Noninvasive Monitoring of Lung Recruitment Maneuvers in Morbidly Obese Patients: The Role of Pulse Oximetry and Volumetric Capnography

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BACKGROUND: We conducted this study to determine whether pulse oximetry and volumetric capnography (VCap) can determine the opening and closing pressures of lungs of anesthetized morbidly obese patients.

METHODS: Twenty morbidly obese patients undergoing laparoscopic bariatric surgery with capnoperitoneum were studied. A lung recruitment maneuver was performed in pressure control ventilation as follows: (1) During an *ascending limb*, the lungs' opening pressure was detected. After increasing positive end-expiratory pressure (PEEP) from 8 to 16 cm H_2O, fraction of inspired oxygen (F_{IO_2}) was decreased until pulse oximetric arterial saturation (Sp_{O_2}) was <92%. Thereafter, end-inspiratory pressure was increased in steps of 2 cm H_2O, from 36 to a maximum of 50 cm H_2O. The opening pressure was attained when Sp_{O_2} exceeded 97%. (2) During a subsequent *decreasing limb*, the lungs' closing pressure was identified. PEEP was decreased from 22 to 10 cm H_2O in steps of 2 cm H_2O. The closing pressure was determined as the PEEP value at which respiratory compliance decreased from its maximum value. We continuously recorded lung mechanics, Sp_{O_2}, and VCap.

RESULTS: The lungs' opening pressures were detected at 44 (4) cm H_2O (median and interquartile range) and the closing pressure at 14 (2) cm H_2O. Therefore, the level of PEEP that kept the lungs without collapse was found to be 16 (3) cm H_2O. Using respiratory compliance as a reference, receiver operating characteristic analysis showed that Sp_{O_2} (area under the curve [AUC] 0.80 [SE 0.07], sensitivity 0.65, and specificity 0.94), the elimination of CO_2 per breath (AUC 0.91 [SE 0.05], sensitivity 0.85, and specificity 0.98), and Bohr's dead space (AUC 0.83 [SE 0.06], sensitivity 0.70, and specificity 0.95] were relatively accurate for detecting lung collapse during the decreasing limb of a recruitment maneuver.

CONCLUSIONS: Lung recruitment in morbidly obese patients could be effectively monitored by combining noninvasive pulse oximetry and VCap. Sp_{O_2}, the elimination of CO_2, and Bohr's dead space detected the individual's opening and closing pressures. (Anesth Analg 2014;118:137–44)

General anesthesia and mechanical ventilation cause impairment of gas exchange due to airway closure and atelectasis.[1–3] Morbidly obese patients frequently develop more atelectasis which impairs gas exchange and respiratory mechanics. Therefore, these patients are a good model of lung collapse because their lungs respond very well to a recruitment maneuver (RM).[4–12]

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A *cycling* lung RM is a ventilator strategy consisting of 3 distinct interventions.[13–15] First, during an RM, end-inspiratory pressure is increased in a controlled and stepwise manner until the lungs' opening pressure is reached. Second, once the lungs are open, their closing pressure is detected during a descending positive end-expiratory pressure (PEEP) trial.[15–17] The closing pressure is the level of PEEP at which lung derecruitment starts. Third, after a new RM, the lungs are kept open by maintaining ventilation at a PEEP level at least 2 cm H_2O above the closing pressure.[15]

Because the lungs' opening and closing pressures are not easy to detect at the bedside, it is common to use predefined levels of end-inspiratory pressure and PEEP during an RM. These general values are based on findings of clinical studies.[14,15,18] However, these predefined end-inspiratory pressure and PEEP values are likely to either over or underestimate the individual's optimal pressures because these are influenced by factors such body mass index (BMI) and the presence of capnoperitoneum.[7–9,15,18]

The aim of this study was to determine whether pulse oximetry together with parameters derived from volumetric capnography (VCap) were able to define the lungs' opening and closing pressures noninvasively during a cycling RM in morbidly obese patients. We hypothesized that instantaneous changes in the area of gas exchange induced by dynamic interventions can be detected noninvasively by pulse oximetric arterial saturation (Spo_2) and by expired CO_2 and could therefore identify the pressures at which the lungs recruit or collapse.

To provide an answer to the above question, we studied a cohort of morbidly obese patients undergoing laparoscopic bariatric surgery with capnoperitoneum.

METHODS

The study was approved by the local ethics committee. After obtaining written informed patient consent, we studied morbidly obese patients undergoing laparoscopic bariatric surgery with the following characteristics: 25 to 60 years of age, ASA physical status II and III, and BMI >40 kg/m^2. We excluded patients with abnormal baseline spirometry, active smoking, bronchospasm, functional New York Heart Association class ≥III, any acute arrhythmias, arterial hypotension, or acute coronary syndrome.

Anesthesia and Monitoring

Anesthesia was induced with propofol 1.5 mg/kg, vecuronium 0.08 mg/kg, and fentanyl 3 to 4 μg/kg of ideal body weight and maintained with sevoflurane 0.5 to 0.7 minimum alveolar concentration plus remifentanil 0.5 μg/kg/h. The lungs were ventilated through a cuffed endotracheal tube using a Servo 900C (Siemens-Elema, Solna, Sweden) in a volume-controlled mode: tidal volume (VT) of 6 to 7 mL/kg of ideal body weight, respiratory rate of 15 breaths per minute, PEEP of 8 cm H_2O, Inspired:Expired (I:E) ratio of 1:2 without inspiratory pause, and fraction of inspired oxygen (Fio_2) of 50%.

