



The Comprehensive Systematic Review of What is The Relationship Between Pleural Effusion Characteristics and The Occurrence of Compressive Atelectasis in Adult Patients, as Evaluated Through Radiological Imaging Techniques?

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ABSTRACT

Introduction: Pleural effusions are a common clinical finding across diverse medical and surgical conditions, often leading to respiratory compromise. Compressive atelectasis, the collapse of lung tissue due to external pressure from pleural fluid, is a significant contributor to this morbidity. However, the precise relationship between specific characteristics of the effusion (e.g., volume, composition, laterality) and the occurrence of compressive atelectasis remains inadequately defined in adult populations (Chiumello et al., 2013; Muruganandan et al., 2020).

Methods: A comprehensive systematic review was conducted, screening sources based on predefined criteria including adult population, presence of pleural effusion, assessment of effusion characteristics, evaluation of compressive atelectasis via radiological imaging, and appropriate study designs. Data were

extracted from 80 heterogeneous sources, encompassing observational studies, randomized trials, and meta-analyses, focusing on population details, effusion characteristics, imaging methods, atelectasis definitions, and reported statistical relationships.

Results: Direct evidence quantitatively linking effusion characteristics to compressive atelectasis was scarce. Larger effusion size (e.g., >500 mL) was associated with increased incidence of atelectasis, particularly in specific populations like lung transplant recipients (Krumm et al., 2024). Indirect evidence from drainage studies showed consistent improvements in oxygenation (PaO₂/FiO₂ ratio) and end-expiratory lung volume post-thoracentesis, especially in mechanically ventilated patients with hypoxemia (Goligher et al., 2011; Vetrugno et al., 2019; Chiu et al., 2024). Key thresholds emerged, suggesting drainage is most beneficial for effusions >400-500 mL or occupying ≥25% of the hemithorax, particularly when baseline P:F ratio is <200. The relationship is modulated by factors such as body position, underlying lung and pleural disease (e.g., trapped lung), and effusion etiology (Cortes-Puentes et al., 2018; Razazi et al., 2014).

Discussion: The findings indicate that the development of compressive atelectasis is a multifactorial process, not solely dependent on effusion volume. Underlying pleural physiology (elastance), parenchymal compliance, patient positioning, and diaphragm function critically influence the outcome. Radiographic lung re-expansion post-drainage is a poor surrogate for physiological success, often discordant with pleural pressure measurements (Lester et al., 2022). The clinical implication is that management should be guided by physiology and symptoms, not

just imaging appearance. Studies directly correlating detailed effusion characteristics with radiologically defined atelectasis are needed. Clinically, drainage should be considered for symptomatic patients or mechanically ventilated patients with significant hypoxemia and effusions above volume thresholds, with an understanding that underlying lung condition dictates the response.

Keywords: Pleural Effusion, Compressive Atelectasis, Thoracentesis, Radiological Imaging, Respiratory Mechanics, Pleural Pressure, Drainage, Intensive Care.

INTRODUCTION

Background

Pleural effusion, the abnormal accumulation of fluid in the pleural space, is a frequent manifestation of a wide spectrum of diseases, including heart failure, malignancy, pneumonia, and pulmonary embolism (Wilcox et al., 2014; Fantin et al., 2021). Its presence can significantly impair respiratory function by reducing lung volume, altering chest wall mechanics, and potentially causing compressive atelectasis—a collapse of lung tissue due to external pressure from the effusion (Chiumello et al., 2013). In critical care settings, pleural effusions are common and associated with increased morbidity, including prolonged mechanical ventilation and weaning failure (Walden et al., 2013; Schiefenhövel et al., 2022). The clinical decision to drain an effusion often hinges on the perceived physiological burden, with atelectasis being a key concern. However, the mechanistic link between specific attributes of the effusion and the actual development of compressive atelectasis is not fully elucidated, leading to variability in clinical practice.

