

# Lung recruitment

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## Effect of lung recruitment and titrated positive end-expiratory pressure (PEEP) vs. low PEEP on mortality in patients with acute respiratory distress syndrome: A randomized clinical trial.

Writing group for the alveolar recruitment for acute respiratory distress syndrome trial (ART) Investigators, Cavalcanti AB, Suzumura ÉA, Laranjeira LN, Paisani DM, Damiani LP, Guimarães HP, Romano ER, Regenga MM, Taniguchi LNT, Teixeira C, Pinheiro de Oliveira R, Machado FR, Diaz-Quijano FA, Filho MSA, Maia IS, Caser EB, Filho WO, Borges MC, Martins PA, Matsui M, Ospina-Tascón GA, Giancursi TS, Giraldo-Ramirez ND, Vieira SRR, Assef MDGPL, Hasan MS, Szczeklik W, Rios F, Amato MBP, Berwanger O, Ribeiro de Carvalho CR.

JAMA. 2017 Oct 10;318(14):1335-1345

PMID 28973363, <http://www.ncbi.nlm.nih.gov/pubmed/28973363>

<b>Design</b>	Multicenter, randomized trial conducted at 120 ICU, 9 countries
<b>Patients</b>	1010 moderate to severe ARDS
<b>Objectives</b>	Determine if RM (recruitment maneuver) with PEEP titration according to the best respiratory-system compliance decreases 28-day mortality
<b>Main Results</b>	Experimental group strategy had an increase in 6-month mortality (65.3% vs. 59.9%; $p = 0.04$ ), a decrease in the number of mean ventilator-free days (5.3 vs. 6.4; $p = 0.03$ ), and an increase in the risk of barotrauma and in the risk of pneumothorax requiring drainage. There were no significant differences in the length of ICU stay, length of hospital stay, ICU mortality, and in-hospital mortality.
<b>Conclusion</b>	A strategy with lung recruitment and titrated PEEP compared with low PEEP increased 28-day all-cause mortality
<b>Comment</b>	A lot of limitations: - COPD and emphysema were not contraindicated and they have an increased risk of pneumothorax - Recruitability was not assessed before the RM and most of the patients (>60%) had a pulmonary ARDS (usually less recruitable), the ART trial did not distinguish between responders and non-responders - The staircase RM is a prolonged increase in pressure with high level of pressure. A mean reduction in driving pressure of only 2 cmH <sub>2</sub> O was found, indicating that the recruitment maneuver was inadequate to open up the lung and increase functional residual capacity in most patients. - Mortality is 60% vs. supposed 36% - Only 10% of the patients were in prone position - Inclusion from november 2011 to April 2017 = 66 month i.e 3 patients /month with 120 ICU - Double triggering and breath stacking was very likely common due to tidal volumes <6ml/kg - Patients were evaluated under a standardized ventilator setting using PEEP ≥10 and FiO <sub>2</sub> = 1 for 30 min. Only patients with a persistent PaO <sub>2</sub> /FiO <sub>2</sub> ≤200 were eligible for randomization.

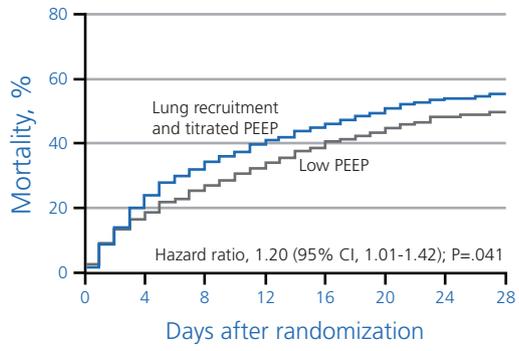


Figure 1: Kaplan Meier curve shows an increase in mortality in RM group

## Effect of intensive vs moderate alveolar recruitment strategies added to lung-protective ventilation on postoperative pulmonary complications: a randomized clinical trial

Costa Leme A, Hajjar LA, Volpe MS, Fukushima JT, De Santis Santiago RR, Osawa EA, Pinheiro de Almeida J, Gerent AM, Franco RA, Zanetti Feltrim MI, Nozawa E, de Moraes Coimbra VR, de Moraes Ianotti R, Hashizume CS, Kalil Filho R, Auler JO Jr, Jatene FB, Gomes Galas FR, Amato MB

JAMA. 2017 Apr 11;317(14):1422-1432

PMID 28322416, <http://www.ncbi.nlm.nih.gov/pubmed/28322416>

<b>Design</b>	Prospective randomized trial: intensive (high-pressure recruitment maneuver and PEEP = 13 cmH <sub>2</sub> O) or moderate (low-pressure recruitment maneuver and PEEP = 8 cmH <sub>2</sub> O) recruitment strategy
<b>Patients</b>	320 hypoxemic patients after cardiac surgery
<b>Objectives</b>	Assess the effect of an intensive alveolar recruitment strategy on postoperative pulmonary complications in patients receiving lung-protective ventilation with small tidal volumes
<b>Main Results</b>	The intensive recruitment strategy group had a mean 1.8 (1.7-2.0) and a median 1.7 (1.0-2.0) pulmonary complications score versus 2.1 (2.0-2.3) and 2.0 (1.5-3.0) for the moderate strategy group. The mean hospital stay for the intensive group was 10.9 days versus 12.4 days in the moderate group (p = 0.04). The mean ICU stay for the intensive group was 3.8 days versus 4.8 days for the moderate group (p = 0.01). Hospital mortality was 2.5% in the intensive group versus 4.9% in the moderate group (p > 0.05).
<b>Conclusion</b>	Among patients with hypoxemia after cardiac surgery, the use of an intensive alveolar recruitment strategy resulted in fewer severe pulmonary complications than a moderate recruitment strategy.
<b>Comment</b>	This study assesses the effect of an intensive recruitment strategy on complications in post-cardiac surgery patients

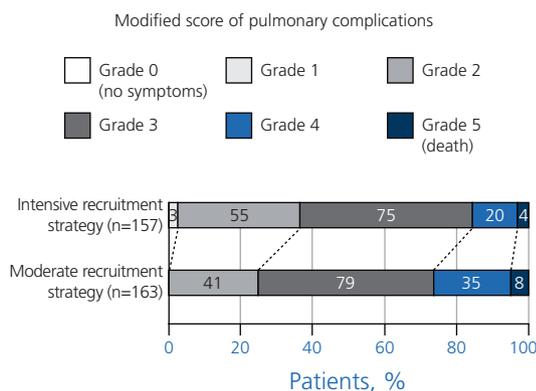


Figure 2: The severity and occurrence of postoperative pulmonary complications were reduced by use of an intensive recruitment strategy

## Open lung approach for the acute respiratory distress syndrome: A pilot, randomized controlled trial

Kacmarek RM, Villar J, Sulemanji D, Montiel R, Ferrando C, Blanco J, Koh Y, Soler JA, Martínez D, Hernández M, Tucci M, Borges JB, Lubillo S, Santos A, Araujo JB, Amato MB, Suárez-Sipmann F

Open Lung Approach Network. Crit Care Med. 2016 Jan;44(1):32-42

PMID 26672923, <http://www.ncbi.nlm.nih.gov/pubmed/26672923>

<b>Design</b>	Prospective, multicenter, pilot, randomized controlled trial
<b>Patients</b>	200 moderate to severe early onset ARDS
<b>Objectives</b>	Compared the ARDSnet protocol using low levels of PEEP with open lung approach (OLA = recruitment maneuver and decremental PEEP trial based on the best compliance)
<b>Main Results</b>	Mortality at day 60 (29% OLA vs. 33% ARDSnet protocol, $p=0.18$ ), ICU mortality (25% OLA vs. 30% ARDSnet protocol, $p = 0.53$ ), and ventilator-free days (8 [0-20] OLA vs. 7 [0-20] d ARDSnet protocol, $p = 0.53$ ) were not significantly different. Airway driving pressure and $\text{PaO}_2/\text{FIO}_2$ improved significantly at 24, 48 and 72 hours in patients in OLA compared with patients in ARDSnet protocol
<b>Conclusion</b>	OLA improved oxygenation and driving pressure

