Multimodal non-invasive monitoring to apply an open lung approach strategy in morbidly obese patients during bariatric surgery

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Abstract

To evaluate the use of non-invasive variables for monitoring an open-lung approach (OLA) strategy in bariatric surgery. Twelve morbidly obese patients undergoing bariatric surgery received a baseline protective ventilation with 8 cmH_2O of positive-end expiratory pressure (PEEP). Then, the OLA strategy was applied consisting in lung recruitment followed by a decremental PEEP trial, from 20 to 8 cmH_2O, in steps of 2 cmH_2O to find the lung's closing pressure. Baseline ventila-tion was then resumed setting open lung PEEP (OL-PEEP) at 2 cmH_2O above this pressure. The multimodal non-invasive variables used for monitoring OLA consisted in pulse oximetry (SpO_2), respiratory compliance (Crs), end-expiratory lung volume measured by a capnodynamic method ($EELV_{CO2}$), and esophageal manometry. OL-PEEP was detected at 15.9 ± 1.7 cmH_2O corresponding to a positive end-expiratory transpulmonary pressure ($P_{L,ee}$) of 0.9 ± 1.1 cmH_2O. ROC analysis showed that SpO_2 was more accurate (AUC 0.92, IC95% 0.87–0.97) than Crs (AUC 0.76, IC95% 0.87–0.97) and $EELV_{CO2}$ (AUC 0.73, IC95% 0.64–0.82) to detect the lung's closing pressure according to the change of $P_{L,ee}$ from positive to negative values. Compared to baseline ventilation with 8 cmH_2O of PEEP, OLA increased $EELV_{CO2}$ (1309 ± 517 vs. 2177 ± 679 mL) and decreased driving pressure (18.3 ± 2.2 vs. 10.1 ± 1.7 cmH_2O), estimated shunt (17.7 ± 3.4 vs. 4.2 ± 1.4%), lung strain (0.39 ± 0.07 vs. 0.22 ± 0.06) and lung elastance (28.4 ± 5.8 vs. 15.3 ± 4.3 cmH_2O/L), respectively; all $p < 0.0001$. The OLA strategy can be monitored using noninvasive variables during bariatric surgery. This strategy decreased lung strain, elastance and driving pressure compared with standard protective ventilatory settings.

Clinical trial number NTC03694665.

Keywords PEEP · Lung recruitment · Atelectasis · Capnography · Morbid obesity · Pulse oximetry · Bariatric surgery

1 Introduction

Mechanical ventilation in morbidly obese (MO) patients undergoing bariatric surgery constitutes a challenge for anesthesiologists [1]. Overweight of adipose tissue exerts an excess load on the diaphragm and chest wall in the supine position [2]. This overload increases pleural pressure above normal values with the corresponding reduction of transpulmonary pressure (P_L = airways—pleural pressure) in dependent lung zones; which decreases lung volume,

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promotes atelectasis and airway closure and impairs respiratory mechanics and gas exchange [3–6]. Besides, the use of capnoperitoneum and the need of high inspiratory oxygen fraction (FIO_2) potentiates further lung collapse mediated by an additional decrease in P_L and resorption atelectasis [7–9]. All these negative effects on the respiratory system could result in perioperative hypoxemia and an increased risk to develop post-operative pulmonary complications [10–15].

The use of arbitrary higher levels of positive end-expiratory pressure (PEEP) during anesthesia has limited effects on atelectasis in MO patients [16–18]. Opposedly, lung recruitment (RM) successfully reverts atelectasis improving end-expiratory lung volume (EELV), respiratory mechanics and gas exchange [19–22]. The open-lung approach (OLA) is a ventilation strategy designed to ventilate the lungs without collapse. It consists of a RM and the detection of the PEEP corresponding to the closing pressure of the lung (CL-PEEP) in order to determine the level of PEEP needed to maintain the open lung condition, i.e. the open-lung PEEP (OL-PEEP) [23].

Several studies have found OL-PEEP to be between 15 and 24 cmH_2O in MO patients during bariatric surgery using different noninvasive monitoring parameters [23–26]. Esophageal manometry is an attractive option for monitoring lung recruitment maneuvers in bariatric surgery as it provides estimates of P_L [26]. Furthermore, an end-expiratory transpulmonary pressure ($P_{L,ee}$) below zero indicates that some dependent areas of the lungs are exposed to very low P_L and are prone to collapse because they reached their local closing pressure [27, 28]. Thus, the polarity change of $P_{L,ee}$ from a positive to a negative value during a decremental PEEP titration has been proposed as a marker for detecting the closing pressure of the lung [29, 30]. To our knowledge, $P_{L,ee}$ has not been investigated for this purpose in MO patients undergoing bariatric surgery.

The main objective of this physiological study was to assess the performance of multimodal non-invasive variables for monitoring an OLA strategy using the polarity change in $P_{L,ee}$ as reference. Secondary objective was to analyze the effect of OLA on transpulmonary mechanics, lung stress and lung strain.

2 Methods

After approval by the local Ethic Committee (NTC03694665 *Clinicaltrial.gov*), we studied morbidly obese patients undergoing laparoscopic gastric bypass surgery who consented, age ≥ 18 years and body mass index (BMI) ≥ 40 kg/m^2. We excluded patients with pulmonary diseases and baseline pulse oximetry hemoglobin saturation (SpO_2) < 97% breathing air.

