Trends in Anaesthesia and Critical Care 3 (2013) 238–245

Contents lists available at SciVerse ScienceDirect

Trends in Anaesthesia and Critical Care

journal homepage: www.elsevier.com/locate/tacc

REVIEW

Alveolar recruitment during mechanical ventilation – Where are we in 2013?

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Keywords:
Lung recruitment maneuvers
PEEP
Anesthesia
Airway pressure
Atelectasis

SUMMARY

Lung recruitment maneuvers have gained popularity over the last years. Their main goal is to overcome lung collapse in order to improve lung function and to decrease the chance of developing ventilator-induced lung injury. Current evidence suggests that such damage can also be observed in healthy lungs that are being mechanically ventilated as during anesthesia. Therefore, recruitment maneuvers could be part of a global protective ventilatory strategy for all ventilated patients. However, many questions like which is the best way to recruit partially collapsed lungs, how much collapsed tissue can be recruited, at which airway pressure and for how long these maneuvers should remain are unanswered. This review attempts to summarize what is known about lung recruitment maneuvers to date.

1. Introduction

Early in the nineties Lachmann described *the open-lung concept* which postulates that only lungs without collapse assure normal organ function.[1] His concept describes that lung units can either be *open* (i.e. normally ventilated and perfused units) or *closed* (i.e. dysfunctional units with ventilation/perfusion – V/Q – mismatches). In practical terms, a closed unit does not only include a physical collapse of airways or acini (atelectasis) but also pathological processes that functionally annul lung units just like mucus-plugs obstruct airways or alveolar flooding. This simplistic description of an *on–off* behavior of lung units is useful to diagnose problems of gas exchange in mechanically ventilated patients.

Based on the Young–Laplace's law (Box 1), Lachmann deducted that partially collapsed lungs needed 1) high airway pressure (Paw) to open up the lungs because collapsed units have a low internal radius; 2) once open, lung units can maintain this state even at lower Paw because open units have a larger internal radius. These two basic principles are the rationale behind lung recruitment maneuvers (RMs) and the choice of adequate levels of PEEP. As simple as these rules may sound, they must be obeyed at *all* times in order to accomplish the goals postulated by Lachmann.[1,2]

RMs are thus defined as ventilatory maneuvers that aim to recover collapsed lung units by a controlled and self-limited increment in trans-pulmonary pressure until total lung capacity is reached (Box 2 – Figs. 1 and 2). Although RMs were originally conceived of a treatment for patients suffering from acute respiratory distress syndrome (ARDS),[1–3] their role and potentially beneficial effects in the treatment of anesthesia-induced atelectasis of patients with healthy lungs is becoming obvious.[4,5]

It is known that the key damaging mechanisms of ventilator-induced lung injury (VILI), tidal recruitment and overdistension, are present in all partially collapsed lungs irrespective of the amount of such collapse.[6–8] It was assumed during the last years that treating lung collapse by an RM can protect the lungs because the known mechanisms of VILI are minimized or even disappear in an open-lung condition. Nowadays, the paradigm of RMs has shifted from a maneuver primarily used to improve pulmonary function to one that should increase the safety of mechanical ventilation. However, there are still some concerns and questions related to RMs that must be addressed. The main aim of this paper is to review the most recent literature on this topic.

2. Type of RMs and time of exposure to high pressures

There are several ways to perform RMs although two main types were systematically reported in the literature: a) *sustained inflation* maneuvers (SI) and b) *cycling* maneuvers[2–5,9] (Table and Figs. 1 and 2). Most other types of published RMs derive from these two basic maneuvers.[10–12]

As lung collapse and recruitment are physical phenomena that can be explained by the Young–Laplace law, a certain opening

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http://dx.doi.org/10.1016/j.tacc.2013.06.003

