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REVIEW

Alveolar recruitment maneuvers in respiratory distress syndrome☆

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Abstract In patients with acute respiratory distress syndrome, heterogeneity in filling of the lung parenchyma results in collapsed or distended lung areas. Protective ventilation strategies based on the use of low volumes have been shown to increase survival in this context. For opening the lung, and in addition to PEEP, recruitment maneuvers are used—this practice remained the subject of debate.

The present review offers an update on the alveolar recruitment techniques, considering the great variability that exists in the application of these maneuvers, and the different factors that influence the response to maneuvering.

PALABRAS CLAVE
Síndrome de distrés respiratorio agudo;
Reclutamiento;
Ventilación mecánica

Maniobras de reclutamiento alveolar en el síndrome de distrés respiratorio agudo

Resumen En los pacientes con síndrome de distrés respiratorio agudo, la heterogeneidad en el llenado del parénquima pulmonar da lugar a que existan tanto áreas distendidas como colapsadas. Las estrategias de ventilación protectora basadas en el empleo de volúmenes bajos han mostrado en este contexto un aumento de supervivencia. Para abrir el pulmón, además de usar la PEEP, se emplean las maniobras de reclutamiento, todavía en debate.

En la presente revisión se analizan los fundamentos y técnicas para realizar reclutamiento alveolar, considerando la gran variabilidad que existe en cuanto a cómo aplicarlas y los distintos factores que influyen en la respuesta a las mismas.

Background

Acute respiratory distress syndrome (ARDS) remains an important cause of severe respiratory failure, with a mortality rate of up to 30–60% according to different studies.[1,2] It has been estimated that patients with ARDS represent up to 10–15% of all patients admitted to the Intensive Care Unit

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(ICU), and 20% of those who require mechanical ventilation during more than 24 h.[3]

The *babylung* concept refers to the great lung parenchyma heterogeneity that characterizes ARDS. Some lung regions are relatively well aerated and participate in gas exchange, while others are collapsed as a result of the inflammatory contents within the alveoli or because of the increase in interstitial pressure and the weight of the lung tissue. In this way, in the dependent pulmonary zones, with the patient in supine decubitus at dorsal level, aeration is poorer than in the non-dependent zones at sternal level. This results in very heterogeneous alveolar filling. Much of the research in relation to the treatment of ARDS has been designed to define protective ventilation strategies based on the use of low tidal volumes, which have been shown to improve patient survival.[4] However, such volumes can favor progressive alveolar collapse due to cyclic opening and closing, which further increases the lung damage. The application of positive end-expiratory pressure (PEEP) can stabilize the alveolus by avoiding the continuous repetition of parenchymal aperture and collapse. Based on the evidence in the literature, modifications in the prescribed mechanical ventilation parameters have been introduced over the years, with the use of lesser tidal volumes and higher PEEP levels.[5] While there is considerable agreement in calculating tidal volume, it is less clear which PEEP levels should be applied on an individual basis. A number of trials have been carried out analyzing the use of high or low PEEP in patients with ARDS—the results suggesting that high PEEP is associated with increased survival in such individuals.[6] On the other hand, however, excessive PEEP levels can worsen the damage by distending regions that are already open, giving rise to adverse hemodynamic effects.[7] In order to ''open the lung and keep it open'',[8] PEEP has been combined with alveolar recruitment (AR) maneuvers—the efficacy of which remains subject to debate.[9,10]

Definition and physiopathology

Alveolar recruitment is defined as the re-expansion of previously collapsed lung areas by means of a brief and controlled increase in transpulmonary pressure.[11] The idea of AR is to create and maintain a collapse-free situation with the purpose of increasing the end-expiration volume and improve gas exchange.

Since the 1970s, different experimental studies have investigated the relationship between alveolar volume and pressure and alveolar shape and size, and the ways in which volume changes affect alveolar structure.[12] In 1952, Day et al. applied different pressure levels to revert atelectasis in animal lungs. These authors found that low pressures are not effective even if maintained for prolonged periods of time, while high pressures are able to open the lungs but cause damage if maintained for a long time.[13] They concluded that a minimum pressure threshold must be exceeded in order to open an atelectatic lung, and that doing so safely requires precise control of the duration of application of such pressure.

Alveolar recruitment therefore has two fundamental components: the pressure level applied, and the time during which it is maintained.[14] The increase in transpulmonary pressure (transalveolar pressure would be a more accurate term) opens the terminal alveolar units according to their critical opening pressure, which varies greatly depending on their location. It has been seen that critical opening pressure is low in non-dependent regions, high in dependent regions, and intermediate in limiting territories.[15] Based on the ''open lung'' theory, it is considered that the entire lung mass could be reopened in the early stages of ARDS if sufficient transalveolar pressure is applied.[8] According to mathematical and experimental models, airway pressures of over 40 cmH_2O must be applied in order to achieve full recruitment.