2.1 Anesthesia and monitoring

Anesthesia was induced with propofol 1.5 mg/kg^{-1}, vecuronium 0.08 mg/kg^{-1} and fentanyl 3–4 μ/kg^{-1} of ideal body weight and maintained with propofol 80 μ kg^{-1} min^{-1} plus remifentanyl 0.5 μ kg^{-1} min^{-1}. The lungs were ventilated with a Servo-i (Maquet, Solna, Sweden) in volume control ventilation using a tidal volume (VT) of 6 mL/kg^{-1} of predicted body weight, PEEP of 8 cmH_2O, inspiratory pause of 15%, FIO_2 of 0.5 and respiratory rate adjusted to obtain an end-tidal CO_2 of 40 ± 5 mmHg (~ 15 bpm).

ECG, noninvasive oscillometric arterial blood pressure, capnography, SpO_2 and FIO_2 were recorded in a laptop from the monitor Cardiocap/S5 (GE Healthcare/Datex-Ohmeda, Helsinki, Finland). Intravenous cristaloids were administered as an initial bolus of 250 mL followed by 3 mL kg^{-1} h^{-1} of ideal body weight. Noradrenaline infusion between 0.01 and 0.05 μ kg^{-1} min^{-1} was added if necessary to maintain a mean arterial pressure ≥ 55 mmHg.

2.2 Respiratory mechanics

Airway pressure, esophageal pressure, and gas flow were measured by a Fluxmed-monitor (MBMED, Buenos Aires, Argentina). Data was downloaded in a second laptop after proper flow and pressure sensors calibration. Respiratory driving pressure (DP) was determined as plateau pressure (Pplat) minus total PEEP ($PEEP_{TOT}$ = external PEEP + intrinsic PEEP). Respiratory system compliance (Crs = VT/Pplat–$PEEP_{TOT}$) and airway resistance (Raw = Ppeak–Pplat/inspiratory flow) were also recorded.

An esophageal catheter (MBMED, Buenos Aires, Argentina) was placed at the mid-esophageal position and inflated with 1 mL of air following manufacturer's recommendations. Its position was checked by the occlusion method described for mechanical ventilated patients [26]. Briefly, manual compressions of the chest were performed during an end-expiratory occlusion, observing the corresponding changes in airway and esophageal pressures. An acceptable catheter position was found when the ratio ΔPes/ΔPaw was close to 1 [27–29].

Transpulmonary pressure (P_L) was calculated as the difference between airway and esophageal (Pes) pressure. Transpulmonary driving pressure (DP_L) was calculated as end-inspiratory ($P_{L,ei}$) minus end-expiratory ($P_{L,ee.}$) transpulmonary pressure. Lung stress was defined as $P_{L,ei}$. Respiratory system *elastance* (E_{TOT} = Pplat–$PEEP_{TOT}$/VT) was divided into its lung (E_L = inspiratory–expiratory P_L/VT) and chest wall (E_{CW} = inspiratory–expiratory Pes/VT) components.

2.3 SpO_2–FIO_2 plot

We performed a SpO_2–FIO_2 diagram decreasing FIO_2 in 0.1 steps, each of 45 s, from 1 to 0.21 or until the lowest FIO_2 at which a predefined threshold value > 90% of SpO_2 was reached. Each pair of SpO_2–FIO_2 values together with the hemoglobin values were introduced in a mathematical model for the non-invasive estimation of shunt and low V/Q areas (http://www.noranaes.org/shuntcurves) [31]. A downward displacement of the curve is caused by shunt (expressed as % of cardiac output—normal values ~ 5–8%). A shift of the curve to the right is due to low V/Q areas (normal V/Q value of 0.8) assuming a constant $PaCO_2/R$ value during the protocol. Any decrease in SpO_2 below 97% was assumed to be related to shunt and/or low V/Q areas induced by lung collapse in those patients with $SpO_2 \geq 97\%$ prior to induction of anesthesia [32, 33].

2.4 Measurement of lung volume and calculation of lung strain

The end-expiratory lung volume measured by CO_2 ($EELVCO_2$) and the effective pulmonary blood flow (CO_{EPBF}; i.e. the portion of cardiac output that participates in gas exchange) was obtained from a previously described capnodynamic method [34, 35]. In brief, a repetitive ventilatory pattern consisting of 9 consecutive breaths in which short expiratory holds are added to the last three breaths induce the necessary changes in the alveolar concentration of CO_2 ($FACO_2$) allowing to solve the differential Fick's principle by means of the following capnodyamic equation:

$$EELVCO_2 \cdot \left(FACO_2^n - FACO_2^{n-1}\right) = CO_{EPBF} \cdot \Delta t^n \cdot \left(CvCO_2 - CcCO_2^n\right) - VTCO_2^n$$

Where n is the current breath, $n-1$ is the previous breath, Δt^n (min) is the current breath cycle time, $CvCO_2$ and $CcCO_2$ (l_{gas}/l_{blood}) are the mixed venous and capillary content of CO_2 and $VTCO_2^n$ (l) is the volume of CO_2 eliminated by the lungs in one breath. By the continuous application of the equation where the oldest breath is substituted by the newest one, $EELVCO_2$ and CO_{EPBF} can be solved in a breath-by-breath fashion [34, 35]. This sequential breathing pattern was performed using the same ventilatory settings as above.

Lung strain was calculated as described by González-López et al. as the ratio between VT and $EELVCO_2$ [36].

2.5 Protocol

After induction of anesthesia, patients were submitted to a capnoperitoneum of 20 cmH_2O in supine 30° reverse Trendelenburg position. The protocol started after completing the gastroenteral anastomoses once the esophageal balloon was in place. Baseline data was collected before RM (Fig. 1).