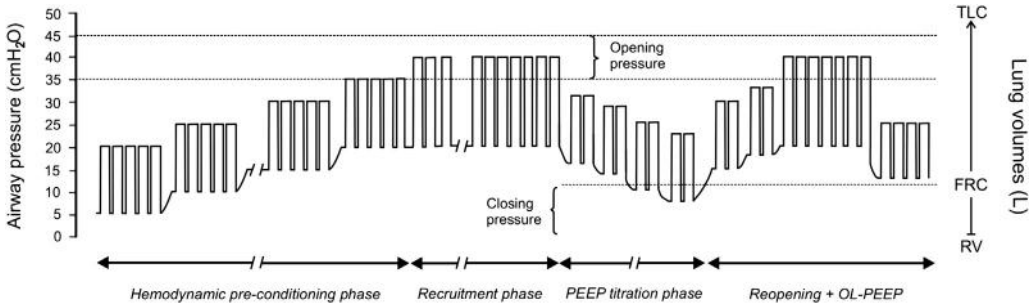

Fig. 1. Schematic representation of a cycling lung recruitment maneuver in healthy lungs. The maneuver is performed in pressure control ventilation using a driving pressure that results in a tidal volume (VT) of 6 mL/kg. Respiratory rate is set to 15, I:E ratio to 1:1 and a FiO_2 to 1. Each rectangle represents a VT. The maneuver consists of four well-defined phases each one with its own objective (for details see Text Box 2). After the recruitment the lungs are ventilated in an *open-lung* condition at normal functional residual capacity and small tidal volumes. TLC = total lung capacity, FRC = functional respiratory capacity and RV = residual volume.

pressure that is specific for each lung must be reached to overcome the collapsed state. Likewise a certain and specific closing positive end-expiratory pressure (PEEP) above the lung's actual closing pressure must be maintained in order to keep the lungs open. Whatever the RM strategy it must take these basic principles into account (Lachmann's precepts – Box 1). Besides, collapsed lung units have a critical opening *time* that must be considered in any RMs.[13,14] The effectiveness of RMs thus depends on the magnitude and the length of time that this pressure is attained. The best combination of pressure and time is yet unknown and should be personalized taking the lung's state into account.

Recently, Arnal et al. showed in ARDS patients that most of the increment in lung volume during an SI is achieved within the first 10 s while beyond this lapse of time systemic arterial pressure decreased.[15] Their results fit well with the results of experimental models in which the time spent for recruitment was investigated.[13,14] Their findings made the authors advocate short SI for clinical use. However, there is evidence showing that fast SI could be harmful for the lung tissue. Riva et al. compared fast SI with slow SI (i.e. a gradual increase in airway pressure during 40 s called "RAMP" maneuver) in a model of acute lung injury.[12] Their results showed that a RAMP followed by PEEP lead to a more homogeneous distribution of ventilation resulting in less stress for the lung tissue compared to the standard SI maneuver.

Silva et al. also investigated this issue in an experimental model of lung injury.[16] They analyzed the type (SI vs step-wise increment in Paw), timing (fast vs slow) and duration (short vs long) of RMs on lung function and activation of the lung's inflammatory response. They found that the combination of step-wise, slow and long RM minimized the biological impact when compared with faster and shorter SI maneuvers. SI showed more hyperinflation and activation of pro-inflammatory and pro-fibrogenic mediators compared to the other RMs although all maneuvers improved the lung function at the same Paw. These data contribute to the published evidence that sudden increments in inspiratory pressures and flows cause transient high shear stress that is capable of damaging the lungs.[17]

In another study, Santiago et al. evaluated the effect of SI on lung function and inflammation in a rat model of ARDS.[18] Animals were separated into a moderate and a severe ARDS group. A classical SI of 40 cmH_2O for 40 s was applied followed by 1 h of mechanical ventilation. The results showed that SI in severe ARDS lungs promoted a modest increment in the inflammatory and fibrogenic response thereby potentiating lung injury. However, in moderate ARDS without alveolar edema such negative effects were not observed. The author suggested that the lung's response to SI depended on the severity of the underlying lung injury and the presence of alveolar edema.

