Efficacy and safety of lung recruitment maneuvers in acute respiratory distress syndrome: a systematic review and meta-analysis

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Efficacy and safety of lung recruitment maneuvers in acute respiratory distress syndrome: a systematic review and meta-analysis

Eficácia e segurança das manobras de recrutamento pulmonar na síndrome do desconforto respiratório agudo: revisão sistemática e metanálise

Eficacia y seguridad de las maniobras de reclutamiento pulmonar en el síndrome de dificultad respiratoria aguda: revisión sistemática y metaanálisis

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Abstract

The physiological rationale behind recruitment maneuvers centers on the mechanical reopening of atelectatic lung units in adult ARDS; nonetheless, current clinical data fails to establish a consistent therapeutic benefit. This PRISMA 2020 systematic review and meta-analysis, registered in PROSPERO (CRD420261419966), examined randomized studies of recruitment maneuvers during invasive mechanical ventilation. Data collection involved an electronic screening of English-language studies published between January 1, 2012, and February 28, 2026, utilizing the MEDLINE/PubMed, Embase, CENTRAL, Scopus, Science Citation Index Expanded, LILACS, and Google Scholar databases. This primary strategy was formally paired with cross-reference tracking and clinical trial registry auditing to maximize study retrieval. Recruitment strategies differed markedly, ranging from open-lung and stepwise protocols to PEEP-titrated recruitment, prone-position combined recruitment, sigh maneuvers and sustained inflation. Five studies were pooled for mortality, with no significant reduction in risk compared with control ventilation strategies (RR 1.07; 95% CI 0.96–1.19; I^2 = 0.0%). Barotrauma or pneumothorax also showed no significant pooled difference, although heterogeneity was substantial (RR 0.95; 95% CI 0.30–3.04; I^2 = 70.3%). The evidence supports a selective, protocol-aware use of recruitment rather than routine aggressive application in unselected ARDS.

Keywords: Acute respiratory distress syndrome; Lung recruitment maneuvers; Mechanical ventilation; Positive end-expiratory pressure; Meta-analysis.

Resumo

A fundamentação fisiológica por trás das manobras de recrutamento centra-se na reabertura mecânica de unidades pulmonares atelectásicas na SDRA em adultos; no entanto, os dados clínicos atuais não conseguem estabelecer um benefício terapêutico consistente. Esta revisão sistemática e meta-análise PRISMA 2020, registrada no PROSPERO (CRD420261419966), examinou estudos randomizados sobre manobras de recrutamento durante a ventilação mecânica invasiva. A coleta de dados envolveu uma triagem eletrônica de estudos em língua inglesa publicados entre 1º de janeiro de 2012 e 28 de fevereiro de 2026, utilizando as bases de dados MEDLINE/PubMed, Embase, CENTRAL, Scopus, Science Citation Index Expanded, LILACS e Google Scholar. Essa estratégia primária foi formalmente combinada com o rastreamento de referências cruzadas e a auditoria de registros de ensaios clínicos para maximizar a recuperação de estudos. As estratégias de recrutamento diferiram significativamente, variando de protocolos de pulmão aberto e escalonados até recrutamento com titulação de PEEP, recrutamento combinado em posição prona, manobras de suspiro e insuflação sustentada. Cinco estudos foram agrupados para análise de mortalidade, sem redução significativa do risco em comparação com as estratégias de ventilação de controle (RR 1,07; IC 95% 0,96–1,19; I^2 = 0,0%). Barotrauma ou pneumotórax também não apresentaram diferença significativa na análise combinada, embora a heterogeneidade tenha sido substancial (RR 0,95; IC 95% 0,30–3,04; I^2 = 70,3%). As evidências apoiam o uso seletivo e orientado

por protocolo do recrutamento, em vez da aplicação agressiva de rotina em casos não selecionados de SDRA.

Palavras-chave: Síndrome da angústia respiratória aguda; Manobras de recrutamento pulmonar; Ventilação mecânica; Pressão positiva no final da expiração; Meta-análise.

Resumen

La base fisiológica de las maniobras de reclutamiento se centra en la reapertura mecánica de las unidades pulmonares atelectásicas en el SDRA en adultos; sin embargo, los datos clínicos actuales no logran establecer un beneficio terapéutico consistente. Esta revisión sistemática y metaanálisis conforme a PRISMA 2020, registrado en PROSPERO (CRD420261419966), examinó estudios aleatorizados sobre maniobras de reclutamiento durante la ventilación mecánica invasiva. La recopilación de datos consistió en una selección electrónica de estudios en lengua inglesa publicados entre el 1 de enero de 2012 y el 28 de febrero de 2026, utilizando las bases de datos MEDLINE/PubMed, Embase, CENTRAL, Scopus, Science Citation Index Expanded, LILACS y Google Scholar. Esta estrategia principal se combinó formalmente con el seguimiento de referencias cruzadas y la auditoría de registros de ensayos clínicos para maximizar la recuperación de estudios. Las estrategias de reclutamiento variaron notablemente, desde protocolos de pulmón abierto y escalonados hasta el reclutamiento con titulación de la PEEP, el reclutamiento combinado en posición prona, las maniobras de suspiro y la inflación sostenida. Se agruparon cinco estudios para analizar la mortalidad, sin que se observara una reducción significativa del riesgo en comparación con las estrategias de ventilación de control (RR 1,07; IC del 95 %: 0,96–1,19; I^2 = 0,0 %). Tampoco se observaron diferencias significativas en el análisis combinado respecto al barotrauma o el neumotórax, aunque la heterogeneidad fue considerable (RR 0,95; IC del 95 %: 0,30–3,04; I^2 = 70,3 %). La evidencia respalda un uso selectivo del reclutamiento, acorde con el protocolo, en lugar de una aplicación agresiva rutinaria en el SDRA no seleccionado.