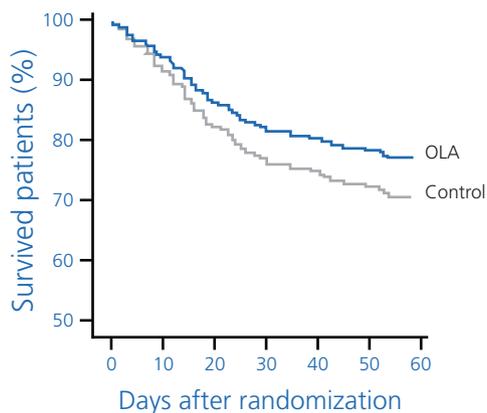


Figure 3: OLA was associated with better survival (with no statistically significant difference) in this pilot study, but a large, randomized controlled trial should be performed to compare outcomes between OLA and the ARDSnet protocol

# How large is the lung recruitability in early acute respiratory distress syndrome: a prospective case series of patients monitored by computed tomography

de Matos GF, Stanzani F, Passos RH, Fontana MF, Albaladejo R, Caserta RE, Santos DC, Borges JB, Amato MB, Barbas CS

Crit Care. 2012 Jan 8;16(1):R4

PMID 22226331, <http://www.ncbi.nlm.nih.gov/pubmed/22226331>

<b>Design</b>	Prospective interventional study: Maximal recruitment strategy, staircase RM (recruitment maneuver) up to 45 cmH2O
<b>Patients</b>	51 early severe ARDS patients
<b>Objectives</b>	Describes the effects of maximal recruitment strategy
<b>Main Results</b>	The opening plateau-pressure was $60 \pm 6$ cmH2O. Mean PaO <sub>2</sub> /FiO <sub>2</sub> ratio increased from $125 \pm 43$ to $300 \pm 103$ after RM and was sustained above 300 throughout seven days. Non-aerated parenchyma decreased significantly from 54% [42-62] to 13% [5-24] RM. The potentially recruitable lung was estimated at 45% [25-53]. ICU mortality = 28% and hospital mortality = 33%.
<b>Conclusion</b>	MR reversed hypoxemia and most of the collapsed lung tissue during the early stage of ARDS

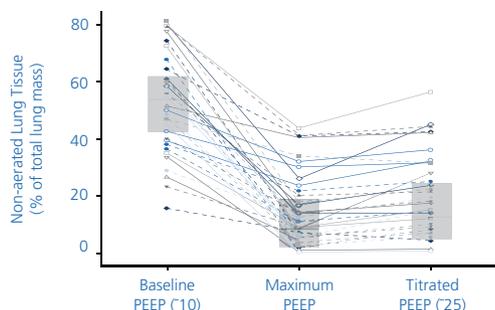
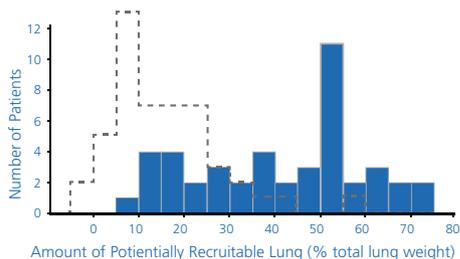


Figure 4: RM following by PEEP titration allowed to decrease the non aerated tissue. Potential of recruitability is variable among ARDS patients and seems higher in early onset ARDS patients (grey histogram) than late ARDS patient (dashed lines)



## Optimal duration of a sustained inflation recruitment maneuver in ARDS patients

Arnal JM, Paquet J, Wysocki M, Demory D, Donati S, Granier I, Corno G, Durand-Gasselín J

Intensive Care Med. 2011 Oct;37(10):1588-94

PMID 21858522, <http://www.ncbi.nlm.nih.gov/pubmed/21858522>

<b>Design</b>	Prospective interventional study: 30 seconds sustained inflation at 40 cmH <sub>2</sub> O
<b>Patients</b>	50 early ARDS patients
<b>Objectives</b>	Measure the dynamics of recruitment and the hemodynamic status during RM (recruitment maneuver)
<b>Main Results</b>	The average volume increase was 210 ±198 ml. Time constant was 2.3 ±1.3 s. Systolic and mean arterial pressures were maintained at 10 s, decreased significantly at 20 and 30 s during the RM, and recovered to the pre-RM value 30 s after the end of the RM. Heart rate, diastolic arterial pressure, and SpO <sub>2</sub> did not change during or after the RM.
<b>Conclusion</b>	Most of the recruitment occurred during the first 10 s and hemodynamic impairment was significant after 10 s = The optimal duration of RM by sustained inflation is around 10 s

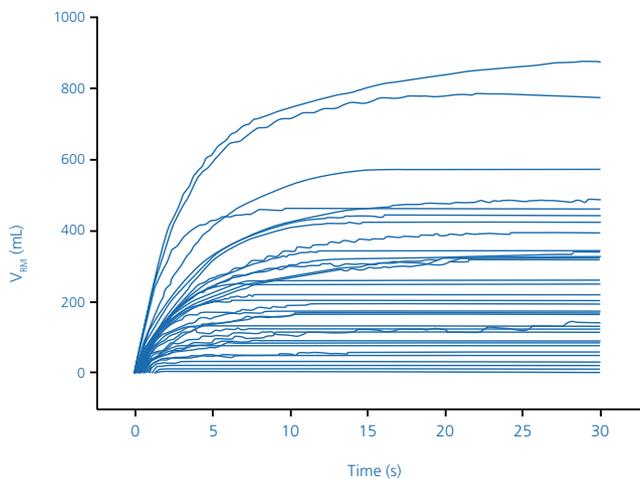


Figure 5: Individual curves of sustained inflation showed that 10 seconds were sufficient to achieve the maximal increase in volume

## Prone position and recruitment manoeuvre: the combined effect improves oxygenation

Rival G, Patry C, Floret N, Navellou JC, Belle E, Capellier G

Crit Care. 2011 May;15(3):R125

PMID 21575205, <http://www.ncbi.nlm.nih.gov/pubmed/21575205>

<b>Design</b>	Prospective interventional study: Each patient was ventilated 6h in both the supine position (SP) and the prone position (PP). A 45 cmH <sub>2</sub> O extended sigh in PC was performed at the beginning of SP RM1 (recruitment maneuver), one hour after turning to the PP (RM2) and at the end of the 6h PP period (RM3).
<b>Patients</b>	16 early ARDS patients
<b>Objectives</b>	Study the effects on oxygenation of both RM and PP
<b>Main Results</b>	Improvements in PaO <sub>2</sub> level and PaO <sub>2</sub> /FiO <sub>2</sub> ratio were transient in SP but durable during PP. PaO <sub>2</sub> /FiO <sub>2</sub> changes were significant only after RM3. This global strategy had a benefit with regard to oxygenation: PaO <sub>2</sub> /FiO <sub>2</sub> ratio increased from 98 mmHg to 166 mmHg 13 hours later at the end of the study. Pplat (plateau pressure) at decreased after each RM and over the entire PP period.
<b>Conclusion</b>	Combined RM and PP increased oxygenation
<b>Comment</b>	This RM method is associated with high VT with a risk of volutrauma.