Considering these newest evidences, a cycling and slow step-wise increment in airway pressures during lung recruitment seems to be safer than SI maneuvers. A recent editorial suggested that SI maneuvers must be eradicated from the clinical practice based on these new findings and also due to the high prevalence of hemodynamic problems that they have.[19–21]

3. Theoretical role of RMs in lung protection

To date two main mechanisms of VILI have been recognized: one is *tidal recruitment* originating from the cyclic opening and closing of unstable lung units during breathing. This repetitive opening and closing induces *shear stress* in the boundary between normally aerated and collapsed zones.[6,7,22,23] CT scans and histological

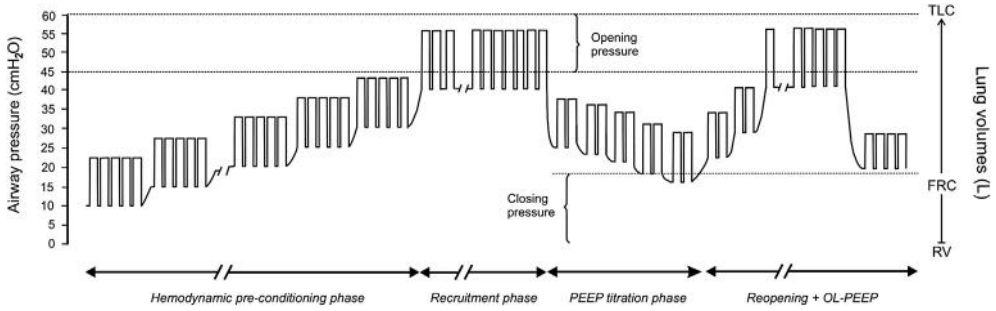

Fig. 2. Schematic representation of a cycling lung recruitment maneuver in sick lungs. The maneuver is performed in pressure control ventilation using a driving pressure of 15 cmH_2O that generally results in a tidal volume (VT) less than 6 mL/kg. Respiratory rate is set to 15, I:E ratio to 1:1 and a FiO_2 to 1. Each rectangle represents a VT. The maneuver consists of four well-defined phases each one with its own objective (for details see Text Box 2). After the recruitment the lungs are ventilated in an *open-lung* condition at normal functional residual capacity and small tidal volumes. TLC = total lung capacity, FRC = functional respiratory capacity and RV = residual volume.

Table 1
Sustained inflation vs cycling recruitment maneuvers.

	Sustained inflation (SI)	Cycling RM
Time of exposure to high recruitment pressures	Short. from 10 to 60 s.	Longer than SI. The recruitment phase typically lasts anywhere from 10 breaths (anesthesia) to at least 2–3 min (ARDS).
Hemodynamic	Highly affected. Hemodynamic assessment is not considered as an integral part of such a maneuver. Thus, hemodynamic instability is an *on–off* problem that cannot be predicted or avoided. High pressure is maintained constant throughout the RM.	The hemodynamic preconditioning phase should detect hypovolemic patients and should therefore reduce the rate of occurrence of hemodynamic problems. The maneuver can be aborted at any Paw in case of hemodynamic deterioration. There is a transient expiratory relief of the high inspiratory recruitment pressures which exerts a positive effect on hemodynamic tolerance.
Stress on lung tissue	High since airflows into and pressures within the lungs increase abruptly.	Lower than SI due to the stepwise nature of the maneuver. Volume and pressure spread progressively to more and more lung units as the recruitment takes place.
Monitoring	Respiratory monitoring is null during the maneuver.	As the ventilator is cycling continuously during this RM, all information on lung mechanics and expired gases can be easily obtained in real-time at the bedside.
PEEP selection after RM	This kind of RM originally did not evaluate the lung's closing pressure and thus the previous level of PEEP is usually applied also after the RM.	The PEEP titration phase detects the lung's closing pressure, which then determines the OL-PEEP at which the lungs are then ventilated for extended periods of time.

analysis revealed a high incidence of bullae and pseudocysts in such lung areas, strongly supporting the link between tidal recruitment and VILI.[24,25]

The other one is the *tidal overdistension*, which refers to the alveolar *strain* (i.e. the ratio between VT and functional residual capacity) that ventral lung units suffer from. Overdistension is due to the enhanced distending pressure during the inspiratory cycle and can be observed in partially collapsed lungs because inspired gas flow is re-directed towards non-dependent ventilated areas.[8,26,27]