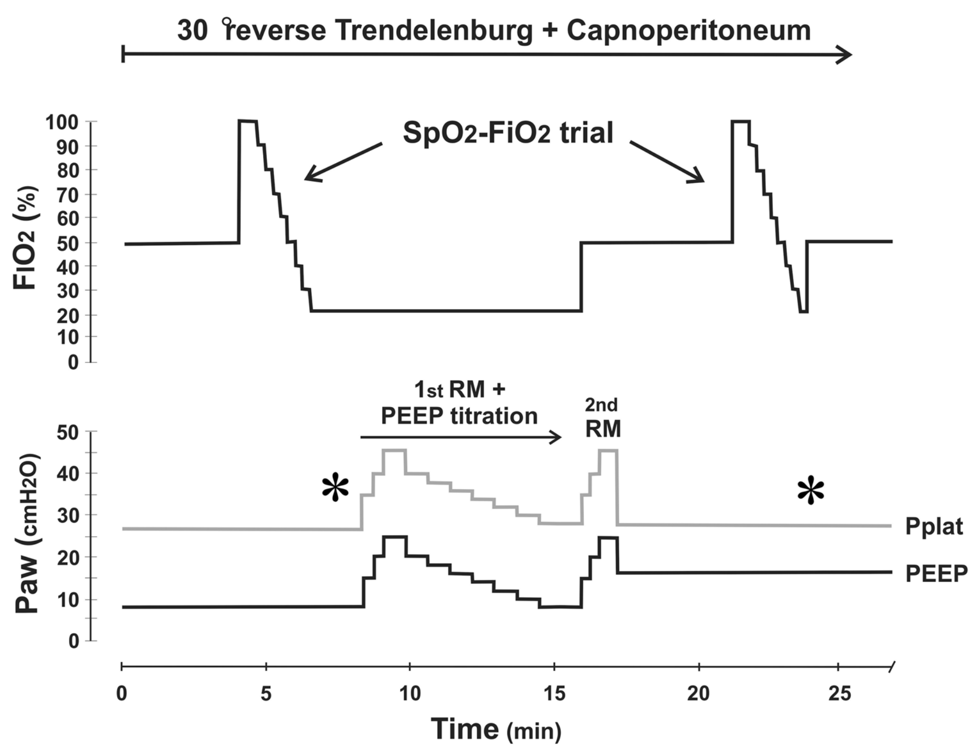

Fig. 1 Study Protocol. *FIO_2* inspired fraction of oxygen, *Paw* airways pressure, *Pplat* plateau pressure, *PEEP* positive end-expiratory pressure and *RM* recruitment maneuver. Asteriks signal the moments of data analysis before 1st RM (baseline condition) and after 2nd RM with the open-lung PEEP (OL-PEEP). The protocol was performed under capnoperitoneum and 30º reverse Tredelenburg position

A SpO_2–FIO_2 trial detected potential oxygenation deficits caused by atelectasis. FIO_2 was then maintained at 0.21 (or at the lowest FIO_2 maintaining the predefined ≥ 90% SpO_2 value to avoid hypoxemia) during the performance of RM and PEEP titration [23].

The lungs were recruited in pressure controlled ventilation using a fixed inspiratory pressure of 20 cmH_2O. Initially, PEEP was increased from 8 to 15 cmH_2O and then to 20 and 25 cmH_2O every five respiratory cycles to reach a final plateau pressure of 45 cmH_2O, applied during ten breaths [23]. The maneuver was stopped if mean arterial pressure decreased below 55 mmHg. The open lung condition (i.e. lungs without atelectasias or airway closure) was confirmed by a $SpO_2 \geq 97\%$ [23–33]. The decremental PEEP trial was then performed in volume control ventilation maintaining the same settings as during baseline except for FIO_2. PEEP was decreased in 2 cmH_2O steps of 45 s, from 20 to 8 cmH_2O, to find CL-PEEP defined by the $P_{L,ee}$ polarity change, the PEEP level at which $P_{L,ee}$ shifts from a positive to a negative value [29]. Thereafter, a second RM was performed and OL-PEEP was set 2 cmH_2O above CL-PEEP. This individualized level was maintained for the rest of the surgical period and a second SpO_2–FIO_2 trial was performed at the end of surgery.

A full set of data was collected at two moments during capnoperitoneum: baseline ventilation with 8 cmH_2O of PEEP and OLA.

2.6 Data analysis

Statistical analysis was performed with SPSS (version 9.0, Chicago, IL). Normal distribution of studied variables was found with the Kolmogorov–Smirnov test. Data are presented as *n* (%) for proportions and mean ± SD or 95% confidence intervals for continuous variables. Paired Student's *t* test with Bonferroni's correction was used to compare baseline ventilation vs CL-PEEP and OL-PEEP. A $p < 0.05$ was considered statistically significant.

The ability of SpO_2, Crs and $EELVCO_2$ to detect lung's closing pressure was evaluated by discrete receiver operating characteristics (ROC) analysis. We assigned a binary classification of "1" to the open-lung condition ($P_{L,ee} \geq 0$) or "0" to the onset of lung collapse when $P_{L,ee}$ becomes negative. Similarly, a value of "1" was assigned to the maximum Crs, the maximum $EELVCO_2$ and pulse SpO_2 values ≥ 97%. On the contrary, a value of "0" was assigned whenever Crs and $EELVCO_2$ started to decrease > 10% from maximum values and when SpO_2 decreased below 97%. These assignments determined true and false positive–negative conditions in a 2 × 2 table from which sensitivity and specificity were calculated.