In some studies, AR maneuvering has been made under radiological guidance using computed axial tomography (CAT). Gattinoni et al. studied the relationship between the percentage of potentially recruitable lung (as measured by CAT) and the clinical and physiological effects of different PEEP levels in 68 patients with ARDS.[16] They found that the percentage of potentially recruitable lung varies greatly from one patient to another, with an average of $13 \pm 11\%$, and that this parameter is related to PEEP response. As a result, it would be very useful to know the lung recruitment capacity before prescribing the ventilation parameters. Patients with greater recruitable tissue showed poorer oxygenation and compliance, a greater dead space, and increased mortality. However, it is not possible to determine the recruitment capacity of a given patient at the bedside. Costa et al. developed an impedance tomography-based algorithm for estimating recruitable alveolar collapse and hyperdistension, similar to that of CAT but without having to move the patient.[17] This algorithm allowed individualized PEEP titration. Other studies have analyzed the pressure—volume curve and especially its hysteresis as a predictor of lung recruitment capacity.[15,18] It has been seen that recruitment occurs along the entire pressure—volume curve, even above the upper inflexion point.[15] Hysteresis intrinsically reflects the recruited volume; as a result, increased curve hysteresis implies increased AR capacity.[18]

In relation to the use of complementary imaging techniques, Tomicic et al. distinguished between anatomical and functional recruitment.[19] Anatomical recruitment refers to the lung tissue in which collapse is reverted, and which can be evaluated by CAT. Functional recruitment in turn is related to improvement of intrapulmonary shunting. Aerating previously collapsed lung zones does not directly imply improved gas exchange, since during partial recruitment part of the perfusion of these alveolar units may be displaced toward other collapsed units, thereby countering both effects. Increased oxygenation will depend on the changes produced in the ventilation—perfusion ratio. Independently of the effect upon oxygenation, it is considered that AR, by increasing the aerated tissue, contributes to minimize the heterogeneity of the lung and avoid cyclic opening and closing. This in turn can prevent ventilator-associated lung injury.[20]

How alveolar recruitment is performed

The techniques used to perform AR and the results obtained vary greatly among the different studies, in terms of both

Table 1 Techniques used for alveolar recruitment and results obtained.

Author (year)	n	Recruitment technique	Timing of recruitment	Main results	Adverse effects
Amato et al.[23] (1998)	53 (AR in 29 patients)	Within protective strategy, recruitment maneuvers: CPAP 35–40 cmH_2O during 40 s	Frequently at the start of the protocol and after disconnecting respirator (maximum one maneuver a day)	Decrease in mortality in protective ventilation group Greater weaning rate	None
Lapinsky et al.[24] (1999)	14	30–45 cmH_2O during 20 s	Not specified	Brief increase in oxygenation	None of significance
Grasso et al.[25] (2002)	22	40 cmH_2O CPAP 40 s	Not specified	Oxygenation improved only in patients with early phase ARDS and no chest wall involvement	Decrease in MAP and cardiac output in non-responders
Brower et al.[26] (2003)	72	CPAP 35–40 cmH_2O during 30 s	Alternate days AR maneuvers/sham maneuvers	Very brief and mild improvement in saturation	Increased drop in AP One case of barotrauma
Dyhr et al.[27] (2003)	8	CPAP 45 cmH_2O during 20 s 2 times, with 1 min between both	After aspirations	Overcomes oxygenation drop that occurs on aspirating	Not specified
Oczenski et al.[28] (2004)	30	CPAP 50 cmH_2O during 30 s	Once	Very brief increase in PaO_2/FiO_2 ratio (less than 30 min)	None of significance
Girgis et al.[29] (2006)	20	CPAP 40 cmH_2O during 40 s	Three times followed by gradual reduction of PEEP and seeking optimum level	Improved PaO_2/FiO_2 ratio	Not specified
Meade et al.[30] (2008)	983	Sustained CPAP 40 cmH_2O during 40 s, within ventilation strategy with open lung	At start and after disconnections (up to 4 a day)	Nonsignificant decrease in mortality. Improved secondary endpoints related to hypoxemia	No significant increase in barotrauma
Pelosi et al.[31] (1999)	10	Three consecutive sighs/minute at 45 cmH_2O plateau pressure, during one hour, with protective ventilation	Ventilation protocol with several phases	Increased PaO_2 and lung volume at end of expiration; drop in $PaCO_2$, greater effect in extrapulmonary ARDS	None of significance
Patroniti et al.[32] (2002)	13	Sighs: CPAP 20% > peak pressure or at least 35 cmH_2O in supportive pressure 3–5 s each min, during 1 h	Ventilation protocol with several phases	Increased oxygenation, lung volume and compliance	Not specified
Pelosi et al.[33] (2003)	10	Three sighs 45 cmH_2O each min during 1 h with ventilation in prone decubitus	Ventilation protocol with several phases	Increased end –expiration volume and PaO_2 with decreased shunt	None of significance