Patients were administered 500 mL of Voluven® (6% hydroxyethyl starch 130/0.4, Fresenius-Kabi, Bad Homburg, Germany) during anesthesia induction followed by a fixed infusion of 200 mL/h Ringer's lactate solution during surgery. Any blood lost during surgery was replaced by saline solution at a ratio of 1:3.

The multiparametric monitor Cardiocap/5 and the software Datex Collect (both GE Healthcare/Datex-Ohmeda, Helsinki, Finland) recorded electrocardiogram, Fio_2, and invasive mean arterial blood pressure (MAP) measured via a 20G catheter placed in the right radial artery.

The NICO monitor and the software DataColl (both Respironics, Wallingford, CT) recorded respiratory, Spo_2, and VCap data. Respiratory data consisted of VT, airway pressures, dynamic respiratory compliance (Cdyn = VT/peak pressure − PEEP), and expiratory airway resistance (Raw = peak pressure − PEEP/flow).

The Spo_2 raw data provided by the NICO monitor delivers 1 Spo_2 value every 4 seconds, which corresponds to 1 real Spo_2 value per breath at 15 breaths per minute. The accuracy and time response of Spo_2 readings during lung recruitment were investigated in a pilot study in 10 morbidly obese patients (see Supplemental Digital Content 1, http://links.lww.com/AA/A682).

The mainstream CO_2 sensor was zeroed and placed at the airway opening. Expired CO_2 concentrations and VT data were downloaded into MATLAB® (MathWorks, Natick, MA), which constructed volumetric capnograms according to the functional approximation using the Levenberg–Marquardt algorithm.[19] We measured (1) $VTCO_{2,br}$ or tidal elimination of CO_2 measured by integrating the area under the curve (AUC) of VCaps[20] and (2) dead space, calculated noninvasively using Bohr's formula[21]:

$$VD_{Bohr}/VT = (PACO_2 - P\bar{E}CO_2)/PACO_2$$

where $PACO_2$ is the mean alveolar partial pressure of CO_2 measured at the midpoint of the alveolar plateau and $P\bar{E}CO_2$ is the mixed expired partial pressure of CO_2.[21–23]

Protocol

Figure 1 shows the graphical representation of the study protocol:

- (T0) Protocol start. After induction of anesthesia, patients were submitted to a capnoperitoneum of 15 mm Hg in a supine 30° anti-Trendelenburg position.
- (T1) Data collection during baseline ventilation as described in Anesthesia and Monitoring section.
- (T2) Spo_2–Fio_2 trial at baseline ventilation to detect potential oxygenation deficits due to lung collapse.[24,25]
- (T3) Ascending limb of the RM searching for the lungs' opening pressure.
- (T4) Descending limb of the RM searching for the lungs' closing pressure.
- (T5) Data collection during ventilation as in T1.
- (T6) Second RM using the lungs' opening and closing pressures found during steps T3 and T4, respectively.
- (T7) Data collection during ventilation as in T1, but in an open-lung condition setting PEEP 2 cm H_2O above the lungs' closing pressure found in T4.

The effect of an RM was evaluated by comparing several different physiological variables obtained at the same ventilator settings (T1, T5, and T7). Arterial blood samples were collected at the end of each step and analyzed within 5 minutes (ABL 615, Radiometer, Copenhagen, Denmark). The difference between alveolar and arterial partial pressure of O_2 ($PA - aO_2$) was also calculated.

Lung Recruitment

An RM was performed in pressure-controlled ventilation separating the intervention into 2 well-defined parts: an *ascending* limb (to find the lungs' opening pressure) and a *descending* limb (to find the lungs' closing pressure; T3–T4 in Fig. 1).

Finding the Lungs' Opening Pressure

We used the Spo_2 signal to detect the lungs' opening pressure in the following way. First, we performed an Spo_2–Fio_2 trial according to Jones and Jones.[24] Fio_2 was decreased by 10% for 1 minute, starting from 100% and ending at 21% or at the lowest Fio_2 at which Spo_2 reached the lowest predefined cutoff value of 92% (above the hypoxemic threshold). This trial was performed to reveal occult potential gas exchange problems which would otherwise have been masked by the high Fio_2 (T2). Second, once the lower levels of values Spo_2 and Fio_2 were determined (Fig. 1, end of T2), we proceeded with the ascending limb of the RM (T3). Making use of Fick's law for diffusion, the lowest safe Spo_2 value is then used as an indirect marker of the area of gas