Palabras clave: Síndrome de dificultad respiratoria aguda; Maniobras de reclutamiento pulmonar; Ventilación mecánica; Presión positiva al final de la espiración; Metaanálisis.

Introduction

Management of acute respiratory distress syndrome (ARDS) in adult intensive care remains clinically demanding. Although refractory hypoxemia is often the most visible manifestation, ventilatory support in ARDS must be delivered within a narrow safety margin. Inflammation, alveolar edema and loss of aerated lung volume reduce the functional lung available for ventilation (Amato et al., 2015). Under these conditions, even protective ventilation may expose some lung regions to overdistension while others remain vulnerable to cyclic opening and closure. This uneven distribution of stress and strain contributes to ventilator-induced lung injury and continues to influence current approaches to mechanical ventilation in ARDS (Fan et al., 2017).

Lung recruitment maneuvers are based on the attempt to reopen collapsed alveolar units by transiently increasing airway or transpulmonary pressure. Their expected physiological effects include increased end-expiratory lung volume, improved aeration and better gas exchange (Gattinoni et al., 2006). Different techniques have been used, including sustained inflation, sigh maneuvers, stepwise increases in airway pressure and open-lung strategies combined with positive end-expiratory pressure (PEEP) titration (Briel et al., 2010). These approaches are often considered under the same conceptual framework, but they are not equivalent. Their effects may vary according to the pressure applied, duration of the maneuver, baseline PEEP, ventilatory mode, timing of application and the patient's potential for lung recruitment.

The interpretation of recruitment maneuvers remains difficult because the first apparent response is usually physiological. The clinical value of recruitment maneuvers rests upon a delicate equilibrium: achieving necessary improvements in gas exchange without subjecting patients to avoidable harm. This trade-off arises because a post-maneuver rise in the PaO_2/FiO_2 ratio offers only a limited reflection of improved aeration, often masked by the systemic consequences of elevated airway pressures (Guérin et al., 2013). By increasing intrathoracic pressure and reducing venous return, these pressures severely challenge cardiovascular performance — especially in cases of low recruitability or limited hemodynamic reserve (Amato et al., 1998). Consequently, any transient gains in oxygenation risk being accompanied by acute clinical events, specifically hypotension, arrhythmias, barotrauma, pneumothorax, or paradoxical desaturation.

The available randomized evidence is difficult to compare. Trials differ in ARDS definitions, baseline severity, recruitment protocols, comparator strategies, PEEP titration methods and timing of outcome assessment. Some studies have focused mainly on oxygenation and respiratory mechanics, whereas later trials have given greater importance to patient-centered outcomes such as ventilator-free days, adverse events and mortality (Hodgson et al., 2011). This heterogeneity has shifted the clinical question from whether recruitment maneuvers improve oxygenation to whether they provide a safe and clinically meaningful benefit in selected adults with ARDS (The Acute Respiratory Distress Syndrome Network, 2000).

This systematic review and meta-analysis evaluate the efficacy and safety of lung recruitment maneuvers in adults with ARDS. It focuses on randomized evidence comparing recruitment maneuvers with conventional lung-protective ventilation, usual ventilatory care, low or moderate PEEP strategies, standard mechanical ventilation or alternative recruitment techniques (Mercat et al., 2008). Additional outcomes include lung mechanics, ventilator-free days, duration of mechanical ventilation, length of stay, rescue therapies and hemodynamic responses. The main outcomes are all-cause mortality, oxygenation and serious adverse events (Calfee et al., 2014). Additional outcomes include lung mechanics, ventilator-free days, duration of mechanical ventilation, length of stay, rescue therapies and hemodynamic responses.

Materials and methods

Study design and registration

This systematic review and meta-analysis followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses 2020 statement (Page et al., 2021). The review question and eligibility criteria were structured according to the PICO framework. The protocol was registered in the International Prospective Register of Systematic Reviews (PROSPERO) under the registration number CRD420261419966.

Eligibility criteria

The review included randomized studies evaluating lung recruitment maneuvers in adults with acute respiratory distress syndrome (ARDS) receiving invasive mechanical ventilation. Eligible designs included parallel-group, crossover, pilot, single-center and multicenter randomized trials. Studies had to report at least one clinical or physiological outcome related to efficacy or safety.

Non-randomized observational studies, pediatric studies, animal or laboratory studies, case reports, case series, narrative reviews, systematic reviews, editorials, comments, letters without original data, conference abstracts without full text and ongoing trials without extractable outcome data were excluded (The ARDS Definition Task Force, 2012). Studies were also excluded when the intervention was not a clearly defined lung recruitment maneuver or when the effect of recruitment could not be separated from other co-interventions.

PICO framework

Table 1. *PICO Framework*

Component	Definition applied in this review
Population	Adults aged 18 years or older diagnosed with ARDS according to the American-European Consensus Conference definition, the Berlin definition, or equivalent criteria reported by trial authors.
Intervention	Lung recruitment maneuvers applied during invasive mechanical ventilation, including sustained inflation, sigh maneuvers, stepwise or incremental pressure recruitment, open-lung strategies, PEEP titration-based recruitment, or recruitment combined with prone positioning when the recruitment effect was extractable.

Comparator	Conventional lung-protective ventilation, usual ventilatory care, low or moderate PEEP strategies, standard mechanical ventilation, or alternative recruitment techniques in randomized comparisons.
Main outcomes	All-cause mortality, oxygenation and serious adverse events.
Additional outcomes	Lung mechanics, ventilator-free days, duration of mechanical ventilation, length of stay, rescue therapies and hemodynamic responses.
Study design	Randomized studies, including parallel-group, crossover, pilot, single-center and multicenter randomized trials.
Main exclusions	Pediatric studies, animal studies, non-randomized designs, reviews, case reports, abstracts without full text, ongoing trials without extractable data, and studies without a clearly defined recruitment maneuver.