3 Results

Twelve MO patients undergoing bariatric surgery were analyzed and their demographic data is presented in Table 1. Hemodynamic variables remained stable during the protocol steps except for CO_{EPBF}, which presented higher values during and after OLA compared to baseline ventilation. RM was hemodynamically well tolerated and successfully applied in all patients (Table 2). In 8 patients intermittent low dose noradrenaline ($\leq 0.05\ \mu\ kg^{-1}$ min) was used as needed.

3.1 PEEP titration after RM

FIO_2 could be decreased to 21% during the whole RM as SpO_2 remained above 90% in all patients. Main studied variables during the PEEP titration trial after RM are presented in Figs. 2, 3 and 4. Figure 2 illustrates SpO_2, Crs and $EELVCO_2$ expressed against $P_{L,ee}$ taking the polarity change as reference of the lung's closing pressure. Thus, the CL-PEEP related to a negative $P_{L,ee}$ value was found at 14.2 ± 1.3 cmH_2O while the OL-PEEP related to a $P_{L,ee}$ above zero was found at 15.9 ± 1.7 cmH_2O. Figure 3 presents SpO_2, Crs and $EELVCO_2$ expressed against PEEP where the vertical dotted line marks the OL-PEEP. This OL-PEEP was associated with SpO_2 of 97.6 ± 0.7%, Crs of 45.1 ± 9.9 mL/cmH_2O and $EELVCO_2$ of 2177 ± 679 mL (Table 2).

The ROC analysis revealed that a $SpO_2 < 97\%$ was more accurate (AUC 0.92—IC 95% between 0.87 and 0.97) than Crs (AUC 0.76—IC 95% between 0.87 and 0.97) or $EELVCO_2$ (AUC 0.73—IC 95% between 0.64 and 0.82)

Table 1 Demographic data of studied patients

Morbidly obese patients (*n* = 12)	
Age (years)	45 ± 10
Gender (% females)	75
Weight (kg)	120 ± 15
BMI (kg/cm^2)	46 ± 4
FEV_1 (L) (%)	2.8 ± 0.3 94 ± 12
FVC (L) (%)	3.3 ± 0.4 92 ± 13
FEV_1/FVC	84 ± 6
Fluids (mL)	725 ± 102
NA infusion (n) Doses in $\mu\ kg^{-1}\ min^{-1}$	(8) ≤ 0.05
Surgery time (min)	131 ± 23

All data is expressed as absolute values, percentage and quotient between them and presented as mean ± SD

BMI body mass index, *FEV_1* forced expiratory flow in one second, *FVC* forced vital capacity, *NA* number of patients that received noradrenaline infusion (n) at doses < 0.05 $\mu\ kg^{-1}\ min^{-1}$

Table 2 Main studied parameters

Parameter	Baseline	CL-PEEP	P value (*a*)	OLA	P value (*b*)
Global respiratory mechanics					
VT (mL)	455 ± 74	453 ± 75	*0.662*	445 ± 80	*0.278*
PEEP (cmH_2O)	7.7 ± 0.5	14.2 ± 1.3	*< 0.0001*	15.9 ± 1.7	*< 0.0001*
Pplat (cmH_2O)	25.3 ± 3.1	26.2 ± 2.9	*0.181*	25.9 ± 2.9	*0.548*
DP (cmH_2O)	18.3 ± 2.2	11.4 ± 2.3	*< 0.0001*	10.1 ± 1.7	*< 0.0001*
Raw (cmH_2O/L/s)	9.6 ± 3.0	7.9 ± 3.1	*0.015*	7.8 ± 3.4	*0.024*
Crs (mL/cmH_2O)	25.9 ± 10.8	41.4 ± 11.4	*0.0001*	45.1 ± 9.9	*< 0.0001*
$EELV_{CO2}$ (mL)	1248 ± 220	1829 ± 886	*0.013*	2177 ± 679	*0.0001*
Transpulmonary mechanics					
$Pes_{,ei}$ (cmH_2O)	18.8 ± 3.0	19.5 ± 2.9	*0.291*	18.5 ± 3.4	*0.764*
$Pes_{,ee}$ (cmH_2O)	13.1 ± 2.1	15.6 ± 1.8	*0.0002*	15.0 ± 1.9	*0.037*
$P_{L,ei}$ (cmH_2O)	6.5 ± 3.2	6.7 ± 2.3	*0.830*	7.5 ± 1.9	*0.312*
$P_{L,ee}$ (cmH_2O)	− 6.0 ± 1.1	− 0.9 ± 1.2	*< 0.0001*	0.9 ± 1.1	*< 0.0001*
DP_L (cmH_2O)	12.5 ± 3.6	7.6 ± 2.3	*0.0001*	6.6 ± 1.4	*< 0.0001*
E_L (cmH_2O/L)	28.4 ± 5.8	16.4 ± 5.9	*0.0001*	15.3 ± 4.3	*< 0.0001*
E_{CW} (cmH_2O/L)	12.3 ± 5.5	9.3 ± 4.3	*0.031*	7.9 ± 4.6	*0.024*
E_{TOT} (cmH_2O/L)	40.7 ± 9.7	25.6 ± 6.7	*< 0.0001*	23.3 ± 5.6	*< 0.0001*
Strain	0.39 ± 0.07	0.27 ± 0.07	*0.007*	0.22 ± 0.06	*0.001*
Hemodynamics					
HR (bpm)	74.9 ± 8.3	74.1 ± 9.3	*0.738*	72.3 ± 10.6	*0.271*
MAP (mmHg)	80.5 ± 5.7	82.8 ± 7.1	*0.212*	83.2 ± 6.5	*0.301*
CO_{EPBF} (L/min)	3.9 ± 0.8	4.6 ± 0.8	*0.005*	4.9 ± 1.0	*< 0.0001*
SpO_2 (%)	93.9 ± 0.7	96.3 ± 0.6	*< 0.0001*	97.6 ± 0.7	*< 0.0001*