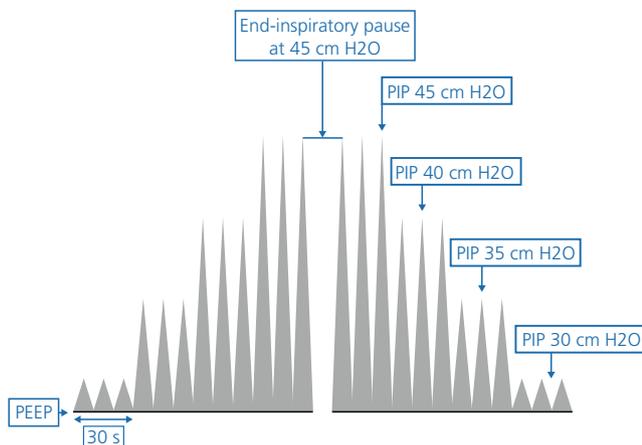


Figure 6: Recruitment protocol in pressure control ventilation: increase of P<sub>insp</sub> by 5 cmH<sub>2</sub>O every 30s, to 45 cmH<sub>2</sub>O; then a 30 s pause is performed; then P<sub>insp</sub> is decrease by 5 cmH<sub>2</sub>O every 30 s to baseline.

# Clinical efficacy and safety of recruitment maneuver in patients with acute respiratory distress syndrome using low tidal volume ventilation: a multicentre randomized controlled clinical trial

Xi XM, Jiang L, Zhu B; RM group

Chin Med J. 2010 Nov;123(21):3100-5

PMID 21162963, <http://www.ncbi.nlm.nih.gov/pubmed/21162963>

**Design** Multicenter RCT: 40 seconds sustained inflation at 40 cmH<sub>2</sub>O/8 h during 5 days versus no RM (recruitment maneuver)

**Patients** 110 ARDS patients

**Objectives** Evaluate the clinical efficacy and safety of RM

**Main Results** In the RM group the PaO<sub>2</sub>/FiO<sub>2</sub> was increased compared to baseline on day one and day two (P = 0.007 and P = 0.001). There were no significant differences in hospital mortality, 28-day mortality and ventilator-free days at day 28. ICU mortality (32.7% vs. 52.7%), the rate of survival with unassisted breathing for at least 48 consecutive hours at day 28 (58.2% vs. 36.2%) and nonpulmonary organ failure-free days at day 28 (17 ±11 vs. 13 ±12) favored the RM group.

**Conclusion** RM had beneficial impact on clinical outcome

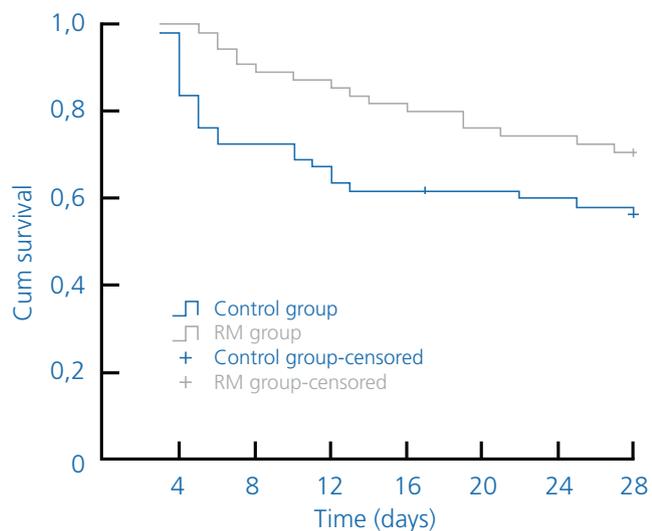


Figure 7: RM increased survival in ARDS patients

## A recruitment maneuver increases oxygenation after intubation of hypoxemic intensive care unit patients: a randomized controlled study

Constantin JM, Futier E, Cherprenet AL, Chanques G, Guerin R, Cayot-Constantin S, Jabaudon M, Perbet S, Chartier C, Jung B, Guelon D, Jaber S, Bazin JE

Crit Care. 2010 Apr;14(2):R76

PMID 20426859, <http://www.ncbi.nlm.nih.gov/pubmed/20426859>

<b>Design</b>	RCT: 30 seconds sustained inflation at 40 cmH <sub>2</sub> O versus no RM (recruitment maneuver)
<b>Patients</b>	40 patients intubated for acute hypoxemic respiratory failure
<b>Objectives</b>	Evaluate the efficacy and safety of RMs performed immediately after intubation
<b>Main Results</b>	5 min after intubation, PaO <sub>2</sub> obtained under 100% FiO <sub>2</sub> was significantly higher in the RM group compared with the control group (93 ±36 vs 236 ±117 mmHg). The difference remained significant at 30 minutes with 110 ±39 and 180 ±79 mmHg, respectively, for the control and RM groups. RM was not associated with increased adverse effects.
<b>Conclusion</b>	RM following intubation in hypoxemic patients improved oxygenation

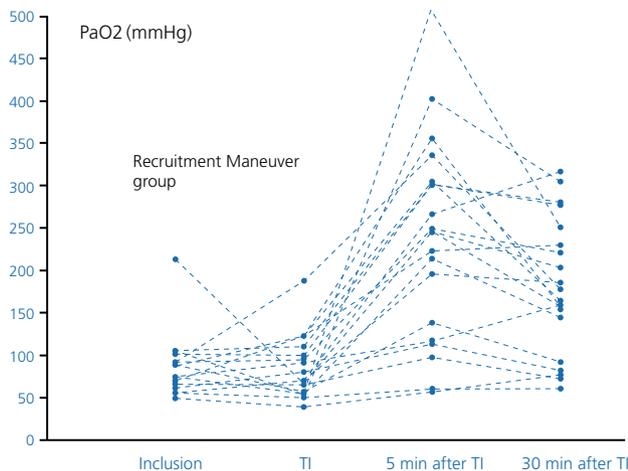


Figure 8: RM after intubation increased oxygenation, and oxygenation remained high after 30 min

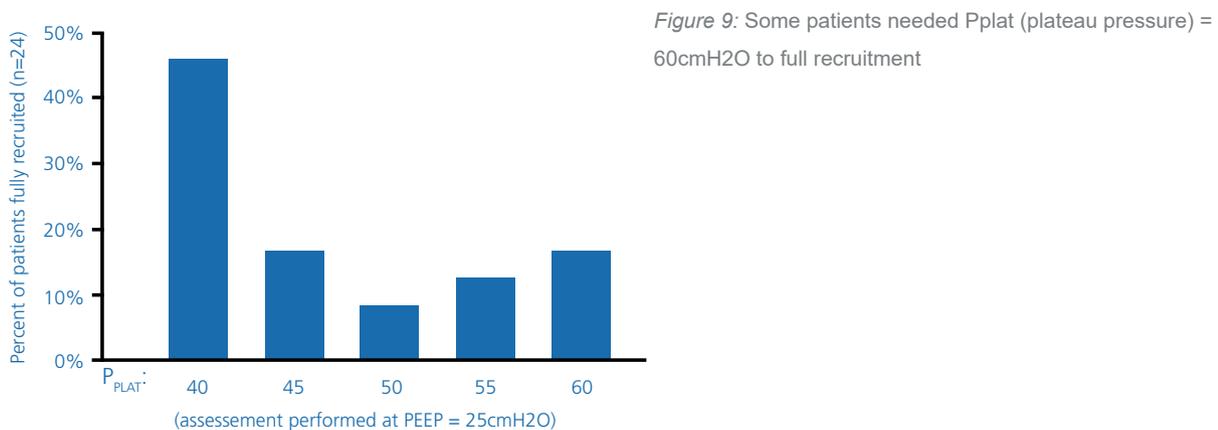
## Reversibility of lung collapse and hypoxemia in early acute respiratory distress syndrome

Borges JB, Okamoto VN, Matos GF, Caramez MP, Arantes PR, Barros F, Souza CE, Victorino JA, Kacmarek RM, Barbas CS, Carvalho CR, Amato MB

Am J Respir Crit Care Med. 2006 Aug 1;174(3):268-78

PMID 16690982, <http://www.ncbi.nlm.nih.gov/pubmed/16690982>

<b>Design</b>	Prospective interventional study: Maximal recruitment strategy, staircase RM (recruitment maneuver) up to 45 cmH <sub>2</sub> O
<b>Patients</b>	26 ARDS patients
<b>Objectives</b>	Test if RM is clinically applicable in early ARDS
<b>Main Results</b>	There was an improvement in oxygenation and reduction in the percent mass of collapsed tissue between P <sub>aw</sub> (airway pressure) = 40 and 60 cmH <sub>2</sub> O.
<b>Conclusion</b>	In early ARDS it was possible to open the lung in the majority of patients



