

Effects of recruitment manoeuvres on haemodynamics, oxygen exchange and oxygen delivery in patients with acute lung injury and acute respiratory distress syndrome

Vanina S Kanoore Edul, Luis P Maskin and Arnaldo Dubin

Acute lung injury (ALI) and acute respiratory distress syndrome (ARDS) carry a high mortality rate and remain one of the major challenges in the intensive care unit.^{1,2} Mechanical ventilation is critical for the survival of patients with ARDS. In recent years, different studies have shown that some patterns of ventilatory support, the “open lung concept” and “lung protective ventilation” (limited plateau pressure [P_{plat}] and low tidal volume [V_T]), can reduce mortality in these patients.³⁻⁶ However, the use of low V_T may induce atelectasis.

An area of controversy is the use of recruitment manoeuvres (RMs). This approach is defined as a sustained high-pressure inflation aimed at overcoming the opening pressure of the lung units having high surface tension. RMs have been advocated as an adjunct to a pressure-limited lung-protective ventilatory strategy. In ARDS, RMs are used in an attempt to open refractory lung units, to improve gas exchange, and to prevent alveolar derecruitment. In addition, some researchers have successfully used RMs during general anesthesia in healthy patients to re-expand collapsed lung regions.^{7,8}

Few studies, however, have investigated the safety and side effects of RMs, and controversial data exist around this issue. As most reports have shown only transient effects on both blood pressure and oxygenation, RMs have traditionally been considered safe^{9,10} and are widely used. Only a few clinical studies have investigated the effect of RMs on cardiac output. Their contradictory results are probably a result of clinical and methodological heterogeneity.^{11,12} From a physiological standpoint, a sudden increase in lung volume and intrathoracic pressures may adversely affect cardiac filling and intrapulmonary blood flow distribution, causing low cardiac output. This issue is even more relevant in mechanically ventilated patients, who often exhibit haemodynamic instability and reduced lung and chest-wall compliance.¹³

The purpose of our study was to evaluate prospectively the impact of a commonly used RM on haemodynamics, gas exchange and oxygen transport in ALI/ARDS patients on mechanical ventilation with high positive end-expiratory pressure (PEEP) levels. Our hypothesis was that the RM would induce severe haemodynamic derangements, with marginal improvement in pulmonary gas exchange.

ABSTRACT

Objective: To evaluate the impact of a recruitment manoeuvre (RM) on haemodynamics, gas exchange, and oxygen transport in patients with acute lung injury (ALI) and acute respiratory distress syndrome (ARDS) under mechanical ventilation.

Design, setting and participants: Prospective interventional study in the intensive care unit of a teaching hospital in Buenos Aires, Argentina. The study was carried out between June 2002 and March 2003. Eleven consecutive patients with ALI and ARDS who required an RM were included. Haemodynamic measurements and blood samples were taken before and during the RM, and at 2 and 30 minutes after the RM.

Intervention: After baseline measurements, positive end-expiratory pressure (PEEP) was set at 40 cmH₂O for 45 seconds.

Main outcome measures: Systemic haemodynamics, oxygen exchange and oxygen delivery.

Results: Mean PEEP before the RM was 14 (SD, 3) cmH₂O, and was maintained after the RM. The RM did not modify the arterial partial pressure of oxygen (P_{aO₂}) but did induce small but significant changes in the mean arterial partial pressure of carbon dioxide (P_{aCO₂}) and arterial minus end-tidal P_{CO₂} gradient (P_a-ET_{CO₂}) at 2 minutes and 30 minutes after the RM ($P < 0.05$). The mean cardiac index dropped from 3.08 (SD, 0.84) to 2.37 (SD, 0.75) L/min/m² ($P < 0.001$) during the RM and then returned to baseline values. Mean systolic blood pressure also fell transiently during the RM, from 131 (SD, 15) to 104 (SD, 25) mmHg, but diastolic and mean arterial pressures remained unchanged. Oxygen consumption and the arterial mixed venous oxygen content gradient increased after the RM ($P < 0.05$).