Information sources and search strategy

A systematic search was conducted in CENTRAL, Embase, Google Scholar, LILACS, MEDLINE, PubMed, Science Citation Index Expanded and Scopus. The search was limited to published studies in English from 1 January 2012 to 28 February 2026. Backward citation searching, forward citation searching and study/register verification were also used to identify linked publications and to support the assessment of selective outcome reporting.

The search strategy combined terms for ARDS, mechanical ventilation, lung recruitment maneuvers and randomized trials. The strategy was adapted to the syntax of each database.

Table 2. *Search strategy summary*

Item	Description
Databases	CENTRAL, Embase, Google Scholar, LILACS, MEDLINE, PubMed, Science Citation Index Expanded and Scopus.
Search period	1 January 2012 to 28 February 2026.
Language	English.
Publication status	Published studies.
Study design filter	Randomized studies.
Additional methods	Backward citation searching, forward citation searching and study/register verification.
Core search concepts	ARDS, acute lung injury, mechanical ventilation, lung recruitment maneuver, alveolar recruitment maneuver, recruitment manoeuvre, sustained inflation, sigh, stepwise recruitment, open-lung approach, PEEP titration, randomized trial and controlled trial.

The PubMed/MEDLINE strategy was based on the following search structure:

- (“Respiratory Distress Syndrome” [MeSH] OR “acute respiratory distress syndrome” OR ARDS OR “acute lung injury”) AND (“lung recruitment maneuver” OR “lung recruitment maneuver” OR “alveolar recruitment maneuver” OR “alveolar recruitment maneuver” OR “recruitment maneuver” OR “recruitment maneuver” OR “sustained inflation” OR sigh OR “stepwise recruitment” OR “incremental pressure” OR “open lung approach” OR “PEEP

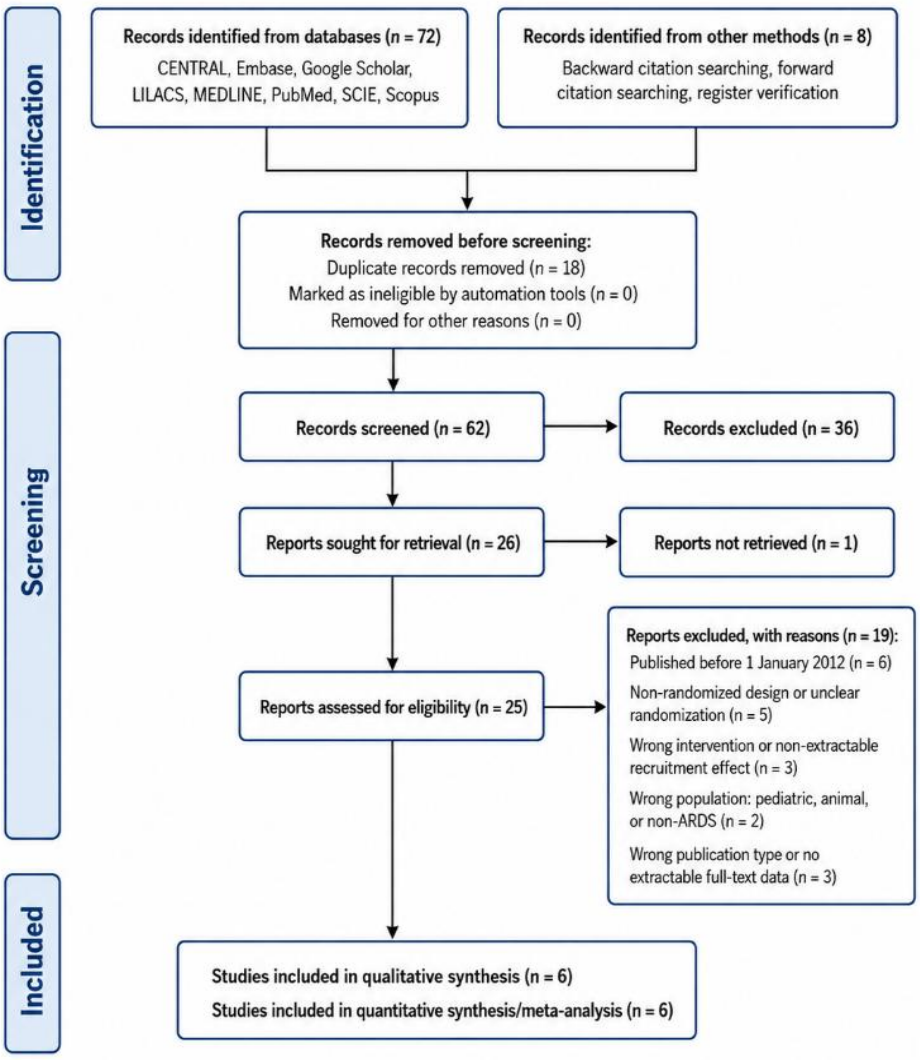
titration") AND ("randomized controlled trial" OR randomized OR randomised OR "controlled trial" OR "clinical trial").

Study selection

All records were exported to a reference manager for duplicate removal. Two reviewers independently screened titles and abstracts. Reports that appeared to meet the eligibility criteria were assessed in full text. Disagreements were resolved by discussion, and a third reviewer was consulted when consensus was not reached. Reasons for full-text exclusion were recorded and incorporated into the PRISMA 2020 flow diagram.

The database search identified 72 records, and eight additional records were identified through backward citation searching, forward citation searching and study/register verification. After removing 18 duplicates, 62 records were screened. Thirty-six records were excluded after title and abstract screening. Twenty-six reports were sought for retrieval, of which one could not be retrieved. Twenty-five full-text reports were assessed for eligibility. Nineteen reports were excluded, and six randomized studies met the inclusion criteria.