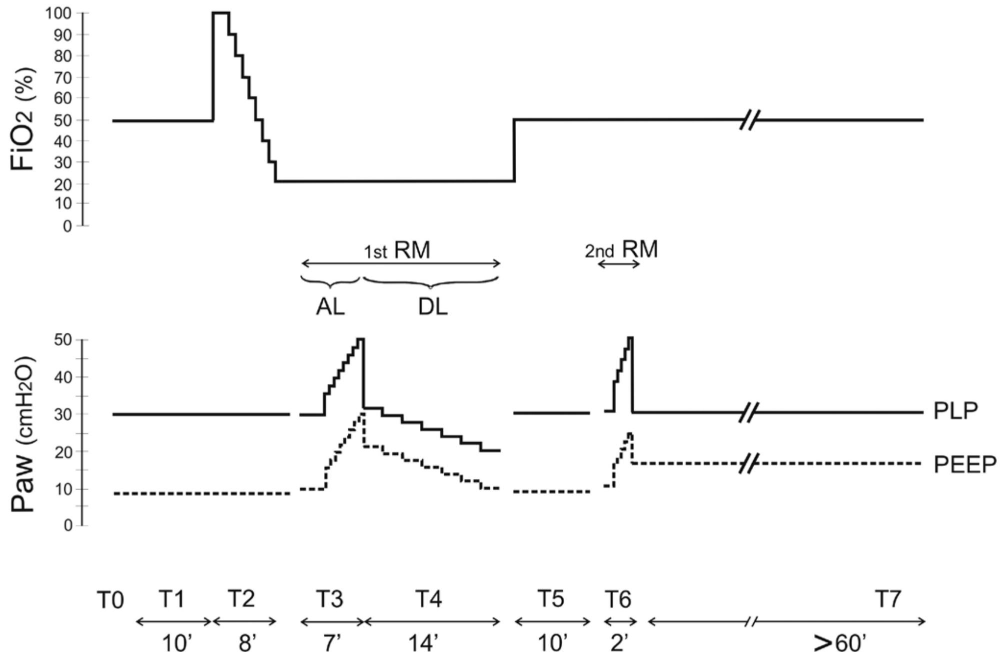

Figure 1. Graphical representation of study protocol. Upper graph, fraction of inspired oxygen (FIO_2) during the protocol. Lower graph, Dotted line represents positive end-expiratory pressure (PEEP) and continuous line plateau pressure (PLP). T0 = patients in supine anti-Trendelenburg position after anesthesia induction and during capnoperitoneum; T1 = baseline ventilation; T2 = pulse oximetric arterial saturation (SpO_2)–FIO_2 trial before recruitment; T3 = ascending limb (AL) of the first recruitment maneuver (RM); T4 = descending limb (DL) of the first RM; T5 = baseline ventilation after the first lung RM and lungs' derecruitment with identical FIO_2 as during T1; T6 = second RM guided by the individual's opening and closing pressures; T7 = ventilation at open-lung condition after the second RM using a PEEP value 2 cm H_2O above the individual's measured closing pressure.

exchange because any effective recruitment would result in a fast increase in SpO_2. With reference to the standard behavior of the oxygen–hemoglobin dissociation curve in normal lungs, a threshold SpO_2 value of ≥97% at the low FIO_2 was used to define an open-lung state (see Supplemental Digital Content 1, http://links.lww.com/AA/A682).

During the *ascending limb* of the RM (T3), the driving pressure (peak – PEEP) was set at 20 cm H_2O, I:E ratio at 1:1, and respiratory rate was maintained at 15 breaths per minute. Initially, PEEP was increased from 8 to 16 cm H_2O to reach an end-inspiratory pressure of 36 cm H_2O, a value safely below the typical opening pressures of anesthetized patients with normal body weight.[18] Thereafter, PEEP was increased every minute by 2 cm H_2O (which led to a parallel increase in end-inspiratory pressure) until an SpO_2 ≥97%. The peak pressure at this stage defined the lungs' opening pressure. Maximum end-inspiratory pressure was 50 cm H_2O if necessary.[12,26] The maneuver was aborted if one of the following conditions occurred: MAP either decreased by >20% from baseline or decreased <55 mm Hg, SpO_2 ≤90%, or appearance of cardiac arrhythmias.

Finding the Lungs' Closing Pressure

The *descending limb* of the RM sought to find the lungs' closing pressure and the PEEP at which the lungs started to recollapse (T4). Starting at a PEEP of 22 cm H_2O, driving pressure was reduced to and fixed at 10 cm H_2O and decreased sequentially until 10 cm H_2O in steps of 2 cm H_2O every 2 minutes. In these healthy lungs, the PEEP at which Cdyn reached its maximum was considered the open-lung condition while the PEEP 1 step lower defined the lungs' closing pressure.[27]

Data Analysis

Statistical analysis was performed with MATLAB. A nonnormal distribution of some variables was found with the Lilliefors test.[a] Wilcoxon test was used for comparisons between variables. Results are expressed as median and interquartile range (IQR). A *P* value <0.05 was considered statistically significant.