Data is presented as mean and SD. Student's *t*-test with Bonferroni's correction, p value compared with baseline (*a* and *b*)

CL-PEEP the PEEP level corresponding to the closing pressure of the lung and *OLA* open lung approach. *VT* tidal volume, *PEEP* positive-end expiratory pressure, *Pplat* plateau pressure, *DP* driving pressure, *Raw* airways resistance, *Crs* respiratory compliance, $EELV_{CO2}$ end-expiratory lung volume measured by the capnodynamic method, $Pes,_{ei}$ end-inspiratory esophageal pressure, $Pes,_{ee}$ end-expiratory esophageal pressure, $P_{L,ei}$ end-inspiratory transpulmonary pressure, $P_{L,ee}$ end-expiratory transpulmonary pressure, $DP_{L,ee}$ transpulmonary driving pressure, E_L lung elastance, E_{CW} chest wall elastance, E_{TOT} total elastance, *HR* heart rate, *MAP*mean arterial blood pressure, and CO_{EPBF} effective pulmonary blood flow, SpO_2 pulse oximetry noninvasive hemoglobin saturation breathing room air

to detect the lung's closing pressure according to the $P_{L,ee}$ polarity change criterion (Table 3).

Figure 4 presents the changes in transpulmonary mechanics during the descending PEEP titration trial. The vertical dotted line marks the OL-PEEP. Below this line, lower levels of PEEP progressively increased DP_L and E_L.

3.2 Effects of the OLA strategy

Table 2 presents the main studied variables before and after OLA. Intrinsic PEEP was not detected in any patient during the protocol. RM and OL-PEEP significantly decreased DP and increased Crs (all $p < 0.0001$) when compared to baseline ventilation. No differences in Pplat was found between these protocol steps ($p = 0.548$) ventilated with similar VT despite a difference in PEEP of 8.2 cmH_2O.

$P_{L,ei}$ was similar before and after OLA with a mean difference of 1 cmH_2O ($p = 0.312$). $P_{L,ee}$ was negative during baseline ventilation in all patients but increased to above zero at OL-PEEP (Table 2). Thus, the resultant DP_L decreased by 5.9 cmH_2O ($p < 0.0001$). Mean E_L, E_{CW} and E_{TOT} almost halved after OLA when compared baseline values (all $p < 0.0001$). These changes in respiratory mechanics were related to a mean increase in $EELVCO_2$ of 868 mL ($p < 0.0001$). This resulted in a 44% decrease in lung strain after OLA compared to baseline ventilation ($p < 0.0001$).

Figure 5 demonstrates the effect of OLA on the SpO_2–FIO_2 plot. The estimated shunt at baseline ventilation was 17.7 ± 3.4% and decreased to 4.2 ± 1.4% at OL-PEEP ($p < 0.0001$). The shift of the SpO_2–FIO_2 plot to the right was 86 ± 65 mmHg during baseline ventilation, which corresponds to a V/Q ratio of 0.5 according to the SpO_2–FIO_2 mathematical model. After OLA and OL-PEEP, the V/Q ratio was normalized to 0.8 with a right shift displacement of about 43 ± 12 mmHg ($p < 0.0001$).

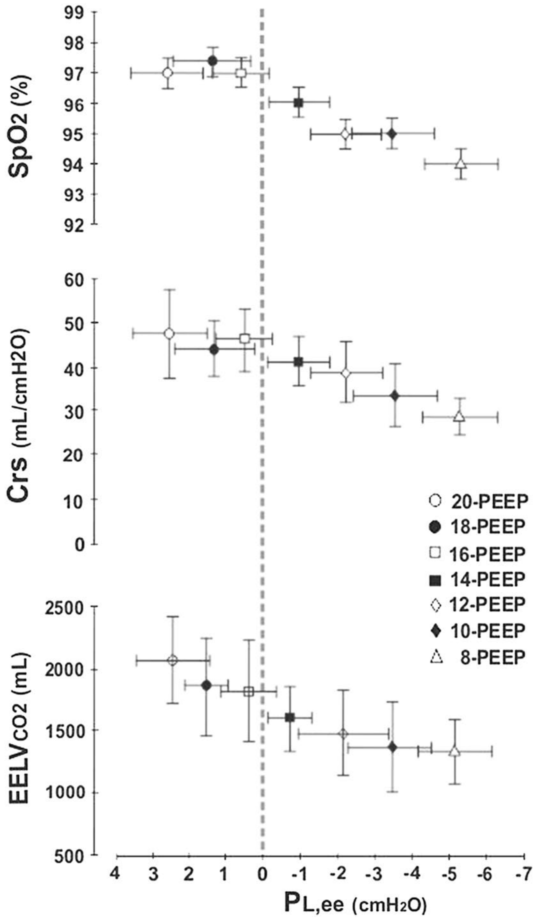

Fig. 2 Main variables during the PEEP titration trial related to end-expiratory transpulmonary pressure. Studied parameters used for the detection of the closing pressure defined as a transpulmonary pressure at end-expiration ($P_{L,ee}$) below zero (vertical dotted line—right hand). *SpO_2* pulse oximetry hemoglobin saturation, *Crs* respiratory compliance and *$EELV_{CO2}$* end-expiratory lung volume measured by volumetric capnography. Data is presented as median and interquartile range