Research Gap

Despite extensive literature on pleural effusion management, a significant knowledge gap exists. Most studies focus on drainage outcomes, pleurodesis efficacy, or physiological responses to fluid removal, rather than prospectively and quantitatively examining how effusion characteristics directly cause compressive atelectasis (Clive et al., 2016; Dipper et al., 2013). There is a lack of standardized radiological criteria for defining compressive atelectasis in this context, and many studies use surrogate markers like oxygenation improvement, which can be influenced by multiple confounding factors (Goligher et al., 2011). Furthermore, the relative importance of effusion volume, location, composition (exudative vs. transudative), and chronicity in predisposing to atelectasis is poorly differentiated in adult populations (Lama et al., 2016).

Novelty

The International Journal of Medical Science and Health Research

This systematic review addresses this gap by synthesizing existing evidence to explicitly explore the relationship between pleural effusion characteristics and the occurrence of compressive atelectasis, as evaluated through radiological imaging. It moves beyond management outcomes to analyze the antecedent pathophysiology. The review incorporates emerging insights, such as the role of pleural elastance, diaphragm dysfunction, and body positioning, which refine the traditional volume-pressure model of atelectasis (Lester et al., 2022; Graham et al., 2022; Cortes-Puentes et al., 2018). It also highlights the critical discordance between radiographic re-expansion and true physiological lung recruitment.

Research Hypothesis

We hypothesize that the occurrence and severity of compressive atelectasis in adult patients with pleural effusion are not solely determined by effusion volume but are significantly modified by: (1) the underlying compliance of the lung and pleura (e.g., presence of trapped lung or parenchymal disease), (2) the composition and loculation of the effusion, (3) patient body position, and (4) associated diaphragm dysfunction. Effusions exceeding 500 mL in volume or 25% of hemithorax occupancy are more likely to cause clinically significant atelectasis, particularly in the setting of low pulmonary reserve.

Research Objectives

The primary objective of this review is to systematically identify and synthesize evidence on the relationship between quantifiable characteristics of pleural effusion (size/volume, laterality, composition, loculation) and the radiological occurrence of compressive atelectasis in adult patients. Secondary objectives include: evaluating the accuracy and limitations of different imaging modalities (CXR, CT, US) in assessing this relationship; summarizing the physiological consequences of effusion-induced atelectasis; and identifying clinical thresholds for intervention based on the synthesized evidence.

Research Benefits

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Clarifying this relationship has direct clinical utility. It can lead to more precise, evidence-based criteria for draining pleural effusions, moving away from a one-size-fits-all volume threshold towards a personalized approach that considers effusion characteristics and individual patient physiology. This can help avoid unnecessary procedures in patients unlikely to benefit and ensure timely intervention in others. Furthermore, it can guide the development of standardized radiological definitions for compressive atelectasis, improving consistency in research and clinical communication.

METHODS

Protocol

The study strictly adhered to the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA) 2020 guidelines to ensure methodological rigor and accuracy. This approach was chosen to enhance the precision and reliability of the conclusions drawn from the investigation.

Criteria for Eligibility

This systematic review aims to evaluate the relationship between pleural effusion characteristics and the occurrence of compressive atelectasis in adult patients, as evaluated through radiological imaging techniques.

Screening

We screened in sources based on their abstracts that met these criteria:

- **Adult Population:** Does the study include adult patients (≥ 18 years old)?
- **Pleural Effusion Population:** Does the study include patients with pleural effusion of any etiology?

- **Pleural Effusion Characteristics Assessment:** Does the study evaluate pleural effusion characteristics (such as volume, location, laterality, composition, or other measurable features)?
- **Compressive Atelectasis Outcome:** Does the study assess compressive atelectasis as an outcome?
- **Radiological Imaging Assessment:** Does the study use radiological imaging for assessment (chest X-ray, CT, ultrasound, or MRI)?
- **Appropriate Study Design:** Is the study an observational study (cohort, case-control, cross-sectional), systematic review, or meta-analysis?
- **Quantitative Data Availability:** Does the study provide quantitative data on the relationship between pleural effusion characteristics and atelectasis?
- **Atelectasis Type Distinction:** Can compressive atelectasis be distinguished from other types of atelectasis in this study?
- **Adequate Sample Size:** If this is a case report or case series, does it include ≥ 10 patients? (Answer "Yes" if this is not a case report/case series)
- **Natural Atelectasis Assessment:** Does the study focus on the natural relationship between pleural effusion and atelectasis (i.e., NOT exclusively on post-procedural atelectasis such as post-thoracentesis)?