The role of SpO_2, $VTCO_{2,br}$, and VD_{Bohr}/VT to detect lung collapse were evaluated by discrete receiver operating characteristic (ROC) analysis.[28] Taking Cdyn as the reference method to detect the lungs' closing pressure, we assigned a binary classification of "1" to the open-lung condition (maximum Cdyn) or "0" to the onset of lung collapse (the first decrement in Cdyn from its maximum value).[27] Similarly, a value of 1 was assigned to the maximum elimination of CO_2 per breath ($VTCO_{2,br}$), the minimum dead space (VD_{Bohr}/VT), and pulse oximetry (SpO_2) values ≥97%. On the contrary, a value of 0 was assigned whenever $VTCO_{2,br}$ started to decrease, VD_{Bohr}/VT started to increase, and SpO_2 decreased <97%. These assignments determine true and false positive or negative conditions in a 2 × 2 table from which sensitivity and specificity were calculated. The AUC of a discrete ROC is equivalent to the Wilcoxon test of ranks.[29] The SE of AUC was calculated from the Wilcoxon statistic.[30]

[a]Sample size was not calculated because (1) this is a preliminary pilot and descriptive study without control group and (2) all morbidly obese patients developed large atelectasis[1–7] and all responded to lung recruitment maneuvers, increasing respiratory compliance exaggeratedly.[11,12,30] Using this information, calculated sample side formula gave <5 patients. Thus, we arbitrarily decided to study 20 patients.

Table 1. Demographic Data of Study Population

n	Age (y)	Gender (F/M)	BMI (kg/m²)	FVC (%)	FEV_1 (%)	FEV_1/FVC	Baseline Spo_2 (%)	Surgery time (min)	Fluids (mL)
20	43 (8)	13/7	46 (5)	93.4 (14)	96.8 (14)	104 (6)	96.2 (1.4)	155 (85)	1150 (131)

Data are presented as median (interquartile range).
BMI = body mass index; FVC = functional vital capacity; FEV_1 = forced expired volume within 1 second; baseline Spo_2 = preoperative value of pulse oximetry breathing room air; fluids = total amount of IV fluids given during surgery.

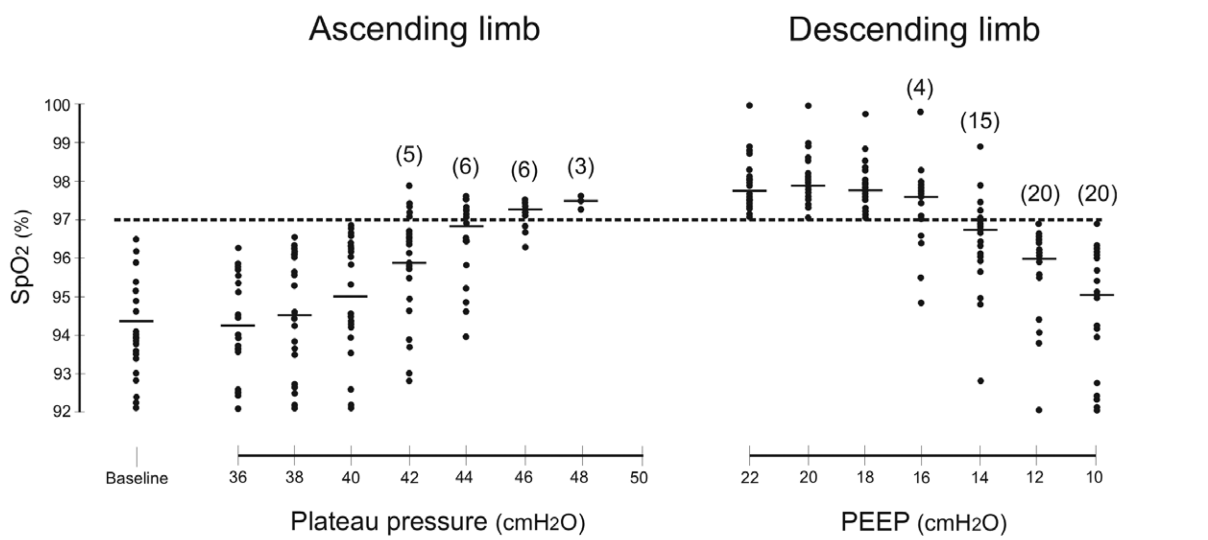

Figure 2. Pulse oximetric arterial saturation (Spo_2) during the ascending and descending limbs of the recruitment maneuver. Each dot represents 1 patient (total *n* = 20). The dotted line represents the predefined threshold value of Spo_2 ≥97% for an open-lung condition at low fraction of inspired oxygen (Fio_2). In the ascending limb (T3), the numbers in parenthesis represent the number of patients who surpassed the above threshold at the respective level of end-inspiratory pressure. In the descending limb (T4), the numbers in parenthesis represent the number of patients who reached the lungs' closing pressure at a particular level of positive end-expiratory pressure (PEEP).

RESULTS

We studied 20 morbidly obese patients all of whom completed the protocol successfully without complications. Patient characteristics are summarized in Table 1.

Lungs' opening pressures ranged between 42 and 48 cm H_2O with a median value of 44 (IQR 4) cm H_2O (Fig. 2). While Cdyn and the elimination of CO_2 increased directly and in proportion to the end-inspiratory pressure, dead space remained rather stable along the ascending limb (Fig. 3).

The lungs' closing pressure was found to be 14 (IQR 2) cm H_2O (Fig. 3). Subsequently, the level of PEEP that kept the lungs from collapsing was 16 (IQR 3) cm H_2O. This level of PEEP was related to the highest $VTCO_{2,br}$ and the lowest dead space at Spo_2 ≥97% (Figs. 3 and 4). ROC analysis showed that these variables were adequate to detect the lungs' closing pressure referencing Cdyn (Table 2).