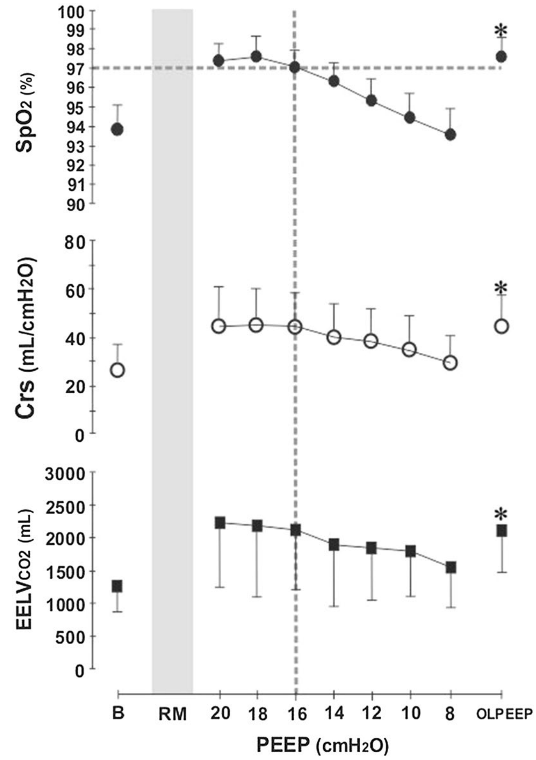

Fig. 3 Main variables during PEEP titration trial. Studied parameters used for the detection of the open-lung positive end-expiratory pressure (OL-PEEP) defined as a transpulmonary pressure at end-expiration above zero (vertical dotted line). *SpO_2* pulse oximetry hemoglobin saturation, *Crs* respiratory compliance and *$EELV_{CO2}$* end-expiratory lung volume measured by volumetric capnography. Data is presented as mean ± SD. *Student's *t*-test with Bonferroni's correction comparing baseline with OL-PEEP ($p < 0.0001$)

4 Discussion

The main findings of this physiological study can be summarized as follows:

- In the studied MO patients undergoing capnoperitoneum, standard protective ventilatory settings with 8 cmH_2O of PEEP were related to negative $P_{L,ee}$, lowest $EELV_{CO2}$ and Crs and highest estimated shunt, suggesting the presence of lung collapse.
- Protective ventilation according to an OLA strategy guided by non-invasive variables was related to positive $P_{L,ee}$, higher $EELV_{CO2}$ and Crs and normal estimated shunt when compared to baseline ventilation.
- SpO_2 was more accurate than Crs and $EELV_{CO2}$ to detect the closing pressure of the lungs during the decremental PEEP trial taking $P_{L,ee}$ polarity change as the reference.
- The OLA strategy resulted in improved airway and transpulmonary driving pressures, lung strain, lung and chest wall elastance suggesting improved lung protective conditions despite significantly higher levels of PEEP when compared to standard protective settings.

Anesthetized MO patients with healthy lungs develop more atelectasis than patients with normal BMI, making mechanical ventilation more challenging [2–6]. Increased intraabdominal pressure due to capnoperitoneum even in reverse Trendelenburg position further deteriorates EELV, gas exchange and lung mechanics [37]. It has been repeatedly demonstrated that in these patients an arbitrary value of 10 cmH_2O of PEEP has limited effects on atelectasis, respiratory mechanics and gas exchange and that only RM and PEEP individualization improves respiratory system function [16–22]. Our results are in line with previous findings, confirming an improved respiratory physiological profile during an OLA strategy when compared to standard lung protective ventilation.

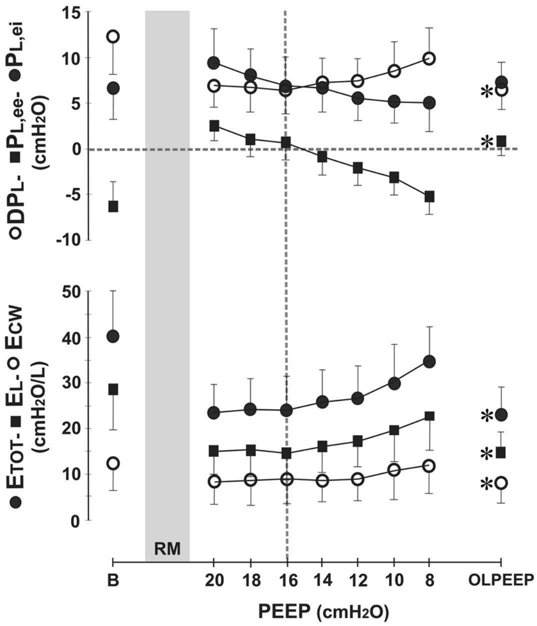

Fig. 4 Transpulmonary mechanics during PEEP titration trial after lung recruitment. Transpulmonary driving pressure (DP_L), end-inspiratory transpulmonary pressure ($P_{L,ei}$), end-expiratory transpulmonary pressure ($P_{L,ee}$), total elastance of the respiratory system (E_{RS}), lung elastance (E_L) and chest wall elastance (E_{CW}) after a recruitment maneuver (RM) and during a descending PEEP titration trial. Baseline ventilation values (B) are showed before RM and the open-lung PEEP (OL-PEEP) values are depicted after RM. Horizontal dotted line marks a transpulmonary pressure of zero. The OL-PEEP was defined as $P_{L,ee} \geq 0$ cmH_2O in our patients (vertical dotted line). Data is presented as mean ± SD. *Student's *t*-test with Bonferroni's correction comparing baseline with OL-PEEP ($p < 0.0001$)

