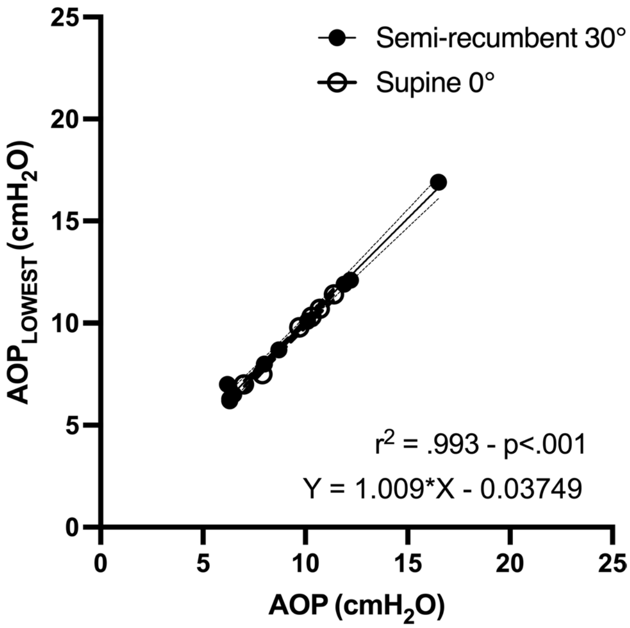

Fig. 2 Relation between flow-based airway opening pressure (AOP) and the lowest value of regional AOP (Lowest regional AOP). Data from patients in semi-recumbent position (SR 30°) are depicted in full circles, and from patients in supine position (SP 0°) in open circles

Characteristics of the patients with regional AOP in the semi-recumbent position

The characteristics of the patients with or without regional AOP are presented in Table 2.

BMI was significantly higher in the patients with any regional AOP than in those without (29.4 [25.4–34.3] $kg.m^{-2}$ vs. 25.6 [22.6–30.7] $kg.m^{-2}$, respectively $p = 0.020$).

Higher total PEEP, plateau pressure, end-expiratory and end-inspiratory esophageal pressure (Pes,i), were also observed in patients with any regional AOP. However, there were no statistically significant differences in transpulmonary pressure, compliance, global and regional V_T, EELV, or gas exchange between patients with or without regional AOP (Table 2).

In the multiple logistic regression, only BMI and Pes,e remained statistically associated with the presence of any regional AOP; Figure S5 in the Online Supplement).

Effect of body position in the dedicated subgroup

Compared to the SR30°, PEEPtot, Pplat, Pes,e and Pes,i increased and tidal volume distribution to ventral regions and EELV decreased in SP0° (Table S3 in the Online Supplement).

These changes were associated with an increase in the highest regional AOP from SR30° to SP0° (8 [5.0-8.6] vs. 8.9 [7.2–10.3] cmH_2O, $p = 0.047$, Table S3 in the Online Supplement)

Albeit not statistically significant, the proportion of patients with global airway closure increased in SP0°, in comparison to the SR30° position (4 (17%) vs. 7 (30%), $p = 0.491$). Similar data were obtained with the incidence of ventral and dorsal regional airway closure (4 (17%) vs. 7 (30%), $p = 0.491$ and 7 (30%) vs. 11 (48%), $p = 0.365$, respectively) (Table S3 in the Online Supplement).

All airway closure or regional AOP (whether ventral or dorsal) observed in SR30° were also observed in SP0° (Table S2 in the Online Supplement).

Complementary study on cadavers

The main characteristics of the four cadavers are detailed in Table S4 of the Online Supplement. Their respiratory mechanics parameters, compared with those of the study patients, are presented in Table S5 of the Online Supplement. Notably, chest wall compliance was significantly lower in the cadavers than in the study patients.

Compared to SR30°, the levels of global AOP and both ventral and dorsal AOP increased in SP0° and SP0°+3 kg. Esophageal pressure also significantly increased and EELV decreased in these conditions. There was however no change in chest wall compliance (Table S6 in the Online Supplement). A representative example of a cadaver is depicted in Figure S6 (Online Supplement).

The changes in AOP - resulting from modifications in condition (from SR30° to SP0° and addition of a 3 kg-weight on the abdomen) - correlated with variations in Pes,e, as shown in Fig. 3. Similar findings were observed with the changes in ventral and dorsal AOP (Figure S7 in the Online Supplement).

Significant correlations were also observed between the changes in AOP and the changes in EELV (Figure S8 in the Online Supplement).

Discussion

The main findings of this study can be summarized as follows: (1) based on EIT, we confirm the absence of gas flowing the lungs at airway pressures below the AOP; (2) the conventional flow-based method does not allow to detect regional AOP, which may lead to clinical consequences; (3) regional airway closure is more frequent in the dorsal regions; (4) body position influences the level of AOP; (5) the impact of supine position or increased abdominal pressure on the incidence and level of AOP suggests that the gravity plays a role in the pathophysiology of this phenomenon.