Figure 4 shows the behavior of Spo_2 and Cdyn during T2, T3, and T4 in patient #11.

Table 3 describes the physiological variables recorded during the fixed ventilator settings at baseline (T1), when the lungs derecruited after the first RM (T5) and at the open-lung condition after the second RM (T7). In general, the physiological condition shown by an improvement in gas exchange and lung mechanics at T7 was better than the physiological condition during the other 2 studied periods. Dead space was similar during all study periods despite higher PEEP values at T7. MAP and heart rate of all patients are depicted in Figure 5. These variables remained stable throughout the study.

DISCUSSION

After decreasing Fio_2, Spo_2 turned into a real-time marker of the area of gas exchange that was able to identify the lungs' opening pressure. The values of the area under the ROC curve found in $VTCO_{2,br}$, VD_{Bohr}/VT, and Spo_2 determined that such variables were useful for detecting the closing pressure at the bedside.

Lung Opening and Closing Pressures in Morbidly Obese Patients

Obese patients develop airway closure and extensive atelectasis during laparoscopic bariatric surgery.[4–10] Even though RMs are highly effective to counteract lung collapse, the exact pressures to reexpand the collapsed lungs of morbidly obese patients are largely unknown and difficult to determine.

Rothen et al.[18] described the lungs' opening pressures to be close to 40 cm H_2O in healthy anesthetized patients using computed tomography scan imaging. They showed that the amount of atelectasis was correlated with their patient's BMI. As a result of the large decrement in transpulmonary pressure in morbidly obese patients undergoing bariatric surgery,[9,10] it can be assumed that their opening pressures should be approximately 40 to 50 cm H_2O.[12,26] Our Spo_2 results support this assumption (Fig. 2). At the highest end-inspiratory pressure, Cdyn and the elimination of CO_2 improved while dead space remained constant (Fig. 3). These findings suggested the absence of alveolar overdistension in our patients during the ascending limb of the RM despite the high airway pressures.

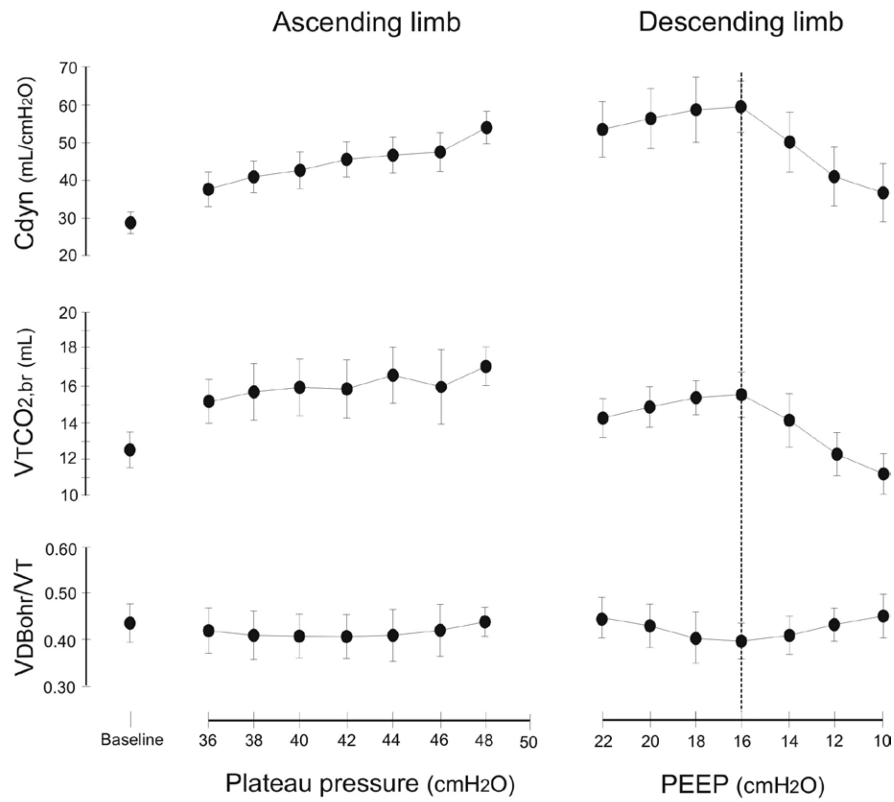

Figure 3. Cdyn, $VTCO_{2,br}$, and VD_{Bohr}/VT during the recruitment maneuver. Cdyn = dynamic respiratory compliance; $VTCO_{2,br}$ = elimination of CO_2 per breath; VD_{Bohr}/VT = ratio of Bohr's dead space to tidal volume; baseline = basal ventilation before the ascending limb; PEEP = positive end-expiratory pressure. The vertical dotted line marks the open-lung condition as defined by the maximum of Cdyn.[27] Data are presented as median (dots) and interquartile range (bars).