Table 1 (*Continued*)

Author (year)	n	Recruitment technique	Timing of recruitment	Main results	Adverse effects
Lim et al.[34] (2001)	20	In 3 steps Vt is reduced (8 to 2 ml/kg) and PEEP is raised (10–25)	Two consecutive times with 1 min interval	Increase in PaO_2 and static compliance	None of significance
Borges et al.[36] (2006)	26	Maximum recruitment maneuvers in pressure control, guided by CAT	Upon admission	Increase in PaO_2/FiO_2, inversely related to percentage collapsed parenchyma	Transient decrease in cardiac output with no clinical repercussions
De Matos et al.[38] (2012)	51	Maximum recruitment maneuvers in pressure control, guided by CAT	Upon admission and after, if Vt decreases 20% or respirator is disconnected	Sustained increase in PaO_2/FiO_2 and decrease in non-aerated lung tissue measured by CAT	None of significance
Monge García et al.[41] (2012)	21	Progressive increase in PEEP to 36 cmH_2O	Not specified	Increase in distensibility and PaO_2/FiO_2	Decrease in cardiac output

CPAP: continuous positive airway pressure; FiO_2: oxygen concentration in inhaled air; AP: arterial pressure; MAP: mean arterial pressure; PaO_2: partial pressure of oxygen; $PaCO_2$: partial pressure of carbon dioxide; PEEP: positive end-expiratory pressure; AR: alveolar recruitment; s: seconds; ARDS: acute respiratory distress syndrome; CAT: computed axial tomography; Vt: tidal volume.

the timing and the duration of application (Table 1). Both conventional and alternative mechanical ventilation modes can be used.

The conventional ventilation modes can be divided into four large groups[20–22]:

1. Sustained continuous positive airway pressure (CPAP): a certain pressure, usually 35–50 cmH_2O, is reached during 20–40 s. The most frequent combination is the application of 40 cmH_2O during 40 s. During this time the supporting pressure must be set to 0 cmH_2O in order to avoid barotrauma. This is the most widely used technique.[23–30]
2. Sigh: increased tidal volume or PEEP during one or several respirations, with adjustment designed to reach a specific plateau pressure.[31–33]
3. Extended sigh: this considers the interaction between pressure and time, and is characterized by a progressive increase in PEEP, together with a decrease in tidal volume during a longer period of time.[34,35]
4. Pressure controlled ventilation, maintaining a pressure delta (usually 15 cmH_2O) to guarantee a tidal volume, with progressive increases in PEEP. Some authors have used so-called maximum recruitment maneuvers, reaching much higher pressures though in a gradual manner, and which in some cases are followed by a gradual decrease in pressure that serves to define the optimum individual PEEP following lung recruitment.[36–38]

Likewise related to pressure controlled ventilation, ''open lung'' ventilation is based on early lung recruitment maneuvering, with sufficient PEEP to open the largest possible number of alveoli and ventilating with the lowest possible lung distension pressure.[39–41]

Other techniques

- High-frequency ventilation: compared with the conventional mechanical ventilation modes, high-frequency ventilation gives rise to higher mean airway pressures, which limits cyclic alveolar closure and increases the end-expiration lung volume.[42] Some studies have evaluated the combination of high-frequency ventilation with sustained CPAP maneuvering with a view to reinforcing its effect in AR.[43]
- Liquid ventilation: from the purely theoretical point of view, partial lung filling with perfluorocarbon gives rise to progressive parenchyma recruitment, beginning in the dependent zones. Studies have been made in animals of the distribution of liquid and gas with different ventilation pressures.[44] This technique has not been found to offer improvement in patients.[45]
- Ventilation in prone decubitus: positioning the patient in prone decubitus varies the distribution of the transpulmonary pressure gradient, giving rise to more homogeneous alveolar filling. It does not substantially modify perfusion, however, and the ventilation–perfusion ratio is therefore improved as a result.[46] Prone decubitus may be regarded as a form of recruitment in itself. If in addition some of the commented conventional ventilation techniques are used, more uniform expansion of the applied pressures will result.[33,46,47]