Controversy has arisen about which of these two mechanisms induces more VILI and more impact on patient outcome. Two well-defined ventilatory strategies aimed to decrease VILI and mortality were described: 1) The NIH approach uses low tidal volume (6 mL/kg of theoretical body weight) trying to limit plateau pressure ($\leq$30 cmH_2O) and PEEP[28]; and 2) the open-lung approach also advocates low VT but high levels of PEEP which are both applied after a RM.[1–3]

Nowadays, the NIH approach is the most used in ARDS patients.[28] While such a ventilator pattern undoubtedly minimizes VILI, its protective effect for the lungs is not *per se* 100%. This is because this "permissive atelectasis" strategy clearly allows tidal recruitment[6–8] as one of the pre-requisites for tidal recruitment is the existence of lung collapse. A critical consequence of positive pressure ventilation in partially collapsed lungs is the increase in driving pressure (plateau − PEEP) as lung compliance decreases. High driving pressure was associated with a high mortality in ARDS patients as described by Frank et al. and Estenssoro et al.[29,30]

The open-lung approach avoids tidal recruitment since the lung collapse is ideally either minimized or totally absent if this strategy is applied correctly.[1–3] On the other hand, the chances of tidal overdistension increase due to the need for higher levels of PEEP and consequently higher Paw after recruitment. However, there is evidence showing that the association between overdistension and high Paw is neither linear nor directly correlated. Thus, Brunner and Wysocki demonstrated that plateau pressure is an inadequate surrogate for stress and strain within lungs during mechanical ventilation.[31] They defined the *stress–strain index* (SSI) to quantify the impact of positive-pressure ventilation on the lungs. The authors determined that the end-expiratory lung volume (EELV) was the critical factor in VILI: SSI increased when the lungs became partially collapsed (low EELV) but decreased after EELV was restored. They concluded that EELV is the main determinant of VILI and the normalization of EELV should be the first therapeutic step to avoid VILI.

This theoretical concept described by Brunner and Wysocki explains why driving pressure decreased after RMs despite the high absolute values of Paw. This is because recovering alveolar units improve compliance and allow for a more homogeneous distribution of ventilation.[32] Matos et al. provided some clue about this particular issue.[33] They found that overall mortality and barotrauma was low when ventilating severe ARDS patients with a plateau pressure $\geq$ 30 cmH_2O and PEEP $\geq$ 20 cmH_2O for the first 5 days. The use of such high Paw fit with the findings of Talmor and colleagues, who monitored trans-pulmonary pressure using an esophageal balloon in ARDS patients.[34] They ventilated most patients with plateau pressures $\leq$30 cmH_2O at PEEPs $\geq$15 cmH_2O keeping driving pressure below 15 cmH_2O but corresponding end-inspiratory and end-expiratory trans-pulmonary pressures of 7 and 0 cmH_2O, respectively.

Therefore, it seems evident that VT and absolute plateau pressures play only a secondary role in the genesis of VILI as long as EELV is restored. RMs and ventilation under open-lung conditions not only theoretically but also in clinical practice decrease tissue stress and strain as lung mechanics improve with adequate levels of EELV. In other words, tidal recruitment is absent in lungs without collapse and tidal overdistension is minimized as compliance increases after a lung recruitment.

4. Potential for recruitment

Not all ARDS patients respond in the same way to positive pressure ventilation Taking this into account, Gattinoni et al. and Caironi et al. classified ARDS patients into those with high or low potential for recruitment.[35,36] They applied an RM using 45 cmH_2O of end-inspiratory pressure with 5 or 15 cmH_2O of PEEP. Then, using CT analysis they measured the potentially recruitable lung as the proportion of the lung weight accounted for non-aerated lung tissue in which aeration was restored by an airway pressure of 45 and PEEP 5 cmH_2O. Patients with a higher potential for recruitment were sicker and had higher mortality rates than patients with lower potential for recruitment. The authors concluded that patients with higher potential for recruitment benefit from PEEP levels >15 cmH_2O while patients with lower potential for recruitment should be ventilated with PEEP levels <10 cmH_2O to avoid tidal overdistension.