## Lung recruitment in patients with the acute respiratory distress syndrome

Gattinoni L, Caironi P, Cressoni M, Chiumello D, Ranieri VM, Quintel M, Russo S, Patroniti N, Cornejo R, Bugeo G

N Engl J Med. 2006 Apr 27;354(17):1775-86

PMID 16641394, <http://www.ncbi.nlm.nih.gov/pubmed/16641394>

**Design** Prospective interventional study: PC with Pplat (plateau pressure) = 45 cmH2O

**Patients** 68 ARDS patients

**Objectives** Examine the relationship between the percentage of potentially recruitable lung and the clinical and physiological effects of RM (recruitment maneuver)

**Main Results** Patients with a higher percentage of potentially recruitable lung had greater total lung weights, poorer oxygenation, lower Crs (compliance of respiratory system), higher levels of dead space and higher rates of death than patients with a lower percentage of potentially recruitable lung.

**Conclusion** In ARDS, the percentage of potentially recruitable lung is extremely variable and is strongly associated with the response to PEEP

**Comment** PEEP was not set according to recruitability. Setting low PEEP in patient with high potential of recruitable lung increases VILI and mortality.

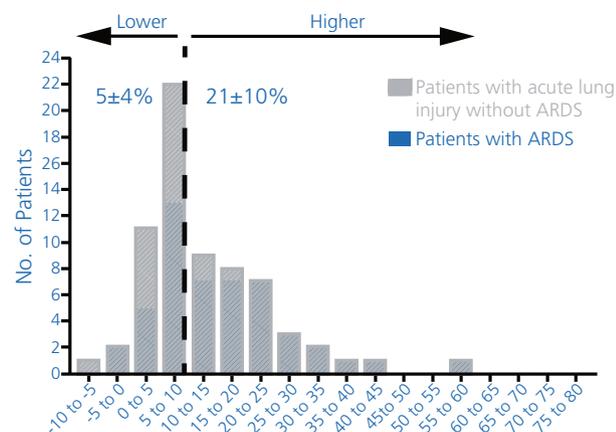
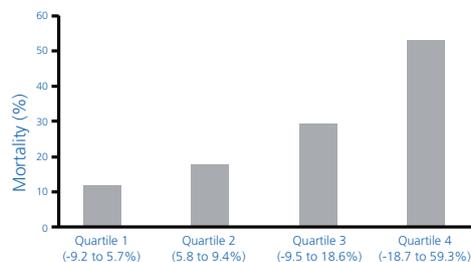


Figure 10: The potential of recruitability is different from patient to patient in ARDS. The patient with the highest potential of recruitability are those with the worst prognosis

Amount of Potentially Recruitable Lung (% total lung weight)



# Lung computed tomography during a lung recruitment maneuver in patients with acute lung injury

Bugedo G, Bruhn A, Hernández G, Rojas G, Varela C, Tapia JC, Castillo L

Intensive Care Med. 2003 Feb;29(2):218-25

PMID 12536272, <http://www.ncbi.nlm.nih.gov/pubmed/12536272>

<b>Design</b>	Prospective interventional study: Staircase RM (recruitment maneuver) up to 30-40 cmH2O
<b>Patients</b>	10 ARDS patients
<b>Objectives</b>	Assess the acute effect of a RM on lung morphology
<b>Main Results</b>	Poorly aerated and non-aerated tissue at PEEP 10 cmH2O = 60 ±9% of lung parenchyma, 1 ±2% was hyperinflated. Increasing PEEP to 20 and 30 cmH2O, compared to PEEP 10 cmH2O, decreased poorly aerated and non-aerated tissue by 16 ±28% and 33 ±14%. Hyperinflated tissue increased up to 3 ±4% with PEEP 30 cmH2O.
<b>Conclusion</b>	RM recruited collapsed alveoli without inducing too much hyperinflation

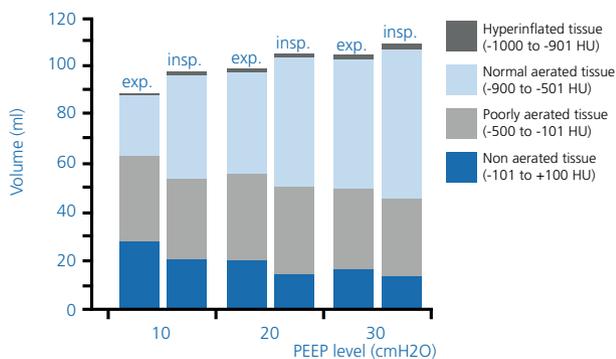


Figure 11: Increasing PEEP, decreased the non aerated tissue without increase of hyperinflated tissue

# Effects of recruiting maneuvers in patients with acute respiratory distress syndrome ventilated with protective ventilatory strategy

Grasso S, Mascia L, Del Turco M, Malacarne P, Giunta F, Brochard L, Slutsky AS, Marco Ranieri V  
 Anesthesiology. 2002 Apr;96(4):795-802  
 PMID 11964585, <http://www.ncbi.nlm.nih.gov/pubmed/11964585>

<b>Design</b>	Prospective interventional study: 40 seconds sustained inflation at 40 cmH2O
<b>Patients</b>	22 ARDS patients. Patients were classified as responders and nonresponders on the occurrence of a 50% increase in PaO <sub>2</sub> /FiO <sub>2</sub>
<b>Objectives</b>	Assess the influence of the elastic properties of the lung and chest wall on the effectiveness of a RM (recruitment maneuver).
<b>Main Results</b>	RM increased PaO <sub>2</sub> /FiO <sub>2</sub> by 20 ±3% in nonresponders (n = 11) and by 175 ±23% (n = 11) in responders. El (elastance of lung) and E <sub>cw</sub> (elastance of chest wall) were higher in nonresponders. Cardiac output and mean arterial pressure decreased by 31 ±2 and 19 ±3% in nonresponders and by 2 ±1 and 2 ±1% in responders.
<b>Conclusion</b>	RM improved oxygenation and was well tolerated in patients who do not have impairment of chest wall mechanics

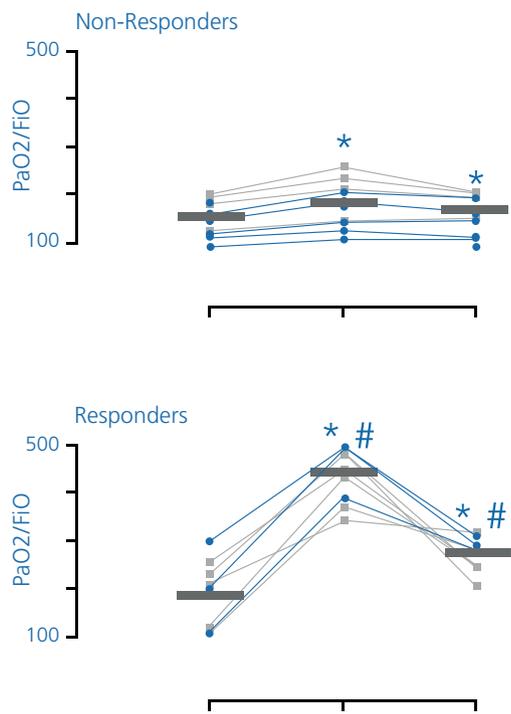


Figure 12: Some patients increased SpO<sub>2</sub> during RM, they were called "Responders" and the others didn't increase SpO<sub>2</sub>, the "Non-responders"

## Recruitment maneuvers: using transpulmonary pressure to help Goldilocks

Baedorf Kassis E, Loring S, Talmor D.