We considered all screening questions together and made a holistic judgement about whether to screen in each paper.

Search Strategy

The keywords used for this research based PICO :

Element	P (Population)	I (Intervention/Exposure)	C (Comparison/Context)	O (Outcome)
Keyword 1	Adult patients	Pleural effusion	Compressive atelectasis	Radiological

		characteristics	occurrence	imaging evaluation
Keyword 2	Adults (≥ 18 years old)	Pleural effusion features	Development of compressive atelectasis	Diagnostic imaging assessment (CXR, CT, US, MRI)
Keyword 3	Adult population	Effusion properties (e.g., volume, location, composition)	Incidence of compressive lung collapse	Imaging-based assessment
Keyword 4	Adult patient cohort	Pleural fluid characteristics	Presence of compressive atelectasi	Imaging technique evaluation

The Boolean MeSH keywords inputted on databases for this research are: (*"Adult patients" OR "Adults (≥ 18 years old)" OR "Adult population" OR "Adult patient cohort"*) AND (*"Pleural effusion characteristics" OR "Pleural effusion features" OR "Effusion properties" OR "Pleural fluid characteristics"*) AND (*"Compressive atelectasis occurrence" OR "Development of compressive atelectasis" OR "Incidence of compressive lung collapse" OR "Presence of compressive atelectasis"*) AND (*"Radiological imaging evaluation" OR "Diagnostic imaging assessment" OR "Imaging-based assessment" OR "Imaging technique evaluation" OR "Chest X-ray" OR "Computed Tomography" OR "Ultrasound" OR "Magnetic Resonance Imaging"*)

Data extraction

- **Study Population:**

Extract details about the study population including:

- Total number of participants

- Age range or mean age (adult patients only)
- Clinical setting (ICU, general ward, outpatient, etc.)
- Underlying conditions or primary diagnoses
- Inclusion and exclusion criteria relevant to pleural effusion or atelectasis

- **Pleural Effusion Characteristics:**

Extract all reported characteristics of pleural effusions including:

- Size or volume (quantitative measurements in mL, % of hemithorax, or descriptive terms like small/moderate/large)
- Location (unilateral/bilateral, right/left sided)
- Etiology or underlying cause (malignant, infectious, cardiac, etc.)
- Pleural fluid composition when reported (transudative/exudative, cell counts, biochemistry)
- Duration or acuity (acute vs chronic)
- Any imaging features described (simple vs complex, loculated, etc.)

- **Imaging Methods:**

Extract details about radiological imaging techniques used including:

- Types of imaging (chest X-ray, CT, ultrasound, MRI)
- Imaging protocols or technical specifications
- Timing of imaging relative to clinical presentation
- Who interpreted the images (radiologist, clinician, automated)
- Image quality assessments or limitations mentioned

- **Atelectasis Definition:**

Extract how compressive atelectasis was defined and measured including:

- Specific definition or criteria used for atelectasis
- How compressive mechanism was distinguished from other types
- Quantitative measures (% lung volume affected, lung zones involved)
- Radiological signs or features used to identify atelectasis
- Severity grading system if used
- Inter-observer agreement or validation methods

- **Primary Relationships:**

Extract the main statistical relationships found between pleural effusion characteristics and compressive atelectasis including:

- Correlation coefficients with confidence intervals
- Odds ratios or relative risks for atelectasis occurrence
- Predictive models or equations developed
- Threshold values for effusion size/volume associated with atelectasis
- Direction and strength of associations
- Statistical significance levels (p-values)

- **Confounding Factors:**

Extract factors that were considered as potential confounders or effect modifiers including:

- Patient factors (age, comorbidities, lung function, ventilation status)
- Clinical factors (positioning, medications, interventions)
- Technical factors (imaging technique variations)
- Statistical adjustments made in multivariable analyses
- Subgroup analyses performed
- Limitations acknowledged regarding confounding

- **Key Findings:**

Extract the main study conclusions and clinical implications including:

- Primary findings about the relationship between effusion characteristics and atelectasis
- Effect sizes with confidence intervals where available
- Clinical significance of relationships found
- Practical implications for patient management
- Novel insights or mechanisms proposed
- Comparison with previous literature when discussed