Figure 1. *PRISMA 2020 flow diagram of study selection*



Data extraction

Two reviewers extracted data independently using a standardized data extraction form. Extracted information included author, year, country, study design, sample size, ARDS definition, ARDS severity, baseline PaO_2/FiO_2 ratio, ventilatory settings, type of recruitment maneuver, pressure level, duration of the maneuver, frequency of application, PEEP titration strategy, use of prone positioning, comparator strategy, follow-up time and reported outcomes. Discrepancies were resolved by consensus or by consultation with a third reviewer.

Table 3. *Data items extracted from included studies*

Domain	Variables extracted
Study characteristics	Author, year, country, study design, setting, sample size and follow-up duration.
Population	ARDS definition, ARDS severity, baseline PaO_2/FiO_2 ratio and relevant baseline clinical characteristics.
Intervention	Type of recruitment maneuver, pressure level, duration, frequency, ventilatory mode, PEEP titration and use of prone positioning.
Comparator	Lung-protective ventilation, usual care, low/moderate PEEP strategy, standard mechanical ventilation or alternative recruitment technique.
Efficacy outcomes	Mortality, oxygenation, respiratory mechanics, ventilator-free days and duration of mechanical ventilation.
Safety outcomes	Barotrauma, pneumothorax, hypotension, arrhythmia, cardiac arrest, severe desaturation and rescue therapies.
Hemodynamic outcomes	Mean arterial pressure, heart rate, vasopressor requirement, cardiac output or cardiac index when reported.

Outcomes

The main outcomes were all-cause mortality, oxygenation and serious adverse events. Mortality included 28-day mortality, intensive care unit mortality, hospital mortality, 60-day mortality, 90-day mortality or the longest follow-up mortality reported by each trial. Oxygenation was assessed using the PaO_2/FiO_2 ratio or equivalent oxygenation indices, preferably within the first 24 hours after the recruitment maneuver. Serious adverse events included barotrauma, pneumothorax, clinically relevant hypotension, arrhythmias, cardiac arrest, severe desaturation or need for rescue therapies.

Additional outcomes included static or dynamic lung compliance, plateau pressure, driving pressure, mean airway pressure, peak airway pressure, ventilator-free days, duration of invasive mechanical ventilation, intensive care unit length of stay, hospital length of stay, rescue therapies and hemodynamic responses.

Risk of bias and certainty of evidence

Methodological quality for the randomized trials was scrutinized via the Cochrane Risk of Bias 2 (RoB 2) framework. This protocol evaluated potential deviations across the randomization sequence, planned interventions, missing data, endpoint measurement, and selective reporting (Suzumura et al., 2014). Consequently, each evaluated outcome was assigned to a low, high, or intermediate risk tier.

The certainty of evidence for the main outcomes was assessed using the Grading of Recommendations Assessment, Development and Evaluation approach. Certainty was rated as high, moderate, low or very low according to risk of bias, inconsistency, indirectness, imprecision and publication bias. A Summary of Findings table was prepared for the most clinically relevant outcomes.

Data synthesis and statistical analysis

A narrative synthesis was performed for all included studies. Studies were described according to recruitment maneuver type, comparator strategy, ARDS severity and reported outcomes. Quantitative synthesis was conducted when at least two clinically and methodologically comparable studies reported the same outcome.

For dichotomous outcomes, risk ratios with 95% confidence intervals were calculated. For continuous outcomes, mean differences with 95% confidence intervals were used when outcomes were measured on the same scale. Standardized mean differences were used when different measurement approaches were reported. A random-effects model was preferred because clinical and methodological heterogeneity was expected. A fixed-effect model was considered when heterogeneity was low and studies were sufficiently comparable.

Statistical heterogeneity was assessed using the I^2 statistic, tau^2 and visual inspection of forest plots. When meta-analysis was not appropriate because of clinical heterogeneity, limited outcome reporting or non-comparable intervention protocols, findings were summarized narratively.

Additional analyses and reporting bias

When sufficient data were available, subgroup analyses were considered according to recruitment maneuver type, ARDS severity, timing of intervention, PEEP strategy, use of prone positioning, trial size and risk of bias. Sensitivity analyses were considered by excluding studies at high risk of bias, crossover studies with potential carryover effects, studies with unclear randomization, mixed populations not strictly diagnosed as ARDS and studies using unusually aggressive or prolonged recruitment protocols (Slutsky & Ranieri, 2013).

Reporting bias was assessed by comparing reported outcomes with available trial registries, protocols or methods sections when accessible. Funnel plots and Egger's test were planned when at least ten studies were available for a given meta-analysis.

Result and Discussion

Characteristics of included studies

Six randomized studies published between 2016 and 2026 were included, with a total of 1,526 adult patients with ARDS. Sample size varied substantially across trials, ranging from 23 to 1,010 participants. The ART Trial contributed the largest proportion

of participants and therefore had the greatest influence on the clinical interpretation of mortality and safety outcomes.

The included studies differed in recruitment strategy, comparator group and outcome focus. Interventions included open-lung ventilation with decremental PEEP titration, recruitment plus PEEP titration by best compliance, modified stepwise recruitment, maximal recruitment open-lung ventilation, PEEP-induced recruitment combined with prone positioning, and randomized comparison between sigh recruitment and sustained inflation. The distribution of studies by publication year and sample size is shown in Figure 2.