The data provided by Gattinoni et al. needs to be scrutinized in more detail. Borges et al. suggested that 45 cmH_2O of end-inspiratory pressure and 5 cmH_2O of PEEP are both less than the lung's opening and closing pressures required in most ARDS patients.[37] They also showed with their results in ARDS patients that the Lachmann precepts of the open-lung condition (Box 1) were not reached in Gattinoni's study. Kacmarek and Villar postulated that the lack of response in Gattinoni's patients could be due to the

length of time for which patients were ventilated (5 ± 6 days) before being recruited.[38] Grasso et al. previously showed that RMs are much less effective when applied to patients who had been on mechanical ventilation for more than 7 ± 1 days.[39]

Recently, Matos et al. shed some light on this controversy by showing compelling data from a study where an RM strategy and PEEP titration were guided by CT in 51 early severe ARDS patients.[33] They performed a combination of maximum recruitment strategy with high plateau pressures (between 45 and 60 cmH_2O) associated with high level of a carefully titrated PEEP (>20 cmH_2O during the first 5 days of mechanical ventilation). They suggested that the concept of "potential for relative recruitment", that is the amount of mass of collapsed tissue that can be re-aerated by an RM in relation to the amount of non-aerated lung mass at baseline PEEP, instead of the total lung mass as proposed by Gattinoni, is much more relevant to evaluate the response and benefit of an RM. Furthermore, they showed that such an RM was a safe treatment to reverse non-aerated lung areas and hypoxemia for days. The authors concluded that CT images cannot predict the chances of a successful reversal of lung collapse by an RM.

Regarding the above results, two important factors seem to affect the concept of "potential for recruitment". One is the target opening–closing pressures needed to be reached by RMs to avoid sub-optimal treatment of lung collapse.[9] Another factor is the timing of an RM during the evolution of ARDS. In general it can be expected that the response will become poorer the later the RM is performed during the course of the disease when lungs become fibrotic. However, the potential for recruitment can only be assessed by actually performing an RM and measure its effect. Thus, it seems more reasonable to perform RMs early during ventilator treatment and not as a rescue therapy for refractory hypoxemia in late stages of ARDS as suggested recently.[40]

5. RMs in combination with other interventions

5.1. Patient's positioning

Changes in body positioning in mechanically ventilated patients seem to have some recruitment effect *per se*. Other mechanisms that explain the beneficial pulmonary effects of changing the body position are more homogeneous regional distribution of ventilation, minimizing compression of lung tissue by the heart, redistribution of lung perfusion to more healthy regions, and improved clearance of airway secretions.[41,42]

There is evidence supporting therapeutic positioning. Prone positioning in ARDS patients was related to an improvement of gas exchange and a decrement in overinflation.[43] Similar findings were found for the supine semi-recumbent or upright position.[44] Recently, Robak et al. showed that the combination of prone and upright positions in ARDS patients improved arterial oxygenation further.[45] Placing mechanically ventilated patients in a kinetic bed – a special bed designed to rotate the patient around the body's longitudinal axis – was related to decreases in the amount of atelectasis and the incidence of ventilator associated pneumonia and was associated with better V/Q matching.[42,46]

The prone position is the most common alternative body positioning studied in mechanically ventilated patients. This position positively influences arterial oxygenation[43] and CO_2 clearance,[47] delaying the occurrence of VILI[48] when compared with the supine position. Despite these physiological benefits, the impact of prone positioning on ARDS mortality is not clear and was contradictory in two recent publications.[49,50] Another study shows survival benefit in a subgroup of critical ARDS patients with $PaO_2/FiO_2 < 100$ mmHg, suggesting that prone positioning should be considered mainly for patients with severe hypoxemia.[51]

The combination of prone positioning and RM was recently tested in ARDS patients by Rival et al.[52] They performed extended sigh-type RMs with 45 cmH_2O ventilating the patients with 10–11 cmH_2O of PEEP in supine 1 and 6 h after turning the patients to the prone position. The authors found the highest arterial oxygenation and the lowest plateau pressure after 6 h in the prone compared with the supine position.