Detection of global and regional airway opening pressure

In the present cohort, global airway closure was observed in 22% of patients, which is globally consistent with previous studies including patients with and without ARDS [4, 5]. We confirmed the absence of gas flowing through the lungs below AOP, and EIT seems reliable in global and regional AOP detection, as mentioned in previous studies [21–23].

Table 2 Clinical features of patients with any regional (ventral or dorsal) airway opening pressure (AOP) observed in the semi-recumbent position, compared with patients without any AOP

	Overall population ($n=46$)	Patients with regional AOP ($n=17$)	Patients without regional AOP ($n=29$)	p value
ARDS, n (%)	40 (87)	15 (88)	25 (86)	> 0.999
Global airway closure, n	10 (22)	10 (59)	0 (0)	**< 0.001**
BMI, kg.m^{-2}	27.5 [23.7 ; 31.3]	29.4 [25.4 ; 34.3]	25.6 [22.6 ; 30.7]	**0.020**
Lung volumes				
VT, mL.kg^{-1}	6.1 [6.0 ; 6.2]	6.1 [6.0 ; 6.4]	6.1 [5.9 ; 6.2]	0.373
ventral	4.4 [3.9 ; 4.9]	4.5 [3.7 ; 5.0]	4.3 [3.7–4.7]	0.628
dorsal	1.7 [1.3 ; 2.7]	1.8 [1.3 ; 2.8]	2.0 [1.5 ; 2.6]	0.978
EELV, mL.kg^{-1}	20.3 [15.4 ; 26.0]	18.2 [14.5 ; 26.0]	21.8 [16.2 ; 26.4]	0.367
ventral	14.0 [10.2 ; 18.0]	11.6 [8.5 ; 15.8]	14.8 [10.8 ; 18.9]	0.128
dorsal	6.4 [4.8 ; 7.8]	6.4 [4.6 ; 8.1]	6.3 [5.0 ; 8.0]	0.946
Pressures				
PEEPtot, cmH_2O	6.0 [5.2 ; 6.9]	6.0 [6.0 ; 9.2]	5.5 [5.0 ; 6.8]	**0.010**
Pplat, cmH_2O	15.0 [13.4 ; 17.0]	16.0 [15.0 ; 20.9]	14 [12.6 ; 16.0]	**0.003**
Pes,e, cmH_2O	7.6 [5.1 ; 11.0]	10.8 [7.0 ; 14.5]	6.6 [4.9 ; 9.0]	**0.019**
Pes,i, cmH_2O	11.0 [8.5 ; 13.3]	13.2 [10.0 ; 19.1]	9.3 [8.3 ; 11.7]	**0.003**
P_Le, cmH_2O	-0.8 [-4.6 ; 1.0]	-3.1 [-5.9 ; 0.0]	0.0 [-2.5 ; 1.2]	0.148
P_Li, cmH_2O	4.5 [1.5 ; 6.8]	2.8 [0.3 ; 7.0]	5.5 [2.6 ; 6.8]	0.550
ΔP_{RS}, cmH_2O	8.3 [7.0 ; 11.0]	9.2 [7.1 ; 11.8]	8.0 [6.5 ; 10.8]	0.260
ΔP_L, cmH_2O	5.7 [4.1 ; 7.0]	5.6 [4.1 ; 8.0]	5.8 [4.2 ; 7.1]	0.624
Compliances				
C_{RS}, $mL.cmH_2O^{-1}$	45 [36 ; 54]	40 [32 ; 51]	47 [38 ; 54]	0.317
C_L, $mL.cmH_2O^{-1}$	66 [52 ; 86]	65 [47 ; 98]	66 [53 ; 87]	0.844
C_{CW}, $mL.cmH_2O^{-1}$	143 [96 ; 185]	125 [84 ; 155]	161 [95 ; 213]	0.172
Gas exchange				
PaO_2/FiO_2, mmHg	123 [87 ; 178]	129 [84 ; 180]	123 [87 ; 175]	0.801
Ventilatory ratio	3.14 [2.67 ; 3.84]	3.38 [2.87 ; 3.88]	2.95 [2.50 ; 3.79]	0.199

p values for variables with statistically significant results are given in bold

All compliances were calculated using the AOP value. *ARDS: acute respiratory distress syndrome, BMI: body mass index, C_L: lung compliance, C_{RS}: respiratory system compliance, C_{CW}: chest wall compliance, EELV: end expiratory lung volume, FiO_2: inspired fraction of oxygen, PaO_2: arterial oxygen partial pressure, peeptot: total positive end expiratory pressure, Pes,e: end-expiratory esophageal pressure, Pes,i: end-inspiratory esophageal pressure, P_Le: end-expiratory transpulmonary pressure, P_Li: end-inspiratory transpulmonary pressure, pplat: plateau pressure, V_T: tidal volume*