Intensive Care Med. 2017 Aug;43(8):1162-1163

PMID 28386726, <http://www.ncbi.nlm.nih.gov/pubmed/28386726>

<b>Design</b>	Post hoc analysis of EPVent study
<b>Patients</b>	28 patients
<b>Objectives</b>	Measure the change in lung elastance during recruitment: A decrease in elastance of lung (negative $\Delta EL$ ) was considered evidence of recruitment and an increase in elastance of lung (positive $\Delta EL$ ) evidence of overdistension.
<b>Main Results</b>	Recruited volume was dependent on transpulmonary pressure during the maneuver and inversely dependent on $\Delta EL$ (elastance of lung): - $\Delta EL$ was positive during recruitment in patients with PL,RM (peak transpulmonary pressure) $\geq 20$ cmH <sub>2</sub> O - $\Delta EL$ was negative when PL,RM was between 10 and 20 cmH <sub>2</sub> O - $\Delta EL$ was negligible in patients with PL,RM below 10 cmH <sub>2</sub> O
<b>Conclusion</b>	The optimal “window” where sufficient pressure expands the lung, optimizes elastance, and avoids overdistension is between 10 and 20 cmH <sub>2</sub> O
<b>Comment</b>	Transpulmonary pressure helps to determine the pressure that is efficient and safe to perform a recruitment maneuver

## Impact of recruitment on static and dynamic lung strain in acute respiratory distress syndrome

García-Prieto E, López-Aguilar J, Parra-Ruiz D, Amado-Rodríguez L, López-Alonso I, Blázquez-Prieto J, Blanch L, Albaiceta GM

Anesthesiology. 2016 Feb;124(2):443-52

PMID 26569171, <http://www.ncbi.nlm.nih.gov/pubmed/26569171>

<b>Design</b>	Animal study and prospective physiological study
<b>Patients</b>	6 oleic acid-injured pigs and 6 patients with moderate-to-severe ARDS
<b>Objectives</b>	Clarify the role of recruitment in strain measurements defined as the ratio between end-inspiratory volume and functional residual capacity
<b>Main Results</b>	In the animal model, recruitment caused a significant decrease in dynamic strain ( $p < 0.01$ ), while increasing the static component. In patients, total strain remained constant for the three ventilatory settings. Increases in tidal volume had no significant effects. Increasing PEEP constantly decreased dynamic strain ( $p < 0.05$ ) and increased static strain ( $p < 0.05$ ). The changes in dynamic and total strain among patients were correlated to the amount of recruited volume.
<b>Conclusion</b>	Recruitment causes a shift from dynamic to static strain in early acute respiratory distress syndrome

## Volume delivered during recruitment maneuver predicts lung stress in acute respiratory distress syndrome

Beitler JR, Majumdar R, Hubmayr RD, Malhotra A, Thompson BT, Owens RL, Loring SH, Talmor D

Crit Care Med. 2016 Jan;44(1):91-9

PMID 26474111, <http://www.ncbi.nlm.nih.gov/pubmed/26474111>

<b>Design</b>	EPVent substudy
<b>Patients</b>	42 ARDS patients
<b>Objectives</b>	Determine whether the volume delivered during a recruitment maneuver (VRM), consisting of sustained inflation at 40 cmH <sub>2</sub> O for 30 s, is inversely associated with lung stress and mortality in acute respiratory distress syndrome
<b>Main Results</b>	VRM ranged between 7.4 and 34.7 ml/kg predicted body weight. Lower VRM predicted high end-inspiratory and tidal lung stress. Low VRM was also associated with an increased risk of death.
<b>Conclusion</b>	Low VRM predicted high lung stress and may predict risk of death in patients with acute respiratory distress syndrome
<b>Comment</b>	This study used VRM to assess the maximum size of the aerated lung to establish the potential recruitability

## Sigh in supine and prone position during acute respiratory distress syndrome

Pelosi P, Bottino N, Chiumello D, Caironi P, Panigada M, Gamberoni C, Colombo G, Bigatello LM, Gattinoni L

Am J Respir Crit Care Med. 2003 Feb 15;167(4):521-7

PMID 12493644, <http://www.ncbi.nlm.nih.gov/pubmed/12493644>

<b>Design</b>	Prospective interventional study: 3 sighs/min
<b>Patients</b>	10 early ARDS patients
<b>Objectives</b>	Evaluate recruitment in supine and prone position
<b>Main Results</b>	Sighs increased PaO <sub>2</sub> in both supine and prone position. The highest values of PaO <sub>2</sub> and EELV (end-expiratory lung volume) occurred with the addition of sighs in prone and remained significantly elevated 1 hour after discontinuation of the sighs. The increase in PaO <sub>2</sub> associated with the sighs, both in supine and prone position, correlated linearly with the increase of EELV.
<b>Conclusion</b>	RM (recruitment maneuver) during ventilation in the prone position provided optimal lung recruitment

## Opening pressures and atelectrauma in acute respiratory distress syndrome

Cressoni M, Chiumello D, Algieri I, Brioni M, Chiurazzi C, Colombo A, Colombo A, Crimella F, Guanziroli M, Tomic I, Tonetti T, Luca Vergani G, Carlesso E, Gasparovic V, Gattinoni L  
Intensive Care Med. 2017 May;43(5):603-611  
PMID 28283699, <http://www.ncbi.nlm.nih.gov/pubmed/28283699>

<b>Design</b>	Bicenter prospective study
<b>Patients</b>	33 ARDS: 5 mild, 10 moderate, 9 severe without ECMO, 9 severe with ECMO
<b>Objectives</b>	Measure the recruitment at different PEEP and plateau pressures
<b>Main Results</b>	The ratio of lung tissue which opened between 30 and 45 cmH <sub>2</sub> O increased with the severity of the disease between $10 \pm 29$ and $185 \pm 134$ g ( $p < 0.05$ ). The intratidal collapses were similar at a PEEP level of 5 cmH <sub>2</sub> O and 15 cmH <sub>2</sub> O, regardless of the severity. Increasing the applied airway pressure up to 45 cmH <sub>2</sub> O decreased the lung inhomogeneity in mild and moderate ARDS, but not in severe ARDS.
<b>Conclusion</b>	Patients with most severe ARDS are the most recruitable. For effective recruitment, pressures higher than 30 cmH <sub>2</sub> O are required

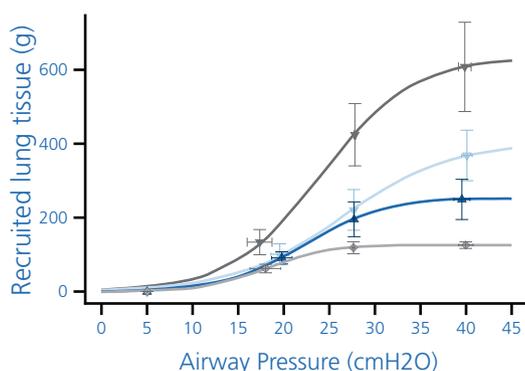


Figure 13: Light gray: mild ARDS; Dark blue: moderate ARDS; Light blue: severe ARDS without ECMO, Dark gray: severe ARDS with ECMO. The more severe the ARDS, the more recruitable the lungs

## Lung recruitment assessed by respiratory mechanics and computed tomography in patients with acute respiratory distress syndrome. What is the relationship?

Chiumello D, Marino A, Brioni M, Cigada I, Menga F, Colombo A, Crimella F, Algieri I, Cressoni M, Carlesso E, Gattinoni L.