Figure 2. *Publication year and sample size distribution of included randomized studies*

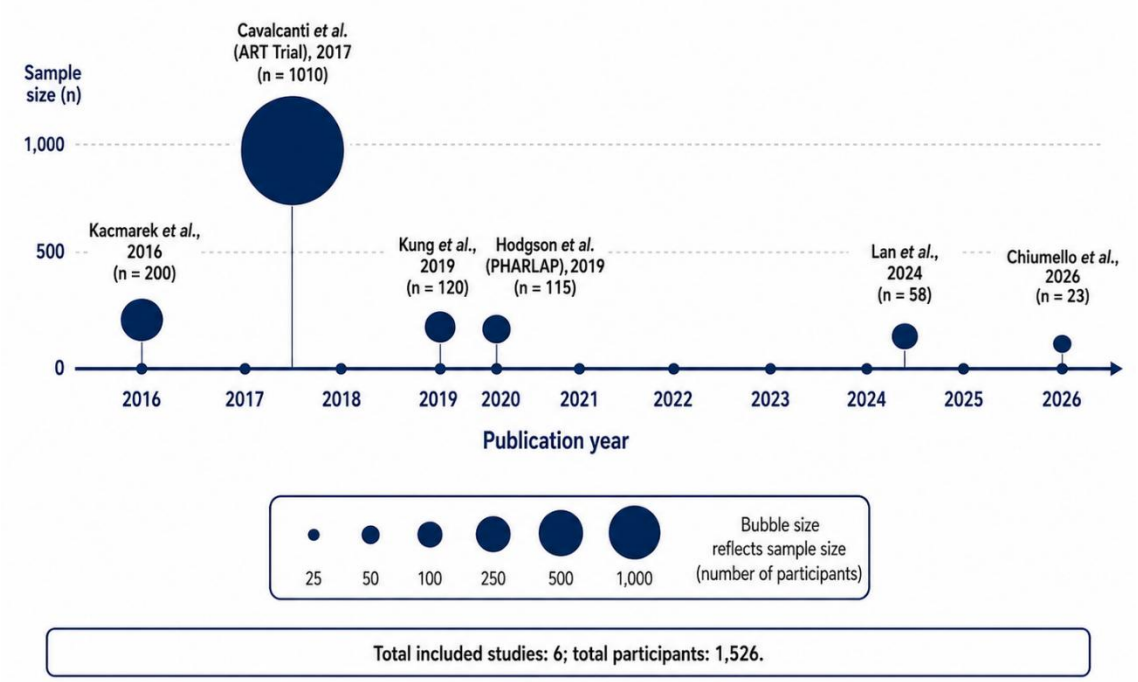


Table 4. *Characteristics of included randomized studies*

Autors	Design	Sample size	Recruitment strategy	Comparator	Main focus
Kacmarek et al. (2016)	Multicenter pilot randomized controlled trial	200	Open-lung approach with recruitment and decremental PEEP titration	ARDSNet low-PEEP protocol	Mortality, oxygenation, driving pressure and ventilator-free days
ART Trial (2017)	Multicenter randomized clinical trial	1010	Lung recruitment maneuver with PEEP titration according to best respiratory-system compliance	Conventional low-PEEP strategy	28-day mortality, ventilator-free days, barotrauma and pneumothorax
Kung et al. (2019)	Prospective randomized controlled trial	120	Modified stepwise lung recruitment maneuver	Lung-protective ventilation alone	28-day mortality, ventilator-free days, ICU-free days and compliance

Hodgson et al. (2019)	Phase II multicenter randomized controlled trial	115	Maximal recruitment open-lung ventilation	Standard mechanical ventilation	Ventilator-free days, mortality, barotrauma and rescue therapies
Lan et al. (2024)	Single-center prospective randomized clinical trial	58	PEEP-induced recruitment maneuver combined with prone positioning	Prone positioning alone	Oxygenation, compliance, EIT-derived ventilation distribution and recruitability
Chiumello et al. (2026)	Randomized crossover study	23	Sigh recruitment and sustained inflation in randomized sequence	Alternative recruitment maneuver pattern	Gas exchange, respiratory mechanics, hemodynamics and EIT-derived lung volumes

Mortality and patient-centered outcomes

Mortality outcomes exhibited substantial inter-study heterogeneity. Notably, the largest trial demonstrated an increased 28-day risk of death associated with lung recruitment and titrated PEEP when contrasted with a conventional low-PEEP approach. Conversely, smaller, underpowered investigations yielded equatorial estimates that failed to establish a definitive survival divergence.

The analysis of ventilator-free days revealed pronounced data divergence, marked by a stark contrast between reports of inter-group equivalence and a pivotal trial documenting fewer ventilator-free days under aggressive recruitment and PEEP titration protocol. This operational discrepancy highlights a critical clinical disconnect, where proxy indicators of respiratory physiology fail to mirror robust, patient-centered endpoints.

Oxygenation and lung mechanics

Short-term physiological improvement was reported in several studies. Open-lung, stepwise and prone-position combined strategies were associated with improvements in oxygenation, respiratory compliance or driving pressure in selected populations. However, the magnitude and persistence of these effects varied across trials.

The response to recruitment appeared to depend on the strategy applied and the patient's potential for lung recruitment. Studies using electrical impedance tomography or recruitability indices suggested that regional ventilation and recruitment capacity may influence oxygenation response. In contrast, the randomized crossover study comparing sigh recruitment and sustained inflation did not show a consistent short-term advantage for either maneuver pattern (Guyatt et al., 2008).

Serious adverse events and safety

Safety evaluations remained pivotal, dominated by a signal of harm in the ART Trial where recruitment coupled with titrated PEEP led to increased mortality and adverse respiratory events. Although smaller, underpowered investigations reported equitable