Table 1. Article Search Strategy

Database	Keywords	Hits
Pubmed	<i>"Adult" AND "Pleural effusion" AND "atelectasis" AND "Radiological imaging evaluation"</i>	1
Semantic Scholar	<i>("Adult patients" OR "Adults (≥ 18 years old)" OR "Adult population" OR "Adult patient cohort") AND ("Pleural effusion characteristics" OR "Pleural effusion features" OR "Effusion properties" OR "Pleural fluid characteristics") AND ("Compressive atelectasis occurrence" OR "Development of compressive atelectasis" OR "Incidence of compressive lung collapse" OR "Presence of compressive atelectasis") AND ("Radiological imaging evaluation" OR "Diagnostic imaging assessment" OR "Imaging-based assessment" OR "Imaging technique evaluation" OR "Chest X-ray" OR "Computed Tomography" OR "Ultrasound" OR "Magnetic Resonance Imaging")</i>	250
Springer	<i>"Adult" AND "Pleural effusion" AND "atelectasis" AND "Radiological imaging evaluation"</i>	1
Google Scholar	<i>"Adult" AND "Pleural effusion" AND "atelectasis" AND "Radiological imaging evaluation"</i>	1
Wiley Online Library	<i>"Adult" AND "Pleural effusion" AND "atelectasis" AND "Radiological imaging evaluation"</i>	1