Am J Respir Crit Care Med. 2016 Jun 1;193(11):1254-63

PMID 26699672, <http://www.ncbi.nlm.nih.gov/pubmed/26699672>

<b>Design</b>	Prospective interventional study
<b>Patients</b>	22 ARDS patients
<b>Objectives</b>	Determine recruitment measured by respiratory mechanics (PV curve and compliance) is comparable with recruitment measured by computed tomography
<b>Main Results</b>	Recruitment measured by PV curve was $54 \pm 28\%$ and $39 \pm 25\%$ using compliance of the gas volume at 5 cmH <sub>2</sub> O of PEEP. Recruitment measured by CT scan as not inflated tissue was $5 \pm 5\%$ and $6 \pm 6\%$ if we consider not and poorly inflated tissue, on the total lung tissue.
<b>Conclusion</b>	Respiratory mechanics and CT measured two different entities. The respiratory mechanics-based methods included gas entering in already open pulmonary units that improve their mechanical properties (used to assess the overall improvement of inflation). The CT scan measured the amount of collapsed tissue that regains inflation.

## A positive response to a recruitment maneuver with PEEP titration in patients with ARDS, regardless of transient oxygen desaturation during the maneuver

Hodgson CL, Tuxen DV, Bailey MJ, Holland AE, Keating JL, Pilcher D, Thomson KR, Varma D

J Intensive Care Med. 2011 Jan-Feb;26(1):41-9

PMID 21262752, <http://www.ncbi.nlm.nih.gov/pubmed/21262752>

<b>Design</b>	Prospective interventional study: Staircase RM (recruitment maneuver) up to 40 cmH <sub>2</sub> O
<b>Patients</b>	20 early ALI patients
<b>Objectives</b>	Evaluate the safety and the respiratory and hemodynamic effects of a staircase RM
<b>Main Results</b>	There were significant improvements in shunt fraction, oxygen saturation (93% ±2% to 97% ±3%), PaO <sub>2</sub> , PaO <sub>2</sub> /FiO <sub>2</sub> , Crs (compliance of respiratory system), and chest x-ray after the RM. 80% of the patients responded and the response was maintained at 1 hour. 8 patients desaturated 6% ±3% in SpO <sub>2</sub> during the RM but 5 of those improved SpO <sub>2</sub> relative to baseline by the end of the RM.
<b>Conclusion</b>	Most patients with early ALI responded to the RM. Desaturation during the RM did not indicate a failed response 1 h later.

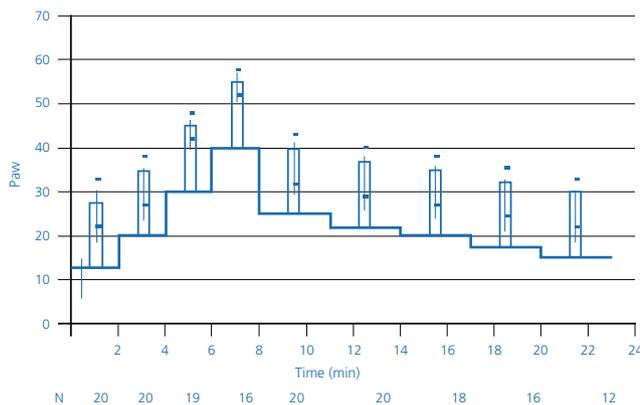


Figure 14: Staircase recruitment maneuver protocol: Increase of PEEP by 10 cmH<sub>2</sub>O to 40cmH<sub>2</sub>O, step = 2min; decrease by 2,5 cmH<sub>2</sub>O, step = 3 min until SpO<sub>2</sub> decrease

# Safety and efficacy of a sustained inflation for alveolar recruitment in adults with respiratory failure

Lapinsky SE, Aubin M, Mehta S, Boiteau P, Slutsky AS

Intensive Care Med. 1999 Nov;25(11):1297-301

PMID 10654217, <http://www.ncbi.nlm.nih.gov/pubmed/10654217>

<b>Design</b>	Prospective interventional study: 20 seconds sustained inflation at 30 to 45 cmH2O
<b>Patients</b>	14 patients with hypoxemic respiratory failure
<b>Objectives</b>	Assess the safety and efficacy of a 20 second sustained inflation
<b>Main Results</b>	Significant improvement in oxygenation occurred in the majority of patients within 10 min. The mean SpO2 improved from 87 ±5 to 94 ±2%. Hypotension and mild oxygen desaturation occurred in some patients during the 20-s inflation, reversing rapidly after inflation was terminated.
<b>Conclusion</b>	Sustained inflation is a safe, clinically applicable RM (recruitment maneuver) that improves oxygenation

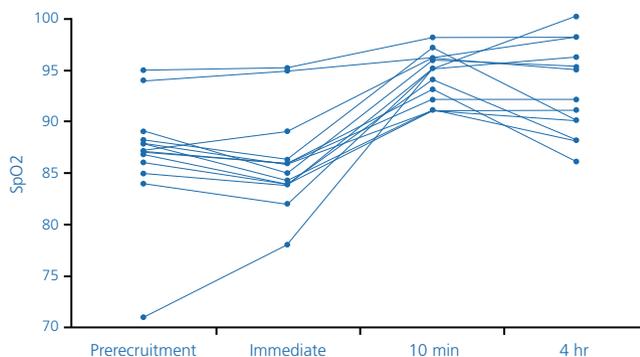


Figure 15: SpO2 increased during the RM and remained higher than baseline after the RM

## Bedside assessment of the effects of positive end-expiratory pressure on lung inflation and recruitment by the helium dilution technique and electrical impedance tomography

Mauri T, Eronia N, Turrini C, Battistini M, Grasselli G, Rona R, Volta CA, Bellani G, Pesenti A  
Intensive Care Med. 2016 Oct;42(10):1576-87  
PMID 27518321, <http://www.ncbi.nlm.nih.gov/pubmed/27518321>

<b>Design</b>	Prospective randomized crossover study
<b>Patients</b>	20 patients; 12 with acute hypoxemic respiratory failure and 8 with acute ARDS
<b>Objectives</b>	Measure PEEP-related lung volume changes by EIT (electrical impedance tomography) and by the helium dilution technique
<b>Main Results</b>	PEEP-induced changes in lung inflation and recruitment measured by electrical impedance tomography and helium dilution showed close correlation ( $r^2=0.78$ , $p<0.001$ and $r^2=0.68$ , $p<0.001$ , respectively) but with relatively variable limits of agreement. At higher PEEP, recruitment was evident in all lung regions ( $p<0.01$ ) and heterogeneity of tidal ventilation distribution was reduced by increased tidal volume distending the dependent lung ( $p<0.001$ ); in the non-dependent lung, compliance decreased ( $p<0.001$ ) and tidal hyperinflation significantly increased ( $p<0.001$ ). In the subgroup of ARDS patients tidal hyperinflation in the dependent lung regions decreased at higher PEEP ( $p=0.05$ ), probably indicating higher potential for recruitment.
<b>Conclusion</b>	A high level of PEEP exerts mixed effects on the regional determinants of VILI (ventilator- induced lung injury)

## Dynamics of end expiratory lung volume after changing positive end-expiratory pressure in acute respiratory distress syndrome patients

Garnero A, Tuxen D, Corno G, Durand-Gasselín J, Hodgson C, Arnal JM

Crit Care. 2015 Sep 18;19:340

PMID 26383835, <http://www.ncbi.nlm.nih.gov/pubmed/26383835>

<b>Design</b>	Prospective interventional study: Staircase RM (recruitment maneuver) up to 40 cmH <sub>2</sub> O
<b>Patients</b>	26 early onset moderate to severe ARDS patients
<b>Objectives</b>	Measure the dynamics of end-expiratory lung volume changes during an increase and decrease in PEEP between 5 and 40 cmH <sub>2</sub> O by steps of 5 cmH <sub>2</sub> O to determine the optimal duration for each step during an SRM
<b>Main Results</b>	During the increase in PEEP, the expected increased volume (respiratory system compliance by the increase in pressure) was achieved within 2 [2-2] breaths and 95% of the additional increased volume (total end expiratory volume change minus expected increased volume) was achieved within 13 [6-16] breaths. During the decrease in PEEP, the expected decreased volume was achieved within 1 [1-1] breath, and 95 % of the additional decreased volume was achieved within 8 [2-15] breaths.
<b>Conclusion</b>	In early ARDS, most of the end expiratory volume change occurred within the first minute