6. Noisy or variable ventilation

Standard positive-pressure mechanical ventilation has a monotonous breathing pattern characterized by the same VT and respiratory rate throughout the treatment. Such monotonous ventilation is known to cause surfactant deficiency, loss of FRC and atelectasis. *Noisy* or *biologically variable ventilation* refers to a ventilatory pattern in which different combinations of VT and respiratory rate are randomly assigned on a breath-by-breath basis. This kind of ventilation mimics to a certain extent the intrinsic variability of breathing observed in healthy subjects.[53]

Similar to mechanical ventilation in prone positioning, the positive effect of noisy ventilation on lung function seems to be related to lung recruitment. Several authors have shown that noisy ventilation improves gas exchange mainly by partial recovery of atelectatic areas when compared with standard ventilation.[54,55] Recently, Graham et al. demonstrated such recruitment effects of noisy ventilation using CT images in an experimental model of ARDS.[56]

Spieth and coworkers have tested the combined effect of noisy ventilation and RM.[57] In a surfactant-depleted pig model, animals were randomly assigned to either the NIH protocol (i.e. protective ventilation with low VT and PEEP) or to an open-lung approach protocol (i.e. RM followed by protective ventilation and high PEEP) with and without noisy ventilation. The results showed that adding noisy ventilation improved gas exchange, lung mechanics and pulmonary blood flow distribution and reduced histological damage compared with both ventilatory strategies without such a variable ventilatory pattern. The use of noisy ventilation after an RM is attractive since the RM assures a complete recruitment of all recruitable lung tissue whilst variable ventilation could assist the PEEP in maintaining an open-lung condition, which is not an easy task in ARDS lungs.

7. Negative abdominal pressure

Chierichetti et al. showed in lung-lavaged rabbits that transient negative abdominal pressure (NAP – created by an iron lung) together with PEEP increased arterial oxygenation and end-expiratory lung volumes after a RM.[58] This positive effect on lung function was related to a better recruitment of para-diaphragmatic atelectasis when compared to the same ventilation without NAP. This study suggests that NAP could be used as an adjuvant for reducing high airway pressures during and after RMs in high risk patients such as those with intracranial hypertension or broncho-pleural fistula, in whom high Paw is contraindicated. However, some concerns and open questions derive from this physiological study.[59] The additional technical equipment, human resources and cost associated with NAP together with the limited clinical practicality of such an intervention are restrictive factors that need to be considered when thinking about this therapeutic option. Another important clinical challenge is the reduction of venous return and cardiac output when reducing abdominal pressure. Future studies are needed to further test the clinical impact of this therapeutic option in real patients.

8. RMs during anesthesia

General anesthesia induces lung collapse in 90% of patients which explains most of the disturbances of gas exchange observed in the peri-operative period.[60,61] It was demonstrated that RMs normalize gas exchange and improve lung mechanics in different kinds of patients and surgical procedures.[4,5,62] Despite such clinical benefits, the question remains whether RMs are really necessary during anesthesia or not. We try to provide an answer based on the latest published evidence:

First, it is important to emphasize that the incidence of hypoxemia during anesthesia is high and varies amongst patients and surgical procedures.[63,64] Blum et al. state that this problem is still a matter of concern.[65] They showed that almost half (46%) of 11,000 anesthetized patients developed oxygenation problems at a degree similar to that of ARDS patients. From these patients, 4% (440) presented severe oxygenation problems with PaO_2/FiO_2 lower than 100 mmHg.

Second, there is evidence that the breathing cycles created by a mechanical ventilator induce injury in previously healthy lungs. The development of VILI in "healthy" but partially collapsed lungs was previously demonstrated in both, animal and human studies.[66–69] During anesthesia, a pulmonary inflammatory response has also been described.[70,71] Originally this pulmonary inflammation was thought to be part of the systemic inflammatory response induced by the surgical insult. However, such local inflammatory response of the lungs seems to be related to VILI. Two main facts support this assumption: 1) some studies clearly demonstrate pulmonary cytokine production during anesthesia. For instance, Zingg et al. showed that cytokines in BAL increased more in the ventilated lung compared to the non-ventilated collapsed one during one-lung ventilation.[72] 2) Protective ventilation with low VT and PEEP attenuates the local inflammatory response when compared with the use of high VT and low PEEP ventilation. In a recent analysis including 1669 anesthetized patients, Hemmes et al. showed a decrease in the risk of developing acute lung injury, pulmonary infections and atelectasis in patients ventilated with low VT plus PEEP and/or RMs compared to ventilation with high VT with low or no PEEP at all.[73]