Conclusion: In our small series of patients with ALI/ARDS ventilated with high levels of PEEP, the RM failed to improve oxygen exchange and induced deleterious effects on haemodynamics.

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Methods

Our study was approved by the Institutional Review Board. Written informed consent was given by the patient's near-

Abbreviations

ALI	Acute lung injury
ARDS	Acute respiratory distress syndrome
Ca-vo ₂	Arterial–mixed venous oxygen content gradient
CPAP	Continuous positive airway pressure
C _{RS}	Quasistatic compliance of respiratory system
FIO ₂	Fraction of inspired oxygen
PaCO ₂	Arterial partial pressure of carbon dioxide
Pa-ETCO ₂	Arterial minus end-tidal partial pressure of carbon dioxide gradient
PaO ₂	Arterial partial pressure of oxygen
PAOP	Pulmonary artery occlusion pressure
PECO ₂	Mixed-expired carbon dioxide pressure
PEEP	Positive end-expiratory pressure
PETCO ₂	End-tidal carbon dioxide pressure
Ppa	Pulmonary artery pressure
Pplat	Plateau pressure
Q _{VA} /Q _T	Venous admixture
RAP	Right atrial pressure
RM	Recruitment manoeuvre
SaO ₂	Arterial oxygen saturation
SpO ₂	Oxygen saturation measured by pulse oximetry
V _D	Dead space
VO ₂	Oxygen consumption
V _T	Tidal volume

est of kin. Our study was performed in the ICU of Clínica Bazterrica, Buenos Aires, Argentina, between June 2002 and March 2003.

Patients

Eleven consecutive mechanically ventilated patients with a diagnosis of ALI/ARDS⁸ were included. All the patients had an arterial line and a pulmonary arterial catheter in place and required an RM according to the treating physician's criteria. Exclusion criteria were: age < 18 years, pregnancy, chronic obstructive pulmonary disease, airway hyper-reactivity, the presence of barotrauma, or intracranial hypertension.

Ventilatory setting and respiratory mechanics

All the patients had orotracheal intubation with a cuffed endotracheal tube and were ventilated with a volume-controlled ventilator (Puritan Bennett 7200, Nellcor Puritan Bennett Inc, Boulder, CO, USA). They were sedated with intravenous midazolam and fentanyl and paralysed with pancuronium bromide. The baseline ventilatory settings were: V_T 5–7 mL/kg; PEEP 8–16 cmH₂O, to obtain a Pplat

< 30 cmH₂O; and fraction of inspired oxygen (FIO₂) to reach arterial oxygen saturation (Sao₂) of 90%–95%, an arterial oxygen partial pressure (Pao₂) of 60–80 mmHg (8.0–10.6 kPa), or both. All patients were monitored with capnography, five-lead electrocardiography and pulse oximetry (SpO₂) during the study.

Flow and airway pressures were measured through ventilator transducers. Quasistatic compliance of the respiratory system (C_{RS}) was calculated as the ratio of volume change over pressure change:

$$C_{RS} = V_T \div [P_{plat} - (\text{external PEEP} + \text{intrinsic PEEP})]$$

Plateau pressure (Pplat) was measured by occluding the airway for 1 second at end inspiration, and intrinsic PEEP was determined by end-expiration occlusion. Each procedure was done during separate respiratory cycles. End-tidal CO₂ pressure (PETCO₂) was continuously measured, and the difference between arterial CO₂ partial pressure (Paco₂) and PETCO₂ (Pa-ETCO₂) was calculated. FIO₂ was not modified during the study.