## Acute physiologic effects of a stepwise recruitment maneuver in acute respiratory distress syndrome

Morán I, Blanch L, Fernández R, Fernández-Mondéjar E, Zavala E, Mancebo J

Minerva Anestesiol. 2011 Dec;77(12):1167-75

PMID 21623343, <http://www.ncbi.nlm.nih.gov/pubmed/21623343>

<b>Design</b>	Prospective interventional study: Staircase RM (recruitment maneuver) up to 40 cmH <sub>2</sub> O
<b>Patients</b>	13 early ARDS patients
<b>Objectives</b>	Assess the clinical impact of RM
<b>Main Results</b>	2 h after the RM, the PaO <sub>2</sub> /FiO <sub>2</sub> was higher than at baseline (187 ±102 versus 339 ±136 mmHg). The RM was discontinued due to severe complications in four patients: 3 for CO <sub>2</sub> decrease, 1 for hypotension, 1 for supraventricular tachycardia.
<b>Conclusion</b>	Staircase RM should be applied carefully and closely monitored

## Acute hemodynamic effects of recruitment maneuvers in patients with acute respiratory distress syndrome

Park KJ, Oh YJ, Chang HJ, Sheen SS, Choi J, Lee KS, Park JH, Hwang SC

J Intensive Care Med. 2009 Nov-Dec; 24(6):376-82

PMID 19846416, <http://www.ncbi.nlm.nih.gov/pubmed/19846416>

<b>Design</b>	Prospective interventional study: 30 seconds sustained inflation at 40 cmH <sub>2</sub> O
<b>Patients</b>	22 ARDS patients
<b>Objectives</b>	Evaluated circulatory and cardiac changes during RM (recruitment maneuver)
<b>Main Results</b>	Mean, systolic, and diastolic blood pressure decreased at 20 and 30 seconds during RM (mean blood pressure: 92 ±12 at baseline to 83 ±18 mmHg at the end of the RM) and subsequently recovered. Heart rate decreased at 10 and 20 seconds during the RM, and tended to increase afterward. Both ventricular dimensions decreased significantly during the RM. The left ventricular ejection fraction and peak velocity of the left ventricle during systole remained stable. The fractional changes in mean BP (blood pressure) and left ventricular end-diastolic dimension were correlated.
<b>Conclusion</b>	A transient decrease in mean BP was observed during the RM, and its degree was correlated with the preload decrease

## Intercomparison of recruitment maneuver efficacy in three models of acute lung injury

Lim SC, Adams AB, Simonson DA, Dries DJ, Broccard AF, Hotchkiss JR, Marini JJ

Crit Care Med. 2004 Dec;32(12):2371-7

PMID 15599138, <http://www.ncbi.nlm.nih.gov/pubmed/15599138>

<b>Design</b>	Animal study: 40 seconds sustained inflation at 45 cmH <sub>2</sub> O, staircase RM (recruitment maneuver) and PC
<b>Patients</b>	28 pigs with VILI, oleic acid injury or pneumococcal pneumonia
<b>Objectives</b>	Evaluate the hemodynamic consequence of 3 RM techniques
<b>Main Results</b>	PC caused a lasting increase of PaO <sub>2</sub> in the VILI model, but in oleic acid injury and pneumococcal pneumonia, there were no differences for any RM technique.
<b>Conclusion</b>	The 3 RM techniques were equivalent in terms of oxygenation

# Pediatric patients

## Respiratory and hemodynamic effects of a stepwise lung recruitment maneuver in pediatric ARDS: a feasibility study

Cruces P, Donoso A, Valenzuela J, Díaz F

Pediatr Pulmonol. 2013 Nov;48(11):1135-43

PMID 23255291, <http://www.ncbi.nlm.nih.gov/pubmed/23255291>

**Design** Prospective interventional study: Staircase RM (recruitment maneuver) up to 25 cmH<sub>2</sub>O

**Patients** 25 pediatric early ARDS patients, age = 5 [1-16] months

**Objectives** Assess the effects on gas exchange and lung mechanics of RM in pediatric ARDS patients

**Main Results** 30 RM were performed, with all completed successfully. No airleaks developed. Mild hypotension was detected during 4 RM. Following RM, Crs (compliance of respiratory system), and PaO<sub>2</sub>/FiO<sub>2</sub> increased without changes in PaCO<sub>2</sub>. Oxygenation improved at 12 and 24 hr. The 28-day mortality rate was 16%.

**Conclusion** RM were safe, well tolerated and improved lung function in children with ARDS

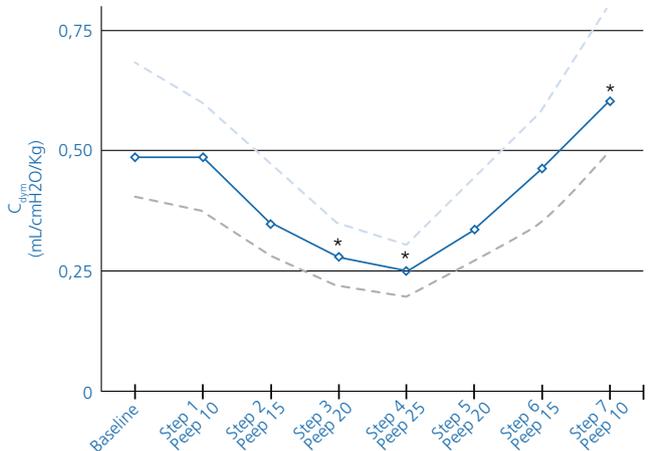


Figure 16: Compliance decreased at high level of PEEP during RM but increase during the decremental PEEP trial and was higher at the end of the protocol than at baseline

## The safety and efficacy of sustained inflations as a lung recruitment maneuver in pediatric intensive care unit patients