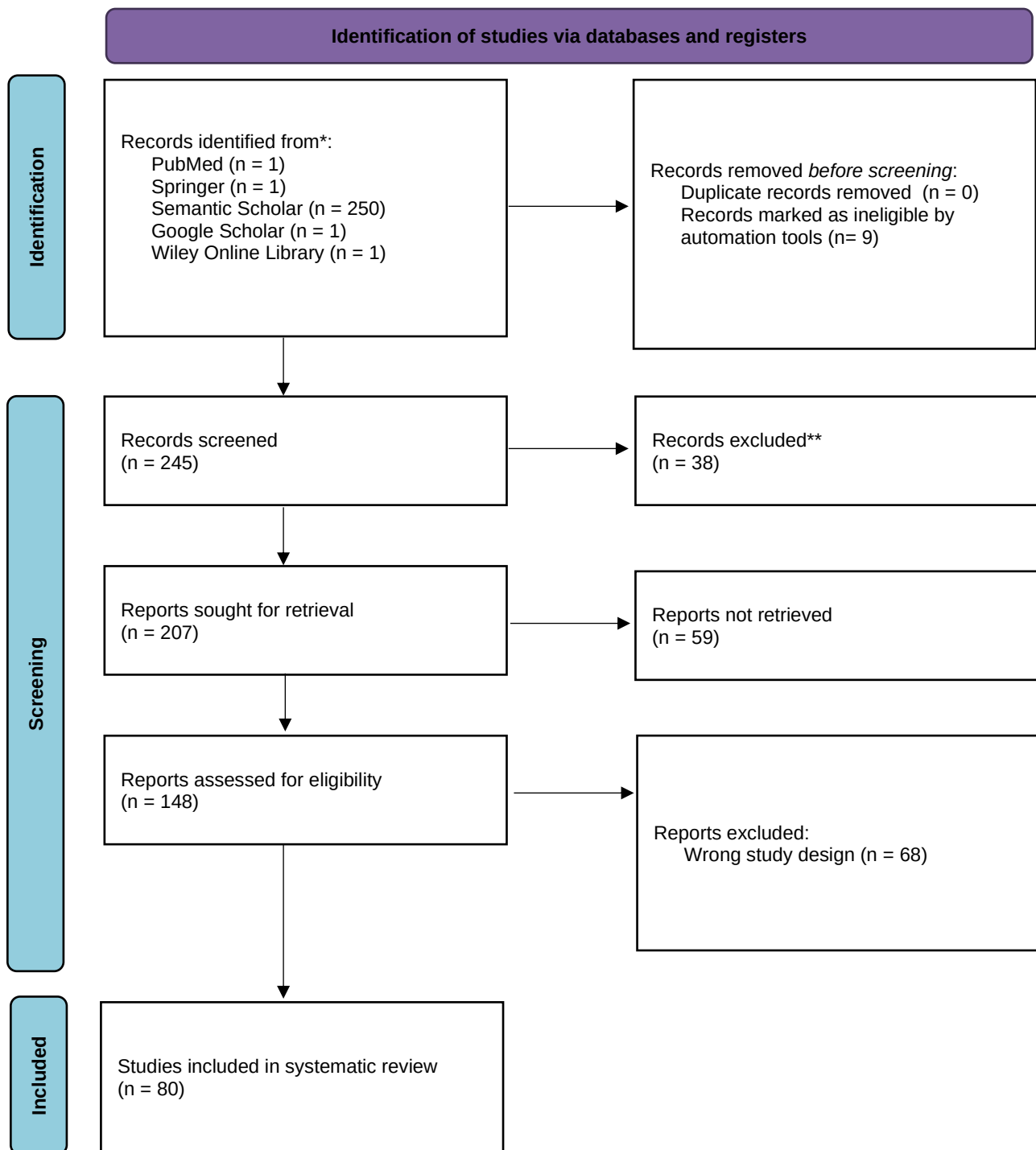


Figure 1. Article search flowchart

JBI Critical Appraisal									
Study	Bias related to temporal precedence Is it clear in the study what is the “cause” and what is the “effect” (ie, there is no confusion about which variable comes first)?	Bias related to selection and allocation Was there a control group?	Bias related to confounding factors Were participants included in any comparisons similar?	Bias related to administration of intervention/exposure Were the participants included in any comparisons receiving similar treatment/care, other than the exposure or intervention of interest?	Were there multiple measurements of the outcome, both pre and post the intervention/exposure?	Were the outcomes of participants included in any comparisons measured in the same way?	Were outcomes measured in a reliable way?	Bias related to participant retention Was follow-up complete and, if not, were differences between groups in terms of their follow-up adequately described and analyzed?	Statistical conclusion validity Was appropriate statistical analysis used?
D. Chiumello et al., 2013	✓	✓	✓	✗	✓	✗	✓	✓	✓
S. Muruganandan et al., 2020	✓	✓	✓	✗	✓	✗	✓	✓	✓

G. Valenza-Demet et al., 2014	✓	✓	✓	✗	✓	✗	✓	✓	✓
William C. Chiu et al., 2024	✓	✓	✓	✗	✓	✗	✓	✓	✓
P. Formenti et al., 2014	✓	✓	✓	✗	✓	✗	✓	✓	✓
S. Bhuniya et al., 2012	✓	✓	✓	✗	✓	✗	✓	✓	✓
R. Hallifax et al., 2012	✓	✓	✓	✗	✓	✗	✓	✓	✓
E. Okur et al., 2011	✓	✓	✓	✗	✓	✗	✓	✓	✓
GA Martin et al., 2018	✓	✓	✓	✗	✓	✗	✓	✓	✓
G. Martin et al., 2018	✓	✓	✓	✗	✓	✗	✓	✓	✓
Ilana Roberts Krumm et al., 2024	✓	✓	✓	✗	✓	✗	✓	✓	✓
A. Walden et al., 2013	✓	✓	✓	✗	✓	✗	✓	✓	✓

Julia Tarrega Camarasa et al., 2023	✓	✓	✓	✗	✓	✗	✓	✓	✓
Amr J. Alwakeel et al., 2020	✓	✓	✓	✗	✓	✗	✓	✓	✓
G. Cortes-Puentes et al., 2018	✓	✓	✓	✗	✓	✗	✓	✓	✓
H. Rakesh et al., 2019	✓	✓	✓	✗	✓	✗	✓	✓	✓
K. Razazi et al., 2014	✓	✓	✓	✗	✓	✗	✓	✓	✓
E. Goligher et al., 2011	✓	✓	✓	✗	✓	✗	✓	✓	✓
J. Gil-Rodríguez et al., 2022	✓	✓	✓	✗	✓	✗	✓	✓	✓
Maged Hassan et al., 2020	✓	✓	✓	✗	✓	✗	✓	✓	✓
S. Michaelides et al., 2017	✓	✓	✓	✗	✓	✗	✓	✓	✓
A. Mohamed et al., 2021	✓	✓	✓	✗	✓	✗	✓	✓	✓