Third, it has been shown that RMs *per se* are safe. Magnusson et al. showed that repetitive RMs in anesthetized patients did not have any negative repercussion for the lung tissue.[74] Only transient hemodynamic effects were described during RMs, which resolve immediately after decreasing the airway pressures.[61,62,75]

Four, anesthesia-induced lung collapse is an underestimated pulmonary complication in the post-operative period.[76] Using CT scans, 50% of atelectasis persists 24 h after surgery in healthy patients but up to several days in morbidly obese and high-risk patients.[77,78] There is a clear link between anesthesia-induced atelectasis and other post-operative complications.[76] Preliminary evidence suggests that intra-operative RMs also seem to be capable of decreasing the amount of atelectasis after surgery. Benoit et al. showed in patients that the combination of RM and low FiO_2 during anesthesia decreased atelectasis formation when compared to a similar treatment but without RM using high FiO_2.[78] Hemmes et al. recently showed that intra-operative RMs play an important role in decreasing post-operative complications due to atelectasis like pneumonia and VILI.[73]

Five, treating lung collapse with non-invasive ventilation (NIV) after surgery decreases morbidity in high risk patients. Squadrone et al. showed that the incidence of pneumonia, wound infection and sepsis decreased in patients receiving NIV when compared with those in whom standard oxygen therapy was applied.[79] Similarly, El Solh et al. showed in morbidly obese patients that the rate of respiratory failure and the length of ICU and hospital stay could be reduced if NIV instead of conventional oxygen therapy was applied after extubation.[80] These studies support the concept that an open-lung condition should also be maintained in the post-operative period as it decreases the risk of pulmonary complications.

Despite the fact that there is clear evidence for disturbances of gas exchange, VILI and pulmonary complications related to lung collapse in the peri-operative period, new studies showed that to date most anesthetized patients are still being ventilated with injurious ventilation patterns. Analyzing 11,000 anesthetic procedures, Blum et al. showed that patients were ventilated with a mean VT of 9 mL/kg, PEEPs of 0–5 cmH_2O and high FiO_2.[65] Jaber et al. showed that more than 80% of 2960 anesthetized patients were ventilated without PEEP.[81] Hess et al. observed that more than 20% of 45,575 anesthetized patients were ventilated with a VT $>$ 10 mL/kg and without PEEP in the last 5 years.[82] These are clear examples that anesthesiologists do not seem to ventilate their patients in a rational way thereby ignoring today's wealth of new knowledge and evidence.

9. Brief summary

Lung recruitment maneuvers are used to treat lung collapse with the aim of improving lung function and reducing ventilator-induced lung injury. *Cycling* recruitment maneuvers have many advantages over *sustained inflations* which are not only related to hemodynamic and monitoring issues but also to the stress they exert on the lung tissue. Physiological and clinical evidence strongly support the recommendation that RMs should be part of any protective ventilatory strategy for *all* mechanically ventilated patients, including the ones with "healthy" lungs as during anesthesia. Future research must now focus on optimization, rationalization and monitoring of recruitments for the multitude of different clinical scenarios and patients.

Conflict of interest statement

None.

Box 1
Basic concept of lung collapse and recruitment.

The small airways and alveoli tend to collapse during mechanical ventilation for the following reasons:

1. Gravity creates loco-regional differences in transpulmonary pressure (Ptp = alveolar − pleural pressure) since the lung's own weight causes a rise in pleural pressure in the most dependent zones. This explains why lung collapse increases along the gravitational vector. Atelectasis due to pathological decreases in Ptp is thus called *compressive* atelectasis.
2. High FiO_2 applied during mechanical ventilation induces lung collapse in hypoventilated but still perfused units. There the volume of oxygen is consumed and not replaced. These *reabsorption* atelectasis are directly proportional to both, the concentration and time of exposition to high FiO_2 and is further promoted by low PEEP and low VT.
3. The high surface tension (*T*) created by the interaction between molecules of different mediums make lung units prone to collapse at the end of expiration. The Young–Laplace law describes this interaction as:

$$P = 2T/r$$

where (P) is the pressure needed to either open up a lung unit or to keep it open. P is directly proportional to the surface tension but inversely related to the unit's internal radius. Thus, closed alveoli and small airways need high P to be recruited (at constant T) because they have a smaller radius. This physical law explains why even partially collapsed lungs need high Paw to be re-expanded but much lower Paw to be kept open.