Duff JP, Rosychuk RJ, Joffe AR

Intensive Care Med. 2007 Oct;33(10):1778-86

PMID 17607560, <http://www.ncbi.nlm.nih.gov/pubmed/17607560>

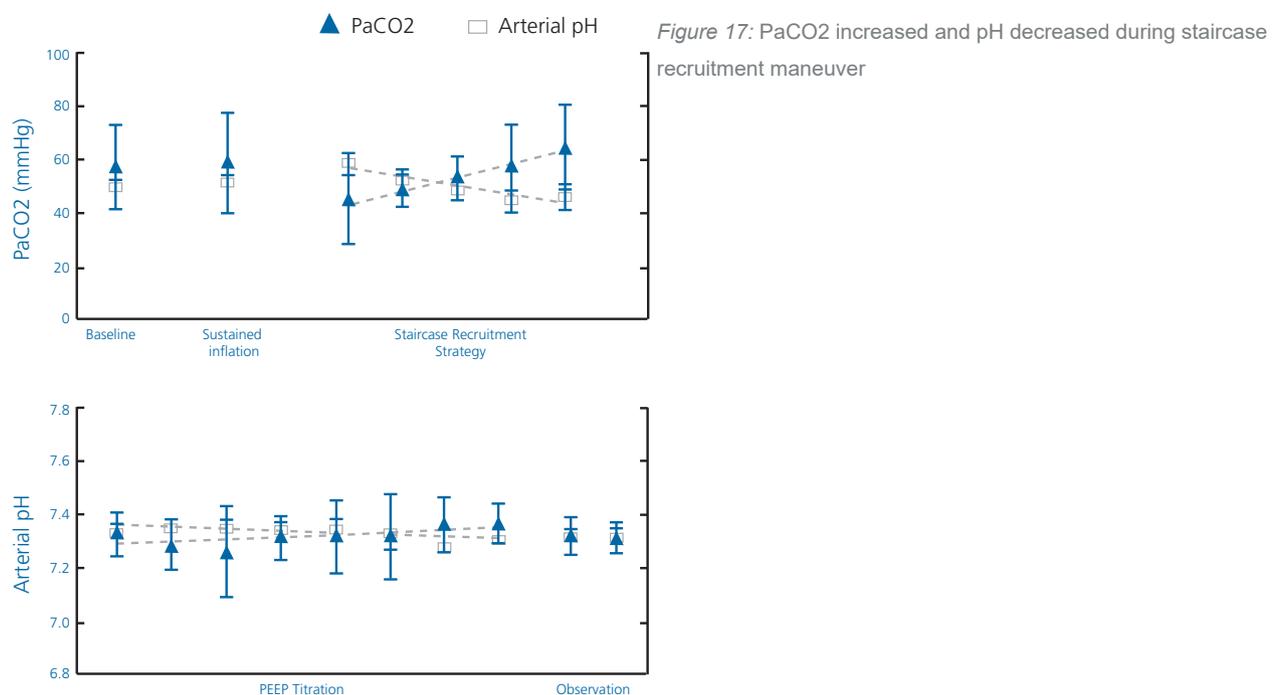
<b>Design</b>	Prospective interventional study: 15-20 seconds sustained inflation at 30-40 cmH <sub>2</sub> O was performed following a ventilator disconnection, suctioning, hypoxemia, or routinely every 12 h
<b>Patients</b>	32 pediatric patients aged from 11 days to 14 years
<b>Objectives</b>	Assess the safety and efficacy of RM (recruitment maneuver) in pediatric patients
<b>Main Results</b>	7/93 RM (7.5%) were interrupted for patient agitation, and 2/93 (2.2%) for transient bradycardia. There was no change in systolic blood pressure, heart rate, or SpO <sub>2</sub> from pre-RM to post-RM, and there were no air leaks. In 3 patients with altered intracranial compliance, 3/8 RM were associated with a spike of intracranial pressure. There was a sustained significant decrease in FiO <sub>2</sub> by 6% lasting up to 6 h post-RM.
<b>Conclusion</b>	RM was safe in pediatric patients

## Comparison of 2 lung recruitment strategies in children with acute lung injury

Kheir JN, Walsh BK, Smallwood CD, Rettig JS, Thompson JE, Gómez-Laberge C, Wolf GK, Arnold JH  
Respir Care. 2013 Aug;58(8):1280-90

PMID 23232733, <http://www.ncbi.nlm.nih.gov/pubmed/23232733>

<b>Design</b>	Prospective, non-randomized, crossover pilot study: 40 seconds sustained inflation at 40 cmH2O and staircase RM (recruitment maneuver) up to 35 cmH2O
<b>Patients</b>	10 pediatric ALI patients from 4 years to 17 years
<b>Objectives</b>	Compare the acute effects of 2 RM strategies
<b>Main Results</b>	Both methods were effective in raising PaO <sub>2</sub> and FRC (functional residual capacity). Sustained inflation was associated with temporary desaturation. During the staircase RM, dead-space and PaCO <sub>2</sub> increased, CO <sub>2</sub> elimination and Crs decreased.
<b>Conclusion</b>	Both methods were effective in raising PaO <sub>2</sub> but staircase RM required caution about CO <sub>2</sub>



## Lung aeration changes after lung recruitment in children with acute lung injury: a feasibility study

Boriosi JP, Cohen RA, Summers E, Sapru A, Hanson JH, Gildengorin G, Newman V, Flori HR

Pediatr Pulmonol. 2012 Aug;47(8):771-9

PMID 22298419, <http://www.ncbi.nlm.nih.gov/pubmed/22298419>

<b>Design</b>	Case series: Staircase RM (recruitment maneuver)
<b>Patients</b>	6 pediatric ALI patients aged from 1 month to 15 years
<b>Objectives</b>	Describe CT-scan lung aeration changes and gas exchange after RM in pediatric ALI patients
<b>Main Results</b>	There was a variable increase in aerated and poorly aerated lung after the RM ranging from 3% to 72% (20% [6-47]). All patients had improvement in PaO <sub>2</sub> /FiO <sub>2</sub> after the RM (14% [8-72]). 4/6 had a decrease in PaCO <sub>2</sub> . One subject had transient hypercapnia during the RM and this correlated with the smallest increase in aerated lung. All patients tolerated the RM without hemodynamic compromise, barotrauma, hypoxemia, or dysrhythmias.
<b>Conclusion</b>	Lung recruitment resulted in improved lung aeration as detected by lung tomography, accompanied by improvements in oxygenation and ventilation

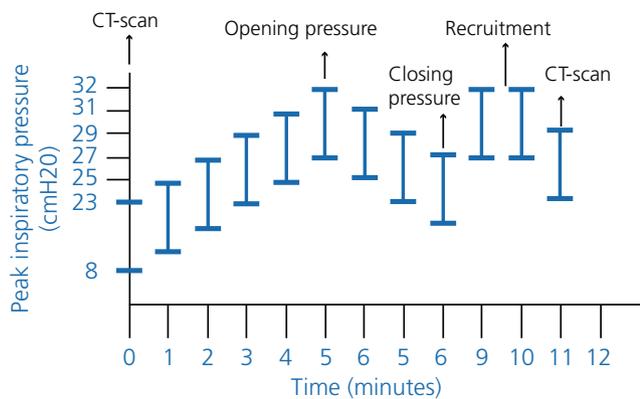


Figure 18: Pediatric staircase recruitment maneuver protocol. PEEP is increased by 2 cmH<sub>2</sub>O every minute to critical opening pressure (PEEP associated with the highest Crs) or P<sub>insp</sub> = 45 cmH<sub>2</sub>O. Then PEEP is decreased by 2 cmH<sub>2</sub>O every minute to critical opening pressure (PEEP associated with the highest Crs). After 2 min is spent at the critical opening pressure and PEEP is settled at critical opening pressure +2 cmH<sub>2</sub>O.

# Additional files

## Recruitment maneuvers and higher PEEP, the so-called open lung concept, in patients with ARDS

Van der Zee P, Gommers D.

Crit Care. 2019 Mar 9;23(1):73.

PMID 30850004, <http://www.ncbi.nlm.nih.gov/pubmed/30850004>

<b>Design</b>	Review
<b>Objectives</b>	Discuss the pathophysiology of ARDS and VILI (ventilator-induced lung injury), limitations and indications of the open lung concept, bedside monitoring to guide the open lung concept
<b>Conclusion</b>	Open lung concept should be applied in patients with severe ARDS with refractory hypoxemia, but only if a patient is a responder to recruitment

## Recruitment maneuvers for acute lung injury: a systematic review

Fan E, Wilcox ME, Brower RG, Stewart TE, Mehta S, Lapinsky SE, Meade MO, Ferguson ND

Am J Respir Crit Care Med. 2008 Dec 1;178(11):1156-63

PMID 18776154, <http://www.ncbi.nlm.nih.gov/pubmed/18776154>

<b>Design</b>	Systematic review
<b>Objectives</b>	Summarize the physiologic effects and adverse events of RM (recruitment maneuver)
<b>Conclusion</b>	Oxygenation was significantly increased after an RM, there were no persistent, clinically significant changes in hemodynamic parameters after an RM. Hypotension and desaturation were the most common adverse events. Serious adverse events (barotrauma [1%] and arrhythmias [1%]) were infrequent.

## Recruitment maneuvers and PEEP titration

Hess DR

Respir Care. 2015 Nov;60(11):1688-704

PMID 26493593, <http://www.ncbi.nlm.nih.gov/pubmed/26493593>

**Design**            Review

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**Conclusion**      Principles and methods for recruitment and PEEP titration

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# Lung recruitment in acute respiratory distress syndrome: what is the best strategy?

Keenan JC, Formenti P, Marini JJ

Curr Opin Crit Care. 2014 Feb;20(1):63-8

PMID 24335655, <http://www.ncbi.nlm.nih.gov/pubmed/24335655>

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**Design**

Review

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**Conclusion**

Why, when and how to perform RM (recruitment maneuver)

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