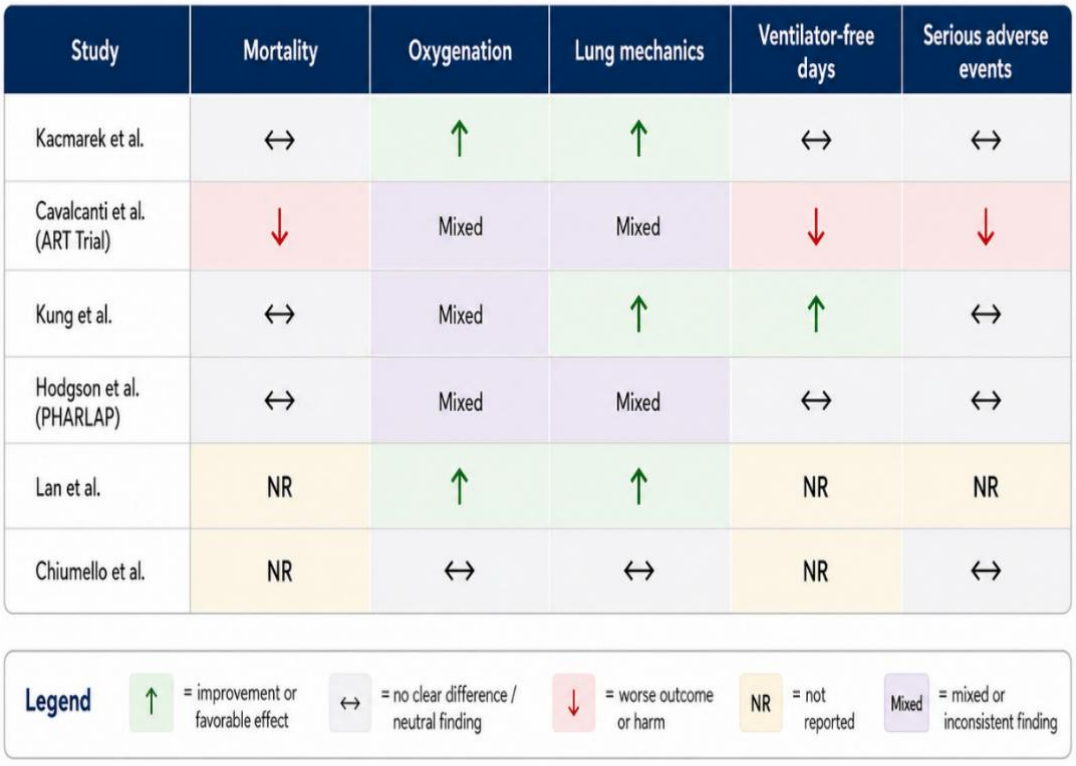
rates of barotrauma and short-term safety profiles, their restricted sample sizes preclude a definitive, cross-study safety synthesis (Retamal et al., 2015).

Overall, the evidence does not support interpreting recruitment maneuvers as a single uniform intervention. The balance between benefit and harm varied according to recruitment protocol, PEEP titration method, baseline severity, recruitability and hemodynamic tolerance.

Direction of effects

The direction of effects across outcome domains is summarized in Figure 4. Across the included studies, oxygenation and lung mechanics tended to improve more often than mortality or ventilator-free days. Harm signals were mainly observed in the largest trial, particularly for mortality, ventilator-free days and serious adverse events. Findings for smaller trials were more neutral or mixed (Papazian et al., 2010).

Figure 3. *Evidence map of the direction of effects across included studies*



Overall synthesis

Data from the six randomized trials underscore a clinical paradox in adult ARDS, where acute improvements in oxygenation and respiratory compliance fail to yield corresponding survival advantages, extended ventilator-free days, or reduced adverse events. This structural disconnect between transient physiological surrogates and definitive patient-centered endpoints is driven by the stark heterogeneity observed across the included literature (Mercat et al., 2008).

This clinical divergence was underscored by the largest trial, which established a distinct signal of harm—specifically elevated mortality and complications—when recruitment was paired with titrated PEEP.Consequently, these heterogeneous findings counter the routine deployment of aggressive recruitment protocols within unselected adult ARDS cohorts. Rather than a standardized intervention, recruitment maneuvers demand a highly individualized framework, restricted to patients with demonstrable lung recruitability and robust hemodynamic reserves, under rigorous clinical surveillance (Meade et al., 2008).

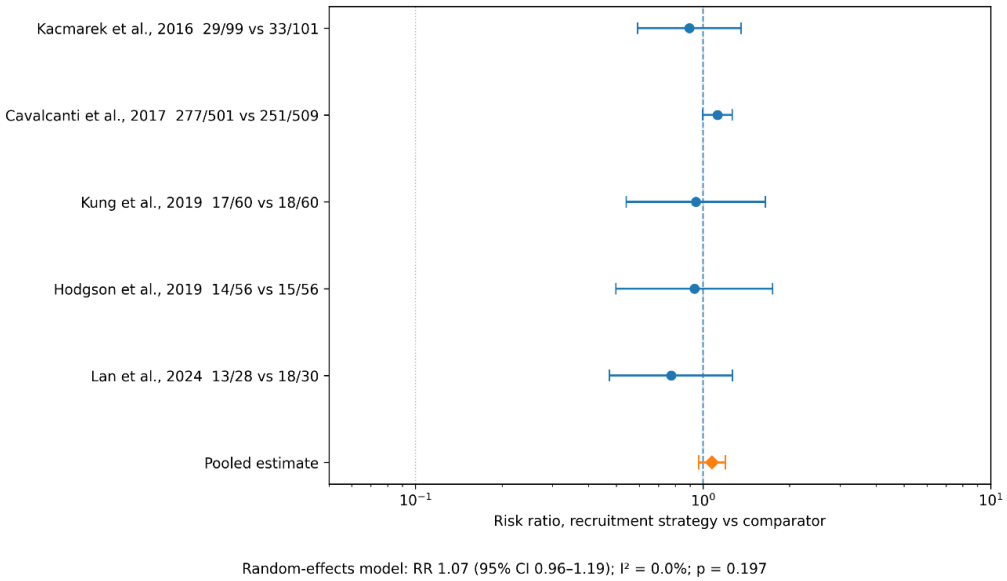
Quantitative synthesis and meta-analysis

For dichotomous outcomes documented across at least two clinically comparable randomized trials, data synthesis utilized a random-effects, inverse-variance approach to compute pooled risk ratios (RRs) and corresponding 95% confidence intervals (CIs). This statistical framework incorporated a standard 0.5 continuity correction to accommodate single-arm zero-event occurrences, while underlying inter-study heterogeneity was quantified via the I^2 statistic and tau^2 estimators.