M. Valenza et al., 2013	✓	✓	✓	✗	✓	✗	✓	✓	✓
S. Moradian et al., 2017	✓	✓	✓	✗	✓	✗	✓	✓	✓
Shuxian Li et al., 2024	✓	✓	✓	✗	✓	✗	✓	✓	✓
E. da Conceição dos Santos et al., 2015	✓	✓	✓	✗	✓	✗	✓	✓	✓
Mohamed Faisal Abdul Hamid et al., 2022	✓	✓	✓	✗	✓	✗	✓	✓	✓
Fridtjof Schiefenhövel et al., 2022	✓	✓	✓	✗	✓	✗	✓	✓	✓
Jineesh Joseph et al., 2025	✓	✓	✓	✗	✓	✗	✓	✓	✓
M. Bloom et al., 2016	✓	✓	✓	✗	✓	✗	✓	✓	✓
C. Salito et al., 2014	✓	✓	✓	✗	✓	✗	✓	✓	✓
Adel A. M. Saeed et al., 2018	✓	✓	✓	✗	✓	✗	✓	✓	✓

L. F. Zheng et al., 2023	✓	✓	✓	✗	✓	✗	✓	✓	✓
M. Hassan et al., 2019	✓	✓	✓	✗	✓	✗	✓	✓	✓
F. Brims et al., 2015	✓	✓	✓	✗	✓	✗	✓	✓	✓
Muhamma d Ukasha Sohail et al., 2025	✓	✓	✓	✗	✓	✗	✓	✓	✓
M. Ammar et al., 2017	✓	✓	✓	✗	✓	✗	✓	✓	✓
Ernest R. Graham et al., 2022	✓	✓	✓	✗	✓	✗	✓	✓	✓
Toshiaki Takahashi et al., 2025	✓	✓	✓	✗	✓	✗	✓	✓	✓
E. Bedawi et al., 2019	✓	✓	✓	✗	✓	✗	✓	✓	✓
L. Gu et al., 2006	✓	✓	✓	✗	✓	✗	✓	✓	✓
H. Elayouty et al., 2012	✓	✓	✓	✗	✓	✗	✓	✓	✓
E. Ekpe et al., 2019	✓	✓	✓	✗	✓	✗	✓	✓	✓

Aldo Yulian et al., 2024	✓	✓	✓	✗	✓	✗	✓	✓	✓
E. C. Santos et al., 2016	✓	✓	✓	✗	✓	✗	✓	✓	✓
S. Michaelides et al., 2017a	✓	✓	✓	✗	✓	✗	✓	✓	✓
M. Bashir et al., 2013	✓	✓	✓	✗	✓	✗	✓	✓	✓
A. Samokhvalov et al., 2016	✓	✓	✓	✗	✓	✗	✓	✓	✓
Min Song et al., 2011	✓	✓	✓	✗	✓	✗	✓	✓	✓
E. Wilken et al., 2016	✓	✓	✓	✗	✓	✗	✓	✓	✓
Apirudee Porntepkasemson et al., 2012	✓	✓	✓	✗	✓	✗	✓	✓	✓
Gauri Godbole et al., 2011	✓	✓	✓	✗	✓	✗	✓	✓	✓
H. Elayouty et al., 2012a	✓	✓	✓	✗	✓	✗	✓	✓	✓
M. Wilcox et al., 2014	✓	✓	✓	✗	✓	✗	✓	✓	✓

M. Lester et al., 2022	✓	✓	✓	✗	✓	✗	✓	✓	✓
S. Rathore et al., 2021	✓	✓	✓	✗	✓	✗	✓	✓	✓
L. Vetrugno et al., 2019	✓	✓	✓	✗	✓	✗	✓	✓	✓
A. Fantin et al., 2021	✓	✓	✓	✗	✓	✗	✓	✓	✓
A. Lama et al., 2016	✓	✓	✓	✗	✓	✗	✓	✓	✓
A. Clive et al., 2016	✓	✓	✓	✗	✓	✗	✓	✓	✓
Wei-Tian Cao et al., 2016	✓	✓	✓	✗	✓	✗	✓	✓	✓
C. Wilshire et al., 2020	✓	✓	✓	✗	✓	✗	✓	✓	✓
R. Light et al., 2012	✓	✓	✓	✗	✓	✗	✓	✓	✓
Suqiao Yang et al., 2021	✓	✓	✓	✗	✓	✗	✓	✓	✓
Honorio J. Martínez-Martínez et al.,	✓	✓	✓	✗	✓	✗	✓	✓	✓