Mixed expired gas was collected for 2 minutes, at each time point of the protocol, in a 40L airtight bag (Douglas bag) connected to the expiratory outlet of the ventilatory circuit. Mean expired Pco₂ was measured from the expired-gas collection (PECO₂). The dead space to tidal volume ratio (V_D/V_T) was calculated by means of Enghoff's modification of the Bohr equation as:

$$V_D/V_T = (Paco_2 - PECO_2) \div Paco_2$$

Gas-exchange analysis and haemodynamic measurements

An arterial catheter was used for monitoring continuous invasive blood pressure and for the intermittent sampling of blood. A 7.0 French flow-directed thermodilution pulmonary artery catheter (Edwards Lifesciences, Irvine, Calif, USA) was used for continuous measurement of pulmonary artery pressure (Ppa) and intermittent measurement of cardiac output, pulmonary artery occlusion pressure (PAOP), right atrial pressure and blood sampling. Cardiac output was measured with the thermodilution technique, by averaging the results of three injections with 10 mL normal saline at 25°C. During the RM, only one cardiac output measurement was performed, as an individual injection throughout the entire respiratory cycle is accurate.¹⁴

Arterial and mixed venous blood gases, oxygen saturation, and haemoglobin were measured with a blood gas analyser and a co-oximeter (AVL 995, AVL List, Gaz, Austria, and OSM 3 Radiometer, Copenhagen, Denmark). Venous admixture (Q_{VA}/Q_T), arterial–mixed venous oxygen content gradient (Ca-vo₂), oxygen delivery, oxygen consumption (VO₂), pulmonary vascular resistance and systemic vascular resistance were calculated by standard formulas.

Table 1. Clinical and demographic characteristics of the patients

Patient (sex)	Age in years	Cause of ARDS	Days on MV	PEEP (cmH ₂ O)	PaO ₂ /FIO ₂	APACHE II score
1 (M)	76	E	1	16	81	27
2 (F)	73	P	5	12	246	37
3 (F)	76	P	2	12	253	20
4 (M)	51	E	1	16	205	16
5 (F)	70	E	2	10	285	20
6 (M)	67	P	7	8	235	24
7 (F)	85	E	1	10	137	45
8 (M)	46	P	2	15	188	28
9 (M)	71	E	1	16	293	28
10 (F)	71	P	3	16	228	20

APACHE = Acute Physiology and Chronic Health Evaluation. ARDS = acute respiratory distress syndrome. E = extrapulmonary. F = female. FIO₂ = fraction of inspired oxygen. M = male. MV = mechanical ventilation. P = pulmonary. PaO₂ = arterial partial pressure of oxygen. PEEP = positive end-expiratory pressure.

Research protocol

After basal measurements, an RM was performed, consisting of an increase in continuous positive airway pressure (CPAP) to 40 cmH₂O for 45 seconds. During the last 20 seconds, cardiac output was measured. Systolic blood pressure, Ppa, heart rate and Spo₂ were measured at 15, 30, and 45 seconds after initiation of the RM. The CPAP level was then gradually reduced and the previous breathing pattern re-established. The measurements and blood sampling were repeated at 2 minutes and 30 minutes after the RM. The manoeuvre was interrupted if there was a fall in systolic blood pressure to <85 mmHg, a cardiac arrhythmia, or an Spo₂ <90%.

Statistical analysis

The data are reported as mean (SD) and were analysed with repeated measures of analysis of variance followed by the Dunnett test (PRISM 3.0, Microsoft Research Cambridge, Birmingham, UK). A P value <0.05 was considered significant.

Results

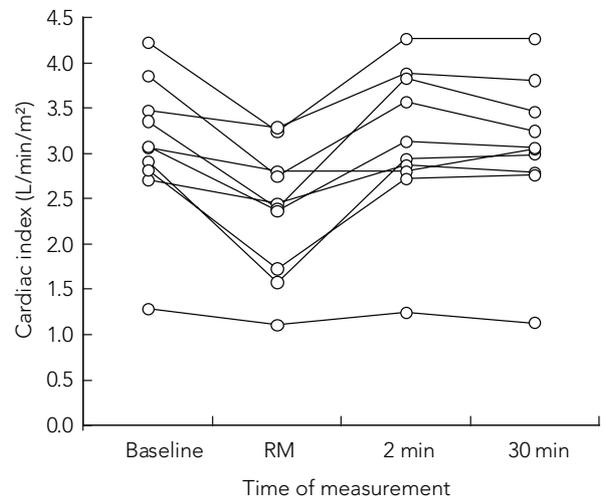
Eleven consecutive patients were studied (six men and five women). The data for one patient whose RM was aborted because of severe hypotension were excluded from the analysis. Clinical and epidemiological characteristics of the patients are shown in Table 1. Extrapulmonary illnesses were the cause of ARDS in 5 patients. The patients had been mechanically ventilated for a mean of 2.5 (SD, 2.0) days before the RM. Ventilatory settings were as follows:

Table 2: Effects of recruitment manoeuvre (RM) on arterial blood gases, gas exchange, pulmonary compliance and oxygen transport variables*

	Baseline	2 min after RM	30 min after RM
pH	7.24 (0.22)	7.24 (0.22)	7.25 (0.23)
PaCO ₂ mmHg	44 (14)	43 (13)	42 (13) [†]
kPa	5.86 (1.86)	5.73 (1.73)	5.59 (1.73)
PaO ₂ mmHg	92 (19)	102 (23)	98 (20)
kPa	12.26 (2.53)	13.59 (3.06)	13 (2.66)
PaO ₂ /FIO ₂	214 (71)	218 (75)	212 (78)
V _D /V _T (%)	74 (8)	73 (7)	72 (7)
Pa-ETCO ₂ mmHg	15 (13)	13 (12) [†]	14 (12) [†]
kPa	1.99 (1.73)	1.73 (1.59)	1.86 (1.59)
Q _{VA} /Q _T (%)	26 (10)	25 (10)	24 (10)
C _{RS} (mL/cmH ₂ O)	32 (8)	32 (11)	33 (9)
Ca-vO ₂ (vol %)	3.3 (0.7)	3.5 (0.7)	3.6 (0.6) [†]
DO ₂ (mL/min/m ²)	363 (110)	389 (126)	381 (122)
VO ₂ (mL/min/m ²)	100 (35)	107 (36)	108 (38) [†]

Ca-vO₂ = arterial-mixed venous oxygen content gradient. C_{RS} = quasistatic compliance of respiratory system. DO₂ = oxygen delivery. FIO₂ = fraction of inspired oxygen. PaCO₂ = arterial partial pressure of carbon dioxide. Pa-ETCO₂ = arterial minus end-tidal partial pressure of carbon dioxide gradient. PaO₂ = arterial partial pressure of oxygen. Q_{VA}/Q_T = venous admixture. V_D/V_T = dead space to tidal volume ratio. VO₂ = oxygen consumption. * Data are mean (SD). † P < 0.05 v baseline.

Figure 1. Individual behaviour of cardiac index



Cardiac index decreased during the recruitment manoeuvre (RM), and then returned to baseline values, at 2 and 30 minutes after the RM, in most of the patients.

Table 3. Effect of recruitment manoeuvre (RM) on haemodynamic measurements*

	Baseline	During RM	2 min after RM	30 min after RM
Systolic BP (mmHg)	131 (15)	104 (25) [†]	121 (12)	126 (15)
Diastolic BP (mmHg)	64 (14)	63 (24)	61 (12)	62 (14)
Mean arterial BP (mmHg)	85 (16)	75 (21)	80 (12)	82 (17)
Right atrial pressure (mmHg)	10 (3)	— [‡]	10 (4)	9 (3)
Pulmonary artery occlusion pressure (mmHg)	14 (4)	— [‡]	13 (4)	14 (4)
Pulse pressure (mmHg)	67 (13)	41 (18) [†]	60 (17)	65 (10)
Heart rate (beats/min)	103 (19)	103 (17)	104 (17)	100 (15)
Cardiac index (L/min/m ²)	3.1 (0.8)	2.4 (0.7) [†]	3.1 (0.9)	3.1 (0.8)

BP = blood pressure. * Data are mean (SD). † $P < 0.05$ v baseline.
‡ Not measured.

mean V_T , 5.7 (SD, 1.5) mL/kg; mean PEEP, 14 (SD, 3) cmH₂O; and mean F_{iO_2} , 0.51 (SD, 0.20).