Accordingly, there are three important airway pressures to be considered regarding RMs:

- The *lung's opening pressure*: It is the critical Paw that recovers all collapsed units. The highest Paw during a respiratory cycle is reached during inspiration. At end-inspiration *plateau* pressure approaches alveolar pressure and is the one which recruits the lung when cycling RMs are performed.
- The *lung's closing pressure*: It is the critical Paw when lung units start collapsing. Lung collapse is an expiratory phenomenon because during this phase of the respiratory cycle alveolar pressures decline and reach their minimum at end-expiration. Therefore, the closing pressure is defined by the level of PEEP at which alveoli start to collapse.
- The *open-lung PEEP* (OL-PEEP) is the level of PEEP set safely *above* the lung's closing pressure after an RM. This level of PEEP should be high enough to prevent re-collapse.

Knowing this physical behavior of the lungs the goal of any RM must follow the sequence: 1) To open the lungs identifying the plateau pressure that surpasses the *lung's opening pressure*; 2) to find the *lung's closing pressure* during a descending PEEP titration trial; 3) to perform a new RM with the above opening pressure but maintaining the lungs open with OL-PEEP.

Box 2
Practical conduct of a lung recruitment maneuver (RM)

RMs are ventilatory strategies aimed at treating lung collapse by applying high Paw in a controlled way for short periods of time. *Cycling* RMs have many advantages over *sustained inflations* and are the recommended way to perform lung recruitment (Table). We described a cycling RM performed in pressure control ventilation which can be separated into 4 well defined steps (Figs. 1 and 2):

- *Hemodynamic pre-conditioning* phase: Patients selected for an RM must be normovolemic in order to avoid potential hemodynamic deteriorations during phases of high intra-thoracic pressures. Clinical tests like a passive leg raising maneuver or a fluid challenge help to detect preload-dependent or frankly hypovolemic patients *before* an RM. The initial increments in PEEP before the actual high recruitment pressures are applied can be used to assess a patient's volemic state. Usually an increment in PEEP from 5 to 10 cmH_2O (anesthetized patients) or from 10 to 15 cmH_2O (critical care patients) stresses the hemodynamic system sufficiently to detect preload-dependencies by a respective response of standard hemodynamic variables. Thus, cycling RMs must be aborted prematurely if mean systemic arterial pressure and cardiac output decrease by $\geq$15% from baseline or else if pulse pressure variation exceeds 10–12% at the increased level of PEEP. In this case, PEEP must be returned to the previous safe value and i.v. fluids should be given to optimize intravascular fluid volume. RM should be restarted only after the patient reaches normovolemia.
- *Recruitment phase*: Recruitments are best performed in a pressure controlled mode of ventilation increasing PEEP in a step-wise fashion whilst keeping driving pressure constant. Pressures are raised until plateau pressure reaches the lung's opening pressure. This recruitment pressure varies among patients ranging from 35–45 cmH_2O in healthy patients (during 10 breaths) to 45–60 cmH_2O in ARDS patients (during 1–2 min).
- *PEEP titration trial phase*: This phase is aimed to detect the lung's closing pressure and, therefore, the OL-PEEP. Once the lungs are recruited, PEEP is decreased from high to low levels, in 2 cmH_2O steps whole keeping tidal volume (when using volume controlled ventilation) or driving pressure (when using pressure controlled ventilation) constant. Dynamic respiratory compliance is used as a non-invasive marker of lung collapse defined when compliance decreases from its highest value.
- *The reopening + open-lung condition phase*: As parts of the lungs have already started to collapse during the previous PEEP titration phase a final recruitment is needed to re-expand it before keeping it open by applying the OL-PEEP. In order to personalize the RM this phase now makes use of the information about the *true* opening pressure and OL-PEEP obtained during the above steps.

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