Heterogeneity of the studies

A range of studies in both animals and humans have applied different AR techniques, with very diverse protocols. The studies are in fact so heterogeneous in terms of the maneuvers employed, the type of patients involved, the parameters, etc., such that it is impossible to compare the different recruitment techniques. Constantin et al. compared CPAP 40 cmH_2O during 40 s with prolonged sigh, and found the latter to afford comparatively greater oxygenation with a greater recruitment of lung tissue.[48] Mahmoud and Ammar likewise compared sustained CPAP with prolonged sigh, and reported better results and tolerance with the latter approach.[49] In 12 patients with ARDS and protective ventilation, Badet et al. applied three different forms of AR after analyzing the optimum PEEP: ventilation with the optimum PEEP level, adding sustained insufflation, and with sighs.[50] These authors recorded a greater increase in oxygenation and static compliance with the third recruitment modality, i.e., upon adding sighs. In recent years, experimental studies have found that slower and more progressive recruitment maneuvers, raising the pressure over several steps or in the form of a ramp until reaching the target level, offer better results with less hemodynamic impairment.[51] In patients, pressure ventilation with pressure increments and decrements operates in this same line.[52]

Ideally, recruitment maneuvering should be performed with the patient under sedation−relaxation, a FiO_2 of 100% and under hemodynamically stable conditions. The meta-analysis carried out by Fan et al. shows that these conditions are often not met or are not documented.[21] Likewise, there are no studies describing the percentage of patients with ARDS in which AR is applied. All these factors greatly complicate the drawing of conclusions regarding the usefulness of AR maneuvering in patients with ARDS.

Variability of response to recruitment maneuvers

The response to AR varies according to different factors referred to both the patient and the characteristics of ARDS:

1. Origin of ARDS: Differences have been found between ARDS of pulmonary and extrapulmonary origin, with greater efficacy in extrapulmonary presentations.[15,31,35,52] This effect appears to be due to less intraalveolar involvement, at least initially, with a predominance of interstitial edema, which appears to be associated with a greater recruitment capacity. However, occupation of the interior of the alveoli, as for example in pneumonia, implies the existence of less recruitable tissue. In contrast, Borges et al. have reported a similar recruitment capacity, independently of the cause of ARDS, on performing maximum recruitment maneuvers.[36]
2. Evolutive phase: Some authors consider recruitment to be effective only when performed in the early phases of lung injury, since in later phases the impaired elasticity does not allow the reversion of collapse, and increases the risk of barotrauma.[25]
3. Patient positioning: As has been commented, this factor has a strong effect upon recruitment response−the latter being greater in prone decubitus, which in itself could be regarded as a form of AR, since it increases transpulmonary pressure in the dorsal region and improves gas exchange.[46,52]
4. Vasoactive drug treatment, by modifying cardiac output, the distribution of pulmonary blood flow and gas exchange, theoretically could also modify the response to AR.[22]
5. Chest expansion capacity: Grasso et al. found AR maneuvering to be ineffective in patients with limited chest expansion.[25]
6. Previous mechanical ventilation parameters: Ventilation with low tidal volumes can cause alveolar closure, which could be compensated by using an adequate PEEP level. It has been observed that the use of higher tidal volumes and particularly of higher PEEP values before AR is associated with a lesser response to recruitment, since maneuvering probably already starts from a recruited lung.[35,53,54]
7. Posterior mechanical ventilation parameters: The posterior mechanical ventilation strategy, particularly as regards PEEP level, is as important as the recruitment technique used.[55]

Indications

In routine practice, AR maneuvering is carried out in situations of severe hypoxemia, as a rescue measure; consequently, patients with ARDS are typically involved. There is no evidence regarding when maneuvering is indicated− in what concrete moments or with what frequency. In some studies, AR maneuvering is performed systematically, while in others it is performed only when the lung is considered to have been ''de-recruited'' −fundamentally after disconnecting the patient from the respiratory for some reason, such as for example the aspiration of secretions.[23]

Maximum recruitment strategies and the open lung theory advocate the early application of ventilation protocols across different phases, in order to achieve adequate lung opening from the start and mechanical ventilation with individualized parameters, particularly as refers to optimum PEEP derived from decremental testing after AR.[36–38] In this way, AR not only aims to revert a point situation of hypoxemia but moreover also forms part of the global measures for reducing the lung damage associated to mechanical ventilation.[20]