P_{aO_2} remained unchanged during the study. There was a small, though statistically significant, decrease in P_{aCO_2} and Pa–ETCO₂ gradient at 2 and 30 minutes after the RM ($P < 0.05$). V_D/V_T and Q_{VA}/Q_T remained unchanged (Table 2).

Cardiac output decreased by 23% (SD, 13%) during the RM, and then returned to basal values (Figure 1). The systolic and pulse blood pressures also dropped during the RM and rapidly normalised afterwards. The mean and diastolic blood pressures did not change throughout the study. PAOP and right atrial pressure also remained unchanged (Table 3).

V_{O_2} showed a small but significant increase after the RM, accompanied by an increase in Ca– v_{O_2} ($P < 0.05$) (Table 2).

Discussion

Our main finding was that the RM induced a transitory but significant reduction in cardiac output and systolic blood pressure.

Despite an initial enthusiasm about the helpful effects of RMs on oxygenation, several studies have challenged their usefulness.¹⁵ The effects depend on the underlying condition of the lungs, the particular recruitment technique applied, and the level of PEEP and V_T used before and after the manoeuvre.¹⁶ Our study confirmed previous evidence of

a lack of success of RMs when the intervention is superimposed on protective ventilation along with high levels of PEEP. Our patients were ventilated with a low tidal volume and high levels of PEEP. This setting could well have produced a nearly complete recruitment of the lung, and thus the application of the manoeuvre did not result in any improvement in P_{aO_2} values.

In spite of the large number of studies evaluating RMs, information related to haemodynamic changes is scarce. In addition, results from animal models are controversial. Some authors have found increases in pulmonary vascular resistance,¹⁷ or transient decreases in cardiac output, oxygen delivery and mean arterial blood pressure during RMs, especially within the context of endotoxin-induced lung injury.^{18–20} However, previous volume expansion partially attenuated these effects. Slow-to-moderate RMs have resulted in significantly less circulatory compromise, suggesting that a more sustained low-pressure recruitment method would be safer.²¹ Nielsen and colleagues studied the effects of two RMs on central haemodynamics during hypo-, hyper- and normovolaemia in a pig model of ALI.²² Using echocardiography and continuous pulmonary flow measurements, they found a significant decrease in cardiac output that was more pronounced in hypovolaemia. In addition, they observed severe right ventricular dysfunction. By contrast, Fujino and colleagues²³ found no such haemodynamic changes in a sheep model.

Clinical studies have shown detrimental haemodynamic effects after an RM in patients with ALI. These changes ranged from mild hypotension and low oxygen saturation,⁹ with a transient decrease in systolic blood pressure and oxygen saturation,^{24,25} to a marked decrease in cardiac output in otherwise haemodynamically stable patients.²⁶ In contrast, another study of patients with ARDS found an increase in mean arterial blood pressure and heart rate with no change in cardiac output.²⁷

Only three studies of patients with ALI/ARDS have investigated changes in cardiac output during RMs. In most studies that have suggested that RMs are safe, the haemodynamic measurements were performed some minutes after, but not during, the manoeuvre. Grasso and colleagues found that changes in cardiac output during RMs were related to chest wall stiffness.¹¹ In a study of 22 patients with ARDS, they found that only patients with low time in mechanical ventilation and higher chest wall compliance were responsive to RMs. In the group with stiff chest walls, the RMs induced overdistension along with a reduced blood pressure and cardiac output, whereas these parameters were not affected in responders. The authors speculated that in patients with a stiff chest wall, the airway pressures are transmitted to pleural pressure to a greater extent and thus reduce the gradient for venous return. They

suggested that in under-resuscitated patients RMs might produce haemodynamic instability. By contrast, in studies by Villagra et al¹² and Talmor et al,²⁸ no haemodynamic changes were observed either during or after RM. The different type of RMs applied might explain the discrepancies between these studies. Our patients experienced drops in blood pressure and cardiac output despite adequate volume resuscitation (as suggested by normal/high values of PAOP and right atrial pressure). However, the impact of chest wall compliance on haemodynamics could not be evaluated because of the lack of measurements of pleural pressure.