All-cause mortality

Five randomized studies contributed data to the mortality meta-analysis. Mortality follow-up ranged from 28 to 60 days according to the outcome reported by each trial. The pooled estimate did not show a statistically significant difference between recruitment strategies and comparator ventilation strategies. The overall pooled RR was 1.07 (95% CI 0.96–1.19; $I^2 = 0.0\%$; $p = 0.197$). This finding indicates no clear mortality benefit from lung recruitment maneuvers. The largest trial contributed most of the statistical weight and showed higher mortality in the recruitment plus titrated PEEP group.

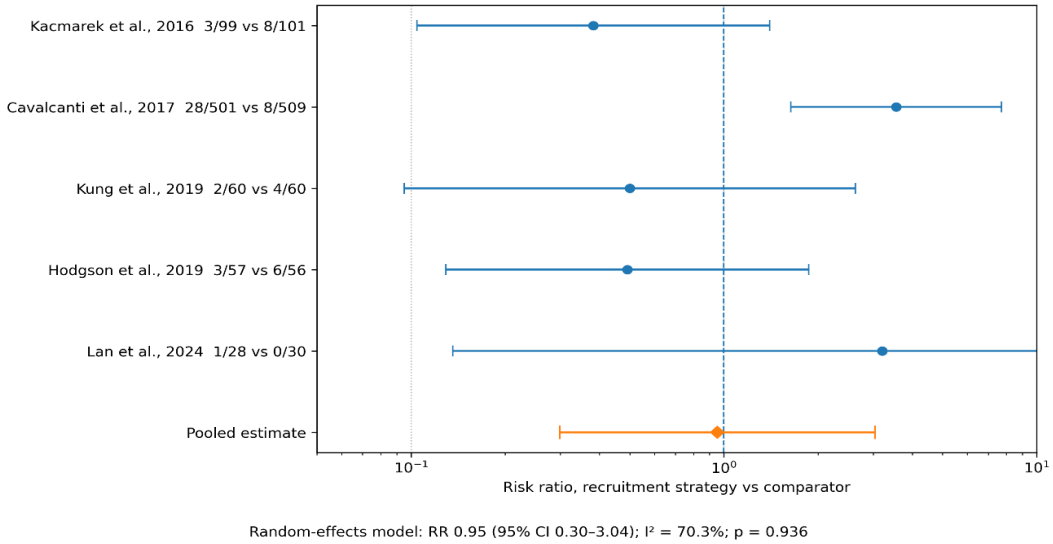
Figure 4. *Forest plot of all-cause mortality*



Barotrauma or pneumothorax

Five studies contributed data to the safety meta-analysis for barotrauma or pneumothorax as reported by each trial. The pooled estimate showed no statistically significant overall difference between recruitment and comparator groups, but heterogeneity was substantial. The pooled RR was 0.95 (95% CI 0.30–3.04; $I^2 = 70.3\%$; $p = 0.936$). The direction of effect differed across studies. The ART Trial showed a clear safety signal against aggressive recruitment plus titrated PEEP, whereas smaller trials reported similar or lower event rates in the recruitment group.

Figure 5. *Forest plot of barotrauma or pneumothorax*



Outcomes not pooled

Oxygenation, lung mechanics, ventilator-free days, length of stay and hemodynamic responses were not pooled quantitatively because the studies differed in measurement timing, reporting format, intervention protocol and outcome definition. Several trials reported PaO_2/FiO_2, compliance, driving pressure or EIT-derived variables at different time points, while some continuous outcomes were reported as medians with interquartile ranges. Therefore, these outcomes were synthesized narratively to avoid inappropriate statistical aggregation.

Overall, the quantitative synthesis showed no significant mortality benefit from lung recruitment maneuvers. Safety findings were inconsistent, with the main signal of harm arising from aggressive recruitment combined with titrated PEEP. Physiological improvements in oxygenation or mechanics were observed in selected studies, but these effects were not consistently associated with improved patient-centered outcomes.

Table 5. *Summary of quantitative synthesis*

Outcome	Studies included	Participants	Effect measure	Pooled estimate	Heterogeneity	Interpretation
All-cause mortality	5	1,501	RR	1.07 (95% CI 0.96–1.19)	$I^2 = 0.0\%$; $tau^2 = 0.00$	No significant mortality benefit
Barotrauma or pneumothorax	5	1,501	RR	0.95 (95% CI 0.30–3.04)	$I^2 = 70.3\%$; $tau^2 = 1.13$	No significant pooled difference; substantial heterogeneity
Oxygenation	Not pooled	—	—	—	—	Synthesized narratively because timing and reporting differed across trials
Lung mechanics	Not pooled	—	—	—	—	Synthesized narratively because variables and time points were not sufficiently comparable
Ventilator-free days	Not pooled	—	—	—	—	Synthesized narratively because reporting format and definitions varied
Hemodynamic responses	Not pooled	—	—	—	—	Synthesized narratively because event definitions were inconsistent

Discussion

Synthesizing data from six randomized trials encompassing 1,526 participants, this systematic review and meta-analysis evaluated the clinical efficacy of lung recruitment maneuvers in adult patients undergoing invasive mechanical ventilation for acute respiratory distress syndrome (ARDS). The compiled evidence revealed highly heterogeneous outcomes; while several investigations documented acute increments in oxygenation, respiratory mechanics, or regional ventilation distribution, these transient physiological surrogates failed to yield corresponding survival advantages, extended ventilator-free duration, or a reduction in serious adverse events (Borges et al., 2006).

The mortality meta-analysis included five randomized studies and showed no significant benefit of recruitment strategies compared with control ventilation approaches. The pooled RR was 1.07 (95% CI 0.96–1.19; $I^2 = 0.0\%$). This result indicates that, across comparable randomized trials, recruitment maneuvers did not reduce all-cause mortality. However, the absence of statistical heterogeneity should be interpreted cautiously because the largest trial contributed most of the statistical weight. For barotrauma or pneumothorax, the pooled estimate was also not significant (RR 0.95; 95% CI 0.30–3.04), but heterogeneity was substantial ($I^2 = 70.3\%$), suggesting important differences across recruitment protocols and safety profiles.