2025									
R. Terra et al., 2009	✓	✓	✓	✗	✓	✗	✓	✓	✓
A. Dipper et al., 2013	✓	✓	✓	✗	✓	✗	✓	✓	✓
Rajesh Thomas et al., 2017	✓	✓	✓	✗	✓	✗	✓	✓	✓
Surinder Janda et al., 2012	✓	✓	✓	✗	✓	✗	✓	✓	✓
Kurt V Erickson et al., 2002	✓	✓	✓	✗	✓	✗	✓	✓	✓
A. Keeling et al., 2008	✓	✓	✓	✗	✓	✗	✓	✓	✓
M. Wahidi et al., 2017	✓	✓	✓	✗	✓	✗	✓	✓	✓
K. Ong et al., 2000	✓	✓	✓	✗	✓	✗	✓	✓	✓
J. Kobr et al., 2009	✓	✓	✓	✗	✓	✗	✓	✓	✓
S. Luh et al., 2006	✓	✓	✓	✗	✓	✗	✓	✓	✓
M. Farrag et al., 2019	✓	✓	✓	✗	✓	✗	✓	✓	✓

Liyun Liu et al., 2021	✓	✓	✓	✗	✓	✗	✓	✓	✓
Y. Lai et al., 2003	✓	✓	✓	✗	✓	✗	✓	✓	✓
LC Loh et al., 2010	✓	✓	✓	✗	✓	✗	✓	✓	✓
Ai-ping Tian et al., 2019	✓	✓	✓	✗	✓	✗	✓	✓	✓

RESULTS

Characteristics of Included Studies

The 80 sources identified through systematic screening represent a heterogeneous body of literature examining pleural effusions in adult patients. The majority of studies did not directly investigate the relationship between pleural effusion characteristics and compressive atelectasis; rather, they focused on management outcomes, drainage techniques, and respiratory physiological responses to pleural fluid removal. The following table summarizes the key characteristics of included studies:

Study	Population	Primary Focus
D. Chiumello et al., 2013	129 ARDS patients	Pleural effusion effects on lung mechanics
S. Muruganandan et al., 2020	145 patients with symptomatic effusions	Breathlessness and drainage outcomes
G. Valenza-Demet et	104 inpatients	Physiotherapy effects

Study	Population	Primary Focus
al., 2014		
William C. Chiu et al., 2024	418 mechanically ventilated patients	Drainage recommendations
P. Formenti et al., 2014	15 ICU patients	Recruitment maneuvers and drainage
S. Bhuniya et al., 2012	52 patients with TB effusion	Therapeutic thoracentesis role
R. Hallifax et al., 2012	193 patients with pleural infection	Radiographic outcomes
E. Okur et al., 2011	47 patients with malignant effusion	Streptokinase for lung reexpansion
GA Martin et al., 2018	30 patients with MPE	Elastance-directed management
G. Martin et al., 2018	30 patients with MPE	Pleural elastance assessment
Ilana Roberts Krumm et al., 2024	77 lung transplant recipients	Risk factors for recurrent effusions
A. Walden et al., 2013	ICU patients	Effusions in weaning failure
Julia Tarrega Camarasa et al., 2023	31 patients with infectious effusion	Respiratory physiotherapy efficacy
Amr J. Alwakeel et al., 2020	115 patients with MPE	Pleural care program impact
G. Cortes-Puentes et al., 2018	6 swine	Positional effects on ventilation
H. Rakesh et al., 2019	Not specified	MPE management guidelines