It has been demonstrated that the use of PEEP without an RM has limited effects on lung function irrespective of the patient's BMI or lung condition.[14,15] However, once effectively recruited, PEEP plays a key role in maintaining the lungs open.[29] PEEP applied after an RM improved gas exchange and lung mechanics in morbidly obese patients, and this effect depended on the level of PEEP applied and was better at 10 cm H_2O than at 5 cm H_2O.[11] In another study, we found that PEEP 15 cm H_2O was even better than 10 cm H_2O to improve lung function in morbidly obese patients during anesthesia with and without capnoperitoneum.[12] Using electric impedance tomography, Erlandsson et al.[31] showed that 15 cm H_2O of PEEP after an RM maintained functional residual capacity and minimized shunt in anesthetized morbidly obese patients.[31] These findings support the concept of using high PEEPs in obese patients to prevent the lungs from collapsing once the lungs have been reexpanded by an RM.

Based on the behavior of Cdyn, we found a median closing pressure of 14 (IQR 2) cm H_2O[27] while a PEEP value 2 cm H_2O above the respective individual closing pressure of each morbidly obese patient was enough to keep the lungs open (Table 2). The PEEP of 16 cm H_2O in our study was similar to the optimal PEEP of 15 cm H_2O described by Böhm et al.[12] and by Erlandsson et al.[31]

Rationale for Using Spo_2 to Detect Changes in the Area of Gas Exchange During an RM

The use of high inspiratory fractions of oxygen has been historically recommended to avoid or treat hypoxemic episodes during anesthesia. One disadvantage of high Fio_2 is that it may disguise even large impairments of gas exchange as long as hemoglobin saturation remains >97%, thereby rendering Spo_2 useless for assessing many pulmonary problems of mechanically ventilated patients. Decreasing Fio_2 forces Spo_2 to operate on the steepest part of the oxygen–hemoglobin dissociation curve. This is the rationale behind the Spo_2–Fio_2 diagram described by Jones and Jones,[24] which helps clinicians characterize lung function at the bedside without blood gas analysis.

The novelty of the present study is that we used the same principle but this time to detect changes in the area of alveolar–capillary membrane during a noninvasive RM. By decreasing Fio_2, we also forced Spo_2 values to move along the steepest part of the oxygen–hemoglobin curve (<97%) always keeping it above the hypoxemic threshold (≥92%). This intervention reveals the presence of previously occult deficiencies of gas exchange such as the ones due to lung collapse. Based on Fick's law of diffusion, we could then use Spo_2 as a real-time marker of changes in the area of gas exchange during an RM:

$$Dg/dt = \lambda \times A \times (P1-P2)/T$$

where the amount of O_2 that passes through the alveolar–capillary membrane per unit of time (Dg/dt) is directly proportional to the coefficient of diffusion for O_2 (λ), and the area of gas exchange (A) and partial pressure difference of O_2 at both sides of the membrane (P1 – P2) are inversely proportional to the thickness of the membrane. Provided that λ, (P1 – P2), and T are constant, any change in the diffusion of O_2, which instantaneously affects hemoglobin O_2 saturation, could only be explained by an instantaneous change in A.

To define an open-lung condition, we arbitrarily selected a cutoff value for Spo_2 of ≥97% based on the typical characteristics of the oxygen–hemoglobin dissociation curve during ambient air breathing.[24] Following this reasoning,