At the regional level, AOP above PEEP 5 cmH_2O was detected in 37% of patients in SR30°. Similar proportions were obtained in a recent work aiming to assess regional airway closure [24]. Of note, the difference between the highest regional AOP and global AOP was lower in our cohort. This can be explained by the PEEP level used during low flow insufflation that was higher in the present study (5 cmH_2O versus 0 cmH_2O) and therefore have prevented the detection of AOP below 5 cmH_2O [24]. The quadrant-by-quadrant analysis used in this study (respective to our model with 2 ROI) and the AOP detection process may also explain the higher incidence of AOP in comparison to our cohort [24].

Interpretation of regional airway opening pressure

Recently, Sun et al. presented the specific regional P-V curve pattern corresponding to an abrupt change in regional compliance as regional airway closure [24]. By confirming the regional AOP phenomenon with two different methods, the present work strengthens these results, especially to differentiate regional AOP from recruitment.

Some clues may help to understand the real nature of this so-called regional AOP. First, the brutal increase of regional compliance observed pleads for a brutal re-opening phenomenon, which is not the pattern usually described in intra-tidal recruitment [25]. Second, AOP seems consistent with the distribution of volumes and pleural pressure in the dependent rather than the non-dependent regions, like in animal models and previous clinical studies [24, 26, 27]. Third, the existence of diverse regional levels of AOP is consistent with the experimental avalanche model of airway closure [28].

After a collective visual analysis of all the P-V curves, we could not reliably distinguish progressive slope changes from abrupt slope changes as proposed by Sun et al. [24]. However, we started our low-flow inflations at a PEEP of 5 cmH_2O, whereas the progressive slope change was observed predominantly for AOP values less than or equal to 5 cmH_2O in the Sun et al. study [24].

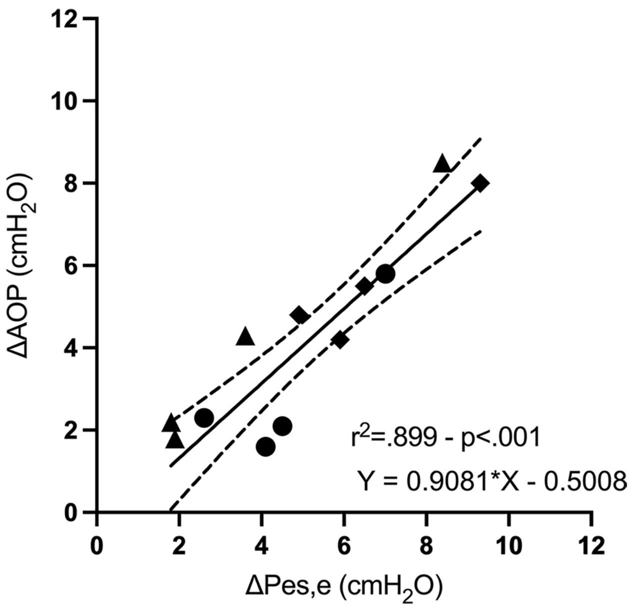

Fig. 3 Relation between change in end-expiratory esophageal pressure (ΔPes,e) and in Airway Opening Pressure (ΔAOP) in cadavers from the semi-recumbent position (SR 30°) to experimental conditions**.** Circles: from SR 30° to supine position (SP0°). Squares: from SR 30° to SR 30° + adjunction of a 3 kg saline bag on the abdomen. Triangles: from SR 30° to SP 0° + adjunction of a 3 kg saline bag on the abdomen

Effect of gravity on airway opening pressure

In our cohort, regional AOP was mostly observed in the dependent regions of the lungs. These results are consistent with previous reports [24]. Data in asymmetrical lung injury suggesting an association between the occurrence of airway closure and regional lung mechanics also supports an effect of gravity [26, 27]. In addition, the study of body position suggests an effect of gravity, by modifying the position of the abdomen related to the thorax, increasing pleural pressure [9] and reducing EELV [7, 8]. In the supine position, esophageal pressure increases, due to the redistribution of lung weight [28]. The association between esophageal pressure and airway closure has already been demonstrated in experimental conditions [29, 30]. The increase in highest regional AOP in SP0° compared to SR30° seems consistent with this mechanism. However, the higher regional AOP observed in ventral region compared to dorsal region in some patients suggests that gravity is not the sole determinant of airway closure. In addition, we found an association between EELV and AOP which is consistent with previous data about airway closure detection by the N_2 wash-out method following general anesthesia [2]. Nonetheless, data related to gas wash-out should be interpreted with caution, due to the difficulty of interpretation of these methods in presence of airway closure [31]. In a previously published cohort, patients with airway closure exhibited lower EELV than those without airway closure [5]. Experimental data in animals also suggest the existence of an EELV-dependent "pre-collapsing state" in small airways [29, 30].