The findings are strongly influenced by the ART Trial by ART Investigators (2017), "Effect of Lung Recruitment and Titrated Positive End-Expiratory Pressure (PEEP) vs Low PEEP on Mortality in Patients With Acute Respiratory Distress Syndrome." That trial reported higher mortality, fewer ventilator-free days and more barotrauma or pneumothorax with recruitment plus titrated PEEP. The present review is consistent with that safety signal and does not support the routine use of aggressive recruitment combined with PEEP titration in unselected adults with moderate-to-severe ARDS.

Other randomized trials suggest a more nuanced interpretation. Kacmarek et al. (2016), in "Open Lung Approach for the Acute Respiratory Distress Syndrome: a Pilot, Randomized Controlled Trial," reported improved oxygenation and driving pressure without a clear improvement in mortality or ventilator-free days. Kung et al. (2019), in "Effects of Stepwise Lung Recruitment Maneuvers in Patients with Early Acute Respiratory Distress Syndrome," found improved respiratory-system compliance, with no clear mortality difference. Similarly, the PHARLAP trial by Hodgson et al. (2019), "Maximal Recruitment Open Lung Ventilation in Acute Respiratory Distress Syndrome," did not demonstrate a clear clinical advantage in ventilator-free days or mortality. These findings support the conclusion that physiological improvement alone is insufficient to establish clinical benefit.

More recent trials reinforce the importance of patient selection and maneuver type. Lan et al. (2024), in "PEEP-Induced Lung Recruitment Maneuver Combined with Prone Position for ARDS," reported improved oxygenation, compliance and dorsal ventilation distribution when recruitment was combined with prone positioning. In contrast, Chiumello et al. (2026), in "Comparison of two different recruitment maneuver patterns in ARDS patients," found no consistent short-term superiority between sigh recruitment and sustained inflation. These results indicate that recruitment maneuvers should not be interpreted as a uniform intervention. Their effects depend on pressure level, duration, PEEP titration strategy, recruitability and hemodynamic tolerance.

The present findings are also consistent with previous systematic reviews reporting that recruitment maneuvers may improve oxygenation but do not reliably reduce mortality. Compared with those reviews, the current synthesis is more restrictive because it focuses on randomized evidence and incorporates recent trials using prone

positioning, electrical impedance tomography and alternative recruitment patterns. This approach strengthens the clinical interpretation but also highlights the limited number of eligible randomized studies.

It followed PRISMA 2020, was registered in PROSPERO, focused on randomized studies and evaluated both efficacy and safety outcomes. The use of meta-analysis for mortality and barotrauma or pneumothorax allowed quantitative assessment of clinically relevant outcomes. Nevertheless, several limitations should be acknowledged. The number of included trials was small, recruitment protocols were heterogeneous, and some outcomes could not be pooled because of differences in measurement timing, reporting format and outcome definition. In addition, the largest trial had a major influence on the pooled estimates, particularly for mortality and safety (Bellani et al., 2016).

From a translational perspective, the collective data countermand the routine deployment of aggressive recruitment protocols within unselected adult ARDS cohorts, restricting their clinical utility to phenotypic sub-populations characterized by demonstrable lung recruitability and preserved hemodynamic reserve under rigorous surveillance and pre-specified cessation thresholds (The National Heart, Lung, and Blood Institute ARDS Clinical Trials Network, 2004). Consequently, future investigational designs must shift away from standardized protocols toward precision-driven recruitment strategies—guided by real-time recruitability metrics, hemodynamic tracking, and advanced imaging modalities—while systematically measuring hard clinical endpoints such as long-term survival, ventilator-free duration, and barotrauma incidence.

Conclusion

In adult patients with acute respiratory distress syndrome (ARDS), lung recruitment maneuvers yielded no statistically significant reduction in all-cause mortality when evaluated against conventional or alternative ventilatory strategies. Although pooled estimates confirmed this lack of survival benefit—compounded by equatorial risks for barotrauma or pneumothorax despite pronounced inter-study heterogeneity—these observations collectively counter the clinical assumption that recruitment protocols behave as a uniform intervention.

While specific trials documented acute increments in oxygenation, respiratory mechanics, or regional ventilation distribution, these transient physiological surrogates failed to yield corresponding patient-centered advantages regarding survival or ventilator-free duration. This clinical divergence was underscored by the largest randomized investigation, which established a distinct signal of harm—specifically worse outcomes—when aggressive recruitment was paired with titrated PEEP. Consequently, these heterogeneous data countermand the routine deployment of aggressive recruitment protocols within unselected adult ARDS cohorts.

Salvaging a clinical utility for recruitment maneuvers requires transitioning from a standardized intervention toward a precision-driven paradigm restricted to phenotypic sub-populations with demonstrable lung recruitability and robust hemodynamic reserves.

Operationally, this individualization shifts the focus of future investigational designs away from transient physiological surrogates and toward hard clinical endpoints, managed under strict airway pressure limits and real-time hemodynamic tracking.

Authors' Contribution Statement

Nataly Rosario Pacheco Serrano: Conceptualization, Investigation, Software, Writing – Original Draft Preparation

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Diana Jazmina Maldonado Borja: Formal Analysis, Project Administration, Visualization

Samuel Olegario Iñiguez Jimenez: Funding Acquisition, Resources, Validation

Statement of Conflict of Interest

The authors declare that they have no conflicts of interest.

Statement on the Availability of Research Data

The research data are included in the manuscript itself

Statement on the Use of AI

The ChatGPT 5.5 artificial intelligence tool was used to assist with grammar checking and the standardization of references

Data Availability Statement

The data is available in the same document

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