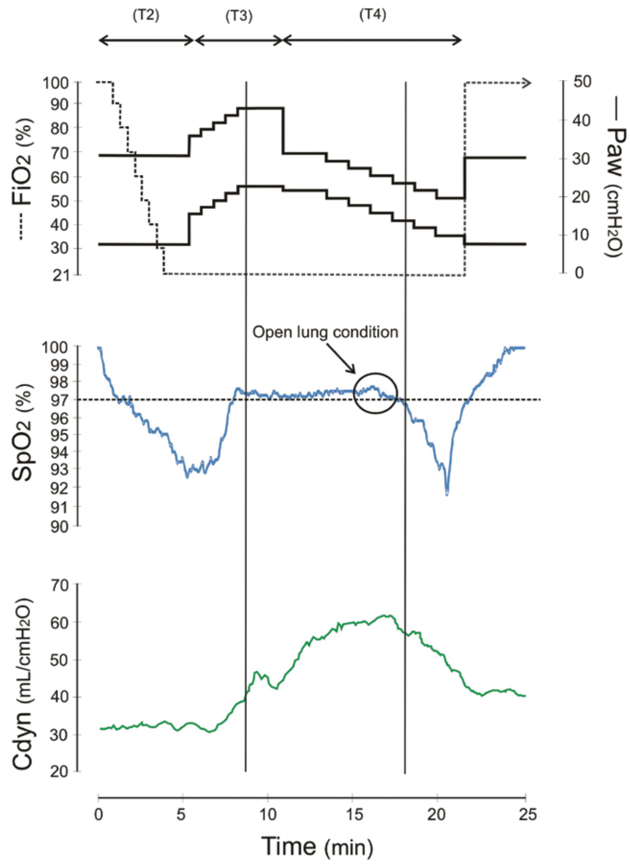

Figure 4. Example of study protocol in 1 patient showing the role of pulse oximetric arterial saturation (Spo_2) in detecting the lungs' opening and closing pressures during a recruitment maneuver (RM). Patient #11 is shown as a representative example for the entire study population. Spo_2 decreased from 100% to 93% when fraction of inspired oxygen (Fio_2) was decreased from 100% to 21%. The ascending limb of RM (T3) starts at this low Spo_2 and Fio_2. Fine horizontal dotted line marks the opening pressure threshold of 97%. Spo_2 increased proportional to the end-inspiratory pressure until the lungs' opening pressure is reached at 44 cm H_2O (left vertical line). Note that the measured Spo_2 at this moment (97%) depends only in the area of gas exchange since Fio_2 is kept constant at 21% during the whole RM. During the descending limb of the RM (T4), Spo_2 remained stable but finally decreased <97%, thereby defining the lungs' closing pressure at 14 cm H_2O (right vertical line). Patient is then ventilated at the open-lung condition using a positive end-expiratory pressure (PEEP) value 2 cm H_2O above the lungs' closing pressure (circle). Paw is the airway pressure expressed in cm of water.

in healthy lungs, an end-inspiratory pressure that yields an Spo_2 ≥97% during the ascending limb of an RM can be defined as the opening pressure (see Supplemental Digital Content 1, http://links.lww.com/AA/A682). In contrast, during the descending limb, a PEEP that results in a decrease of Spo_2 <97% can be defined as the lungs' closing pressure.

Lung RMs performed at low Fio_2 force Spo_2 to move along the steepest part of the oxygen–hemoglobin dissociation curve, and thus Spo_2 behaves in a similar way as invasive intra-arterial online Pao_2 measurements[32] (Fig. 4). The comparable behavior of Spo_2 and Pao_2 over the selected saturation range suggests that Spo_2 is a simple and good surrogate of arterial oxygenation that can efficiently monitor RM in this well-defined context.

Table 2. Sensitivity, Specificity, and Area Under the Curve (AUC) to Detect the Lungs' Closing Pressure of Different Variables

	AUC	SE	Sensitivity	Specificity
$VTCO_{2,br}$	0.91	0.05	0.85	0.98
VD_{Bohr}/VT	0.83	0.06	0.70	0.95
Spo_2	0.80	0.07	0.65	0.94

Data were analyzed by discrete receiver operator characteristics (ROCs) considering Cdyn as the reference variable to detect the lungs' closing pressure. AUC ROC and SE were calculated from the Wilcoxon statistic.[30]

Cdyn = dynamic respiratory compliance; $VTCO_{2,br}$ = elimination of CO_2 per breath; VD_{Bohr}/VT = dead space; Spo_2 = pulse oximetry.

The Role of VCap-Derived Parameters to Monitor RMs

The elimination of CO_2 per breath can be used as a marker of alveolar ventilation and the efficiency of gas exchange during nonsteady-state conditions like RMs.[33,34] Lung recruitment is characterized by an increment in Cdyn and the area of gas exchange. Thus, when using a fixed driving pressure, $VTCO_{2,br}$ increases in proportion to the augmentation in alveolar VT and the area of gas exchange during the ascending limb of an RM, assuming stable hemodynamics and metabolism. The opposite effect will be seen when the lungs recollapse during the descending limb of an RM. Figure 3 and Table 2 illustrate the similarities between Cdyn and $VTCO_{2,br}$ during the complete RM sequence and how $VTCO_{2,br}$ could detect the lungs' closing pressure according to the above rationale.

It has been demonstrated that "dead space" measured invasively using Enghoff's modification of Bohr's equation was useful to detect lung collapse in lung-lavaged animals.[35] Because this formula, however, includes shunt in its dead space calculation, it was reasoned that during PEEP titration in collapse-prone experimental models this index primarily represents changes in shunt and not in dead space. In the present study, we therefore applied Bohr's original formula to calculate dead space, a value that is not contaminated by shunt.[21,22] We found that the lowest VD_{Bohr}/VT value occurred at the PEEP level that keeps the lungs open, and when the lungs became collapsed, the VD_{Bohr}/VT value predictably increased again. Our data resemble those of the classical publication of Suter et al.,[36] in which the "best PEEP" was defined, among other variables, by the lowest dead space.

Conclusions

This study shows that pulse oximetry and VCap can effectively monitor the dynamic changes in the area of gas exchange which are induced by RMs. They can be used to determine a lung's opening and closing pressures and may thus guide clinicians during the implementation of an open-lung ventilation strategy.

DISCLOSURES

Name: Gerardo Tusman, MD.
Contribution: This author helped in study design, conduct of the study, data collection, data analysis, and manuscript preparation.
Attestation: Gerardo Tusman reviewed the original study data and data analysis and is the archival author.
Name: Iván Groisman, MD.
Contribution: This author helped in data collection and data analysis.
Attestation: Iván Groisman collected and analyzed the data.