Clinical perspectives

Our data suggest that regional AOP may be present even in absence of global airway closure and that conventional flow-based method does not allow to detect regional AOP, leading to an underestimation of the minimal PEEP which may be required to avoid tidal opening and closing in some lung regions. This is in line with previous findings showing regional dependencies of lower inflection points derived by regional pressure-impedance curves [23].

Furthermore, our data suggest that strict supine position may induce potentially deleterious changes by increasing AOP and that clinicians should reassess AOP after changing bed inclination for clinical reasons (e.g. procedures or ECMO).

The interrogations around the nature of regional AOP (whether this is recruitment or regional airway closure), should not distract from the clinical relevance of airway closure. Effect of de-recruitment in patients with ARDS is well known [25]. Albeit the concrete effect of complete airway closure on patients' outcome is still unknown, intra-tidal bronchial cyclic closing and re-opening may promote lung injury [32]. Further studies are however needed to confirm that PEEP setting above the highest AOP detected is suitable for patients with ARDS. Specific attention should be given to patients at risk of decreased EELV or increased pleural pressure, such as patients with obesity or most severe ARDS.

Study limitations

This work presents several limitations. First, the sample size is small, and results need to be confirmed in larger cohorts. Second, the P-V curve start at PEEP 5 cmH_2O may have underestimated the proportion of patient with regional AOP. Since most patients experience ARDS, we chose not to decrease PEEP to 0 cmH_2O for safety reasons. The clinical significance of AOP lower than 5 cmH_2O is questionable, as these patients are unlikely to be ventilated with a PEEP level lower than 5 cmH_2O in clinical practice. Third, the global EELV measurements in the context of complete airway closure should be interpreted with caution. Fourth, in the present work, Thiel cadavers exhibit lower chest wall compliance than patients and potential differences in airway tone may impact airway closure. Albeit these experimental data allow additional insight in AOP mechanics, clinicians should be careful in the extrapolation of these results. Finally, we could spot some methodologic issues about EIT processing: the sample size of 25 Hz could induce a lack of precision in global and regional AOP measurements and the ROI selection methodology, based on a simple split of the raw EIT mapping at a single PEEP level, may have underestimated the size of the dorsal region. All these limitations may have caused an underestimation or misclassification of regional AOP.

Conclusions

EIT-based detection of complete airway closure is feasible and reliable in patients with ARDS. Regional AOP cannot be detected by the classical P-V method. Global and regional AOP increase in conditions with increased pleural pressure and decreased EELV, as strict supine position, thus suggesting the role of the gravitational gradient in the mechanism. At this point, the clinical relevance of regional AOP remains uncertain. Further studies are needed to assess the potential benefits of incorporating this variable in ventilator settings.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13054-025-05809-6.

Supplementary Material 1

Acknowledgements

The authors would like to address a special thanks to the ICU medical and paramedical teams for their support and the daily care they provide to patients in their respective centers.We would also thank the teams from the CAVIAR research group and the University of Quebec-Trois-Rivières for their collaboration in the present work.

Author contributions

BP, AL, and FB contributed to the study conception and design. BP, AL, AC, DC, and FB participated to the data collection and performed data analysis. BP, AL, JCR, AM and FB prepared the first draft of the manuscript. All authors contributed to the data analysis and to the critical revision. All authors read and approved the final manuscript.

Data availability

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate

Ethics approval was obtained according to local legislation (Ethic committee, Angers University Hospital, France, #2023-042). As the study reports data routinely acquired in usual care, signed informed consent was waived, according to local legislation. All procedures on cadavers were conducted according to local legislation after approval from the local Research Ethics Board (CER-09-148-06.05).

Consent for publication

Not applicable.

Competing interests

AL reports salary for research activities from Air Liquide Medical Systems. JCR reports part-time salary for research activities from Air Liquide Medical Systems and Vygon and grants from Creative Air Liquide, outside this work. AM reports personal fees from Faron Pharmaceuticals, Air Liquide Medical Systems, Pfizer, Resmed and Draeger and grants and personal fees from Fisher and Paykel and Covidien, outside this work. FB reports consulting fees from Löwenstein Medical and Air Liquide Medical Systems and research support from Covidien, GE Healthcare and Getinge Group, outside this work. The other authors have no conflict of interest to declare.

Received: 12 October 2025 / Accepted: 13 December 2025
Published online: 21 December 2025

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