Table 3 Area under the curve (AUC), sensitivity and specificity of studied variables to detect closing pressure

Parameter	AUC	Sensitivity	Specificity
Crs	0.76 (0.87–0.97)	0.83 (0.75–0.88)	0.62 (0.53–0.70)
$EELV_{CO2}$	0.73 (0.64–0.82)	0.60 (0.51–0.69)	0.85 (0.78–0.91)
SpO_2	0.92 (0.87–0.97)	0.82 (0.75–0.89)	0.96 (0.93–0.99)

Data was evaluated by the discrete Receiver Operator Characteristics (ROC) analysis considering end-expiratory transpulmonary pressure < zero as the reference variable to detect the lung's closing pressure. Crs is the respiratory compliance, $EELV_{CO2}$ is the end-expiratory lung volume measured by CO_2 and SpO_2 is the hemoglobin saturation calculated by pulse oximetry. (95% confidence intervals)

The decremental PEEP trial after RM is an essential component of the OLA. It is a widely accepted, well described method to find the lung's closing pressure and individualize OL-PEEP [23, 24, 28, 30]. This PEEP level is consistently associated to highest EELV, respiratory compliance and arterial blood oxygenation in MO [23, 24]. Given the potential

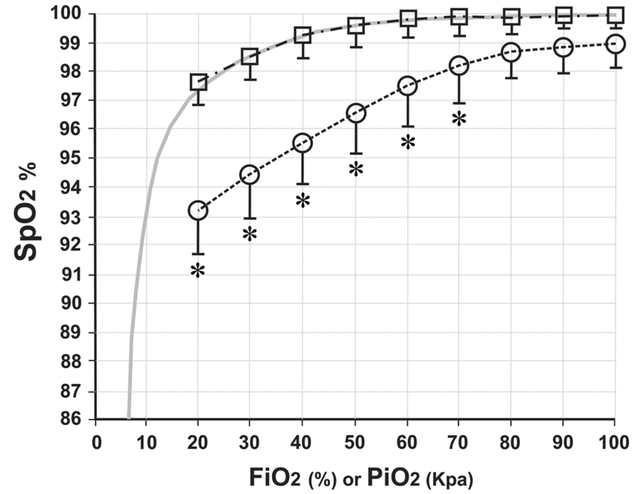

Fig. 5 SpO_2–FiO_2 trial before and after lung recruitment. Data was obtained at baseline ventilation before lung recruitment (circles) and after lung recruitment (squares); presented as mean ± SD. The gray line represents the reference normal hemoglobin saturation curve breathing air with an anatomical shunt of ~ 5%. The estimated shunt before lung recruitment was 17.7 ± 3.4% and after lung recruitment was 4.2 ± 1.4%. Asteriks showed statistical significance between moments at the same FiO_2 level (Student's *t*-test with Bonferroni's correction; $p < 0.05$). Data is presented as mean ± SD

benefits of achieving and maintaining an open lung condition during bariatric surgery, recent studies have focused on the usefulness of noninvasive bedside physiological variables such as Crs, dead space, CO_2 elimination per breath, EIT images and SpO_2 for monitoring RM and decremental PEEP titration [23, 24, 28, 30]. These variables, however, need to be put in the context of the particularly complex mechanical behavior of MO patients with an increased chest wall elastance and increased lung collapse. To our knowledge, the relationship between these non-invasive variables with transpulmonay mechanics during bariatric surgery and their synergistic use to optimize lung protective settings has not been investigated before. Thus, we found that SpO_2, Crs and $EELV_{CO2}$ accurately identified CL-PEEP in real-time using the $P_{L,ee}$ polarity change as the reference [29, 30].

When guiding PEEP titration by $P_{L,ee}$, we obtained similar OL-PEEP values during capnoperitoneum to those referred by Nestler et al. using EIT (18 cmH_2O) [38] and those of our previous study using Crs (16 cmH_2O) as the reference [23]. These values are however much lower than the ones described by Eichler et al. [26]. These authors found values of up to 20-25 cmH_2O when using $P_{L,ee}$ > zero and EIT to guide PEEP selection. It is important to highlight that PEEP values were obtained during an *incremental* PEEP titration and not during a *decremental* PEEP trial as in the current study as recommended for an OLA strategy. Lung hysteresis could explain why Eichler et al. found higher PEEP than the other studies in MO.