Table 3. Main Study Variables Before (T1) and After Recruitment (T5) and During Open-Lung Condition (T7)

Variables	Baseline ventilation (T1)	*P* value T1 vs T5	Baseline ventilation after 1st RM (T5)	*P* value T5 vs T7	Open-lung condition (T7)	*P* value T1 vs T7
Gas exchange						
F_{IO_2}	0.5	—	0.5	—	0.5	—
pH	7.34 (0.05)	0.9460	7.34 (0.04)	0.0009	7.32 (0.05)	0.0006
Pa_{O_2}/F_{IO_2} (mm Hg)	257 (132)	0.3436	284 (97)	<0.0001	466 (69)	<0.0001
Pa_{CO_2} (mm Hg)	43 (5)	0.4306	42 (5)	0.2429	44 (5)	0.6733
$P_A - a_{O_2}$ (mm Hg)	210 (72)	0.2393	181 (59)	0.0001	95 (38)	0.0001
Sa_{O_2} (%)	98 (1.5)	0.3850	99 (1.5)	0.0017	99 (0)	0.0002
Sp_{O_2} (%)	97.4 (3.7)	0.2235	98.7 (2.4)	0.0002	99.9 (0.4)	0.0001
Lung mechanics						
VT (mL)	474 (43)	0.4249	480 (58)	0.3793	486 (74)	0.1198
PIP (cm H_2O)	28 (4)	0.0077	25 (4)	0.0016	29 (4)	0.4734
PEEP (cm H_2O)	8	—	8	<0.0001	16 (3)	<0.0001
Cdyn (mL/cm H_2O)	27 (6)	0.0036	30 (9)	<0.0001	48 (16)	<0.0001
Raw (mL/cm H_2O/s)	9 (3)	0.2853	8 (2)	0.0047	7 (2)	0.0002
VCap						
$VTCO_{2,br}$ (mL)	12.4 (1.6)	0.9676	12.7 (2.1)	0.3941	13.0 (1.8)	0.3369
VD_{Bohr}/VT	0.36 (0.06)	0.8181	0.36 (0.05)	0.7149	0.37 (0.07)	0.7971

Data are presented as median (interquartile range).

RM = recruitment maneuver; Pa_{O_2}/F_{IO_2} = ratio of partial pressure of O_2 in the arterial blood and the fraction of inspired oxygen (F_{IO_2}) applied; Pa_{CO_2} = partial pressure of CO_2 in the arterial blood; $P_A - a_{O_2}$ = alveolar–arterial difference of O_2; Sa_{O_2} = O_2 saturation of hemoglobin in arterial blood calculated during blood gas analysis; Sp_{O_2} = O_2 saturation of hemoglobin determined noninvasively by pulse oximetry; VT = tidal volume; PIP = peak inspiratory airway pressure; PEEP = positive end-expiratory pressure; Cdyn = dynamic respiratory compliance; Raw = expiratory airways resistance; $VTCO_{2,br}$ = amount of CO_2 eliminated per breath; VD_{Bohr}/VT = ratio of physiological dead space and tidal volume; Vcap = volumetric capnography.

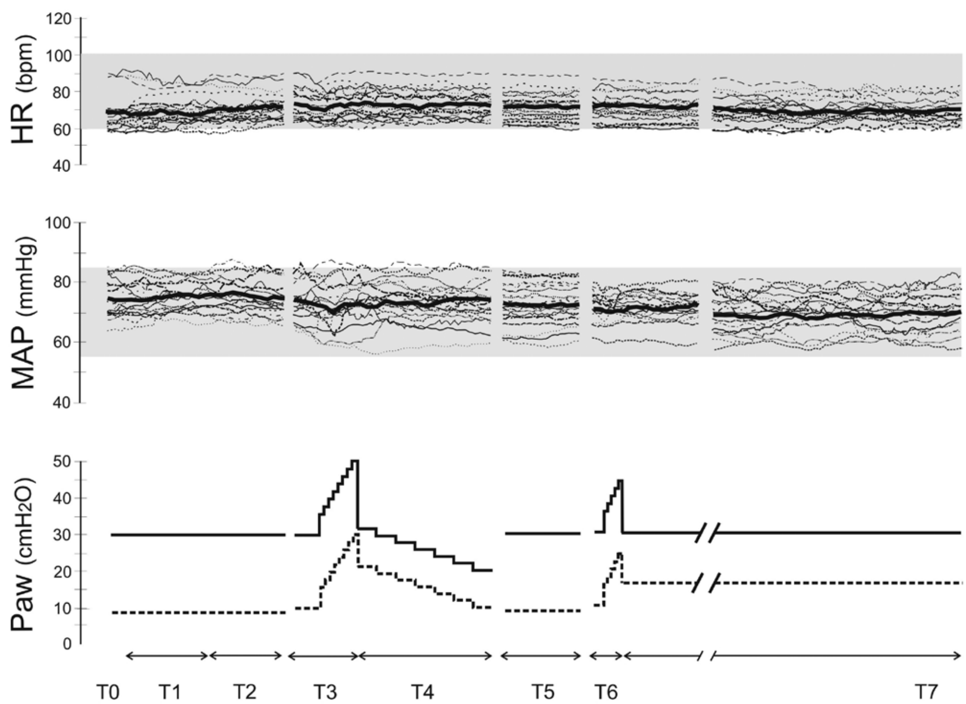

Figure 5. Hemodynamic data. Heart rate (HR) and invasive mean arterial blood pressure (MAP) are depicted during the protocol. Each fine line represents 1 patient, and the black thick line represents the median value of all 20 patients. The gray shaded areas mark the normal range. Paw is the airway pressure expressed in cm of water.

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