Haemodynamic changes during RMs are secondary to an increased intrathoracic pressure, which compresses the right atrium and pulmonary vessels, thereby impeding venous return to the heart and outflow from the right ventricle. Because of the ventricular interdependency, these events lead to a reduced left ventricular stroke volume. At the same time, hyperinflation passively compresses the alveolar vessels, thus increasing pulmonary vascular resistance, which in turn leads to acute pulmonary hypertension and precipitates acute right ventricular failure and right ventricular ischaemia. However, pulmonary vascular resistance may decrease if the RM or PEEP can reverse the hypoxic pulmonary vasoconstriction by restoring lung volumes. In addition, hyperinflation of the lungs may induce bradycardia and a negative inotropic response through a vagal afferent reflex. Finally, decreased chest wall compliance allows the airway pressure to be transmitted to the intrathoracic pressure, leading to more striking haemodynamic changes.¹³ Thus, the effectiveness of the manoeuvre and its haemodynamic results will be influenced by the type of RM, as well as chest wall compliance, volume status, baseline levels of PEEP and cardiac function.

We found that, despite a large fall in cardiac output during the manoeuvre, cardiac output rapidly returned to baseline levels after 2 minutes. In addition, Vo_2 and $Ca-vO_2$ increased 2 minutes after the manoeuvre and remained high at 30 minutes after the procedure. A possible explanation for these changes would be the repayment of an oxygen debt acquired during the RM.

We found a small but statistically significant decrease in arterial P_{CO_2} and $Pa-ETCO_2$ at 30 minutes after the RM. A non-significant decrease in dead space was also seen. In our group of patients, the baseline values of $Pa-ETCO_2$ were high (15 [SD, 13] mmHg), reflecting the severity of the ventilation-to-perfusion ratio (V_A/Q_T) mismatching. The application of external PEEP may result in alveolar recruitment and redistribution of pulmonary blood flow, with a decrease in the intrapulmonary shunt. The fall in $Pa-ETCO_2$

might be interpreted as a result of some alveolar recruitment because it was produced by a decreased arterial P_{CO_2} .

Some authors have found differences when using diverse RMs such as sustained inflation (SI), incremental PEEP, or pressure-controlled ventilation (PCV). Odenstedt and colleagues showed less circulatory depression with slow-to-moderate RMs compared with PCV or SI.²¹ Lim and colleagues found that SI, incremental PEEP and PCV all depressed cardiac output, but the reduction was greater with SI.¹⁸ Both studies noted mild improvements in oxygen exchange. However, these effects were rapidly lost. A systematic review of RM in patients with ALI showed that all the manoeuvres induce some degree of cardiovascular compromise as well as transient improvements in gas exchange.²⁹

An important limitation of our study was the small number of subjects and the application of only one manoeuvre. We can not predict whether a larger number of patients, higher levels of CPAP or the repetitive application of RM would have produced different results. Moreover, as we did not perform measurements of chest wall compliance, it was not possible to analyse its influence on haemodynamics.

In summary, in our small group of patients with ALI/ARDS ventilated with high levels of PEEP in a protective strategy, the RM induced deleterious effects on haemodynamics and failed to improve oxygen exchange.

Author details

Vanina S Kanoore Edul, Investigator,¹ and Staff Physician²

Luis P Maskin, Staff Physician³

Arnaldo Dubin, Associate Professor,¹ and Director²

1 Cátedra de Farmacología Aplicada, Facultad de Ciencias Médicas, Universidad Nacional de La Plata, La Plata, Argentina.

2 Servicio de Terapia Intensiva, Sanatorio Otamendi y Miroli, Buenos Aires, Argentina.

3 Servicio de Terapia Intensiva, CEMIC, Buenos Aires, Argentina.

Correspondence: terapia@sanatorio-otamendi.com.ar

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