Outside the context of Intensive Care Medicine, AR plays an important role in the operating room. In effect, AR maneuvering can be of benefit in opening atelectatic areas associated with anesthesia, particularly in obese patients, and during the immediate postoperative period of certain operations involving a high risk of respiratory complications.[56]

Results

On analyzing the results of AR, it must be mentioned that most studies do not establish criteria for defining a positive response to AR maneuvering, and only describe variable improvements in oxygenation. Grasso et al. classified responders as those patients in which the PaO_2/FiO_2 ratio increased at least 50% after AR maneuvering,[25] while Villagrá et al.[54] and Girgis et al.[29] accepted a much lesser increase (20%) as representing a positive response. It has been reported that maximum recruitment can be assumed with a FiO_2 of 100%, if $PaO_2 + PaCO_2 = 400$, or if the PaO_2/FiO_2 ratio is >350, with a collapsed lung tissue mass of less than 5%.[36] Instead of focusing on oxygenation-related outcomes, some studies define response in terms of lung mechanics, analyzing the effect of AR upon parameters such as compliance.

Many studies have reported improved oxygenation as a result of AR maneuvering in both basic experimentation in animals, in which different techniques are used to induce lung injury,[57] and in patients with ARDS.[23–25,27–38,58] However, some authors have described no beneficial effects.[26]

The increase in oxygenation is usually brief, and some studies have found the effect to fade after as little as 15–30 min[28] –though the duration of effect is usually about 3–6 h. In 51 patients with severe ARDS, De Matos et al. prescribed pressure ventilation according to the open lung theory, using maximum recruitment techniques, and found the benefits in terms of gas exchange and respiratory mechanics to persist for several days.[38] The authors consider that the pressures classically reached during AR maneuvering (40–45 cmH_2O) are not enough to aerate the collapsed lung in severe ARDS, and that the capacity of AR should be reconsidered on the basis of more ''aggressive'' techniques, though applying them on a progressive basis.

Amato et al. reported a decrease in mortality in the group of patients subjected to AR maneuvering in the context of protective ventilation; the outcome therefore must be related to the series of adopted measures, not directly to AR.[23] The increase in oxygenation observed as a result of AR has not been found to be accompanied by any relevant impact upon the clinical outcomes. There are no differences in terms of the duration of mechanical ventilation, hospital stay or mortality on performing this technique.[58]

Side effects

The increase in transpulmonary pressure is sometimes accompanied by adverse effects–the most frequently reported being hypotension and desaturation.[25,26] In the studies that have included more complete invasive hemodynamic monitorization, decreases have been described in cardiac output, systolic volume and preload, together with a rise in heart rate.[25,36,41] The invasive monitoring of arterial pressure is not enough to evaluate all the hemodynamic changes that occur with recruitment maneuvering, since the values may even increase temporarily.

Other complications are barotrauma, arrhythmias, hypoventilation and acidosis, and it has even been postulated that bacterial translocation can occur from within the alveoli–though the results of the different studies are contradictory in this sense.[59] In general, such effects are usually brief and of scant importance; a change in ventilation strategy is therefore usually not required.

It has been observed that when sustained insufflation maneuvers are carried out, side effects are more frequent than with other techniques. In the case of maneuvering with pressure ventilation, there appear to be fewer cases of barotrauma or adverse hemodynamic effects, despite the fact that much higher pressures are reached in the airway, since maneuvering is applied in a more progressive manner.[52] Gil Cano et al. analyzed the incidence of barotrauma in 100 patients ventilated using an open lung strategy.[60] They described pneumothorax in 7 patients and subcutaneous emphysema in two individuals–all of which presented primary ARDS. No changes in the mechanical ventilation parameters proved necessary.

Conclusions

On the basis of the existing evidence, AR maneuvering cannot be recommended as a general practice in clinically stable ARDS patients. Such maneuvering usually affords variable and temporary improvement in oxygenation, without beneficial effects upon mortality. The potential effects of AR depend on a series of factors referred to both the patient and the ventilation parameters before and after application of the technique. In this context, the PEEP level prescribed after maneuvering, with a view to avoiding ''derecruitment'', is of crucial importance.

The more recently introduced AR maneuvers, which reach higher airway pressures in a more progressive manner, can prove useful during mechanical ventilation in seeking an optimum PEEP level; however, it is not clear whether the use of this parameter is accompanied by beneficial clinical outcomes.

Repeated AR maneuvering should not be attempted in non-responders, since it may have adverse effects.

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Conflict of interest

The authors declare that they have no conflicts of interest.

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