4.1 Clinical implications

Our results suggest that noninvasive parameters, can improve the implementation and maintainance of an intraoperative OLA strategy in MO patients. We found a clear physiological relation between the closing pressure defined by the $P_{L,ee}$ polarity change and the decrease in SpO_2, Crs and $EELVCO_2$ (Figs. 2, 3). Similar to our previous findings [23], SpO_2 showed a very good performance to detect the start of lung collapse as this is a very sensitive signal to the sudden changes in venous admixture induced by lung collapse, provided FiO_2 is maintained at 0.21. Opposedly, the moderate sensitivity/specificity of Crs to reflect the CL-PEEP could be related to the increase in chest wall elastance induced by capnoperitoneum. The higher intraabdominal pressure decreased absolute Crs values and limited the margin of changes in this signal during PEEP titration. $EELV_{CO2}$ is a new variable that showed moderate sensitivity and specificity in detecting CL-PEEP. This physiologically interesting variable adds complementary intuitive information as it increased after RM and decreased at the moment of the polarity change in $P_{L,ee}$. Further studies will have to determine the precise role of $EELV_{CO2}$ in guiding the complex lung changes induced by the OLA. Given the fast and dynamic changes induced by the OLA one could speculate that the combination of these different non-invasive parameters could be used synergistically in a multimodal monitoring approach. This would allow to characterize this complex behavior from its different perspectives such as gas exchange (SpO_2), dynamic lung mechanics (Crs, DP, P_L) and static lung volumes $EELV_{CO2}$ to ultimately taylor this ventilation strategy to the individual response of each patient.

Beyond the known physiological benefits of an OLA strategy, its lung protective effects and potential to reduce post-operative pulmonary complications are still a matter of debate [39–41]. The lung protective effects of an OLA strategy is always a trade-off between the gain of minimizing atelectasis and the risk of increasing overdistension depending on the PEEP levels required to maintain an open lung condition. On the one hand eliminating atelectasis reduces two well known lung stress raisers: tidal recruitment and lung heterogeneity, and the resulting increase in the size of the functional lung can contribute to reduce stress and strain [12–15]. On the other hand if the level of PEEP needed to stabilize the lung is high, end-inspiratory stress and strain could increase to dangerous levels if inspiratory settings are not strictly limited [42].

We found that Pplat and transpulmonary end-inspiratory pressures were similar between baseline and OLA (Table 2, Fig. 4). These surrogates of lung stress did not change whereas lung strain taking EELV instead of FRC for its calculation [36], was almost halved during OLA compared to baseline protective ventilatory settings. The decrease in lung strain, lung elastance and driving pressures indicate that an OLA strategy reduced dynamic cyclic deformation of the lungs during tidal breathing [43]. The lower driving pressure could decrease the risk of postoperative pulmonary complications according to the findings of Serpa Neto et al. [44].

In a recent randomized controlled clinical trial a lung recruitment strategy together with a fixed PEEP of 12 cmH_2O did not reduce postoperative pulmonary complications compared with a standard ventilation strategy with 4 cmH_2O of PEEP in MO patients [45]. Comparison of this study with ours is difficult: first our study was not an outcome but a physiological descriptive study, second, the use of a rather atypical and likely inefficient recruitment maneuver in MO patients [22–25], more resembling a sigh, raises concerns of whether an open lung condition was achieved, which unfortunately was never assessed in this trial, and third no individualized level of PEEP was used. One of the aims of our study was precisely to provide easy clinical variables to assess and monitor the open lung status something essential in any study comparing such ventilation strategies. Finally, even though our study was not designed to test patient's outcome our findings of a decrease in lung strain, elastance and driving pressure support the role of OLA to protect the lungs [15, 36, 42–44].

It is important to mention that hemodynamics were not affect by the use of RM and high PEEP in the studied patients. This data are in line with previous publications describing a good hemodynamic tolerance to RM and high PEEP in normovolemic MO patients [23]. Furthermore, by eliminating atelectasis and minimizing shunt OLA increased CO_{EPBF} as pulmonary blood flow through well ventilated areas also increased.

5 Limitations

This is a physiological study designed to analyze the feasibility of noninvasive variables, including $P_{L,ee}$, for monitoring the lung's opening and closing pressures. This task was performed by a rather complex protocol and setup that limited the number of studied patients. We believe that the recorded physiological information obtained in this representative group of MO patients is important to monitor the OLA and to understand the repercussion of this ventilatory strategy in lungs stress and strain. To our knowledge, this information is lacking in MO with healthy lungs subjected to bariatric surgery.

This study was not designed to analyze patient's outcome nor postoperative pulmonary complications; questions that only can be answered by randomized and controlled clinical trial with a high number of patients.

Despite its many shortcommings, esophageal manometry is currently the only clinically feasible method to estimate pleural pressure. The measured Pes represents only the pleural pressure in lung regions of the horizontal plane surrounding the position of the esophageal balloon and is likely affected by the mediastinal weight, leading to an underestimation of the actual vertical pressure gradients between ventral-to-dorsal lungs areas. The magnitude of these artifacts in MO patients is unknown. Yoshida et al. recently demonstrated that Pes at end-expiration closely reflected values in dependent to middle lung regions in pigs and in human cadavers [46]. They also described that P_L obtained from Pes absolute values and not from an inidirect estimate such as the chest wall-to-respiratory system elastance ratio, better represented the dependent lung regions where atelectasis usually predominate in anesthetized MO patients. Thus, our $P_{L,ee}$ calculation based on absolute Pes and using the polarity change criterion is an adequate means for determining the closing pressure after RM and PEEP titration in this population of MO with high chest wall elastance [29, 46].

6 Conclusions

This physiological data shows that the OLA strategy and the resulting open lung condition can be characterized and monitored using noninvasive variables during bariatric surgery. This strategy decreased lung strain, lung elastance and driving pressure when compared with baseline ventilation using standard protective settings.

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Compliance with ethical standards

Conflict of interest Gerardo Tusman and Fernando Suarez Sipmann perform consultant services for Maquet Critical Care Matías Madorno who is partner and manager of MBMed S.A; a company that produce respiratory monitoring equipments. GT and FSS perform consultant services for Getinge/Maquet Critical Care.

Informed consent Informed consent was obtained from all individual participant included in the study.

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