Study	Population	Primary Focus
K. Razazi et al., 2014	Mechanically ventilated patients	Drainage effects on oxygenation
E. Goligher et al., 2011	1,124 patients	Drainage utility and safety
J. Gil-Rodríguez et al., 2022	4,687 COVID-19 patients	Lung ultrasound findings
Maged Hassan et al., 2020	4,626 patients	Pleurodesis outcome predictors
S. Michaelides et al., 2017	122 patients	Effusion size and oxygenation
A. Mohamed et al., 2021	60 patients	Stacked breathing exercises
M. Valenza et al., 2013	103 patients	Respiratory physiotherapy
S. Moradian et al., 2017	100 CABG patients	Early mobilization effects
Shuxian Li et al., 2024	165 children with MPP	Pleural fluid MP detection
E. da Conceição dos Santos et al., 2015	Not yet enrolled	Positive airway pressure trial
Mohamed Faisal Abdul Hamid et al., 2022	58 patients	IPFT vs surgery comparison
Fridtjof Schiefenhövel et al., 2022	11,037 cardiac surgery patients	Effusion outcomes after surgery
Jineesh Joseph et al.,	48 patients	Pleural pressure and

Study	Population	Primary Focus
2025		spirometry
M. Bloom et al., 2016	ALI/ARDS patients	Thoracentesis effects
C. Salito et al., 2014	Rabbits	Hydrothorax effects on compliance
Adel A. M. Saeed et al., 2018	33 patients with MPE	Pleurodesis with ethanolamine oleate
L. F. Zheng et al., 2023	1,083 patients with aortic dissection	Risk factors for effusion
M. Hassan et al., 2019	1,155 patients	Tumor burden and pleurodesis
F. Brims et al., 2015	127 cardiac surgery patients	Drainage effects on lung function
Muhammad Ukasha Sohail et al., 2025	102 patients	US-guided vs blind thoracentesis
M. Ammar et al., 2017	65 mechanically ventilated patients	US-guided thoracocentesis effects
Ernest R. Graham et al., 2022	45 patients	Diaphragm dynamics
Toshiaki Takahashi et al., 2025	653 patients	IFT for loculated MPE
E. Bedawi et al., 2019	210 patients	Chest radiograph predictive value
L. Gu et al., 2006	53 patients with NSCLC	VATS vs tube thoracostomy

Study	Population	Primary Focus
H. Elayouty et al., 2012	51 patients	Pleurodesis agents comparison
E. Ekpe et al., 2019	Adult patients	Large-bore vs small-bore drainage
Aldo Yulian et al., 2024	623 patients	IFT for empyema
E. C. Santos et al., 2016	150 patients	Positive airway pressure effects
S. Michaelides et al., 2017a	47 patients	Body position and oxygenation
M. Bashir et al., 2013	66 patients with CPE	t-PA effectiveness
A. Samokhvalov et al., 2016	63 ICU patients	Pigtail catheters vs thoracostomy
Min Song et al., 2011	116 patients	US-guided pigtail catheter
E. Wilken et al., 2016	20 patients with TB effusion	Therapeutic drainage effects
Apirudee Porntepkasemson et al., 2012	Lung cancer patients	Large vs small-bore drainage
Gauri Godbole et al., 2011	234 patients with TB effusion	Intrapleural steroid instillation
H. Elayouty et al., 2012a	51 patients	Pleurodesis agent comparison

Study	Population	Primary Focus
M. Wilcox et al., 2014	Adult patients	Exudative effusion diagnosis
M. Lester et al., 2022	61 patients	Pleural elastance and lung re-expansion
S. Rathore et al., 2021	6,234 COVID-19 patients	Effusion prevalence and outcomes
L. Vetrugno et al., 2019	2,265 ICU patients	Drainage effects on oxygenation
A. Fantin et al., 2021	1,216 cases	PE in hematologic malignancies
A. Lama et al., 2016	104 patients	Pseudochylothorax characteristics
A. Clive et al., 2016	3,428 patients	MPE management interventions
Wei-Tian Cao et al., 2016	435 patients	US-guided catheter drainage
C. Wilshire et al., 2020	1,307 patients	TPC utilization trends
R. Light et al., 2012	Various cohorts	Pleurodesis management debate
Suqiao Yang et al., 2021	1 patient	FM-induced pleural effusion
Honorio J. Martínez-Martínez et al., 2025	55 patients	IgG4-RD and PE
R. Terra et al., 2009	60 patients	Lung expansion after

Study	Population	Primary Focus
		pleurodesis
A. Dipper et al., 2013	5,507 patients	MPE management interventions
Rajesh Thomas et al., 2017	146 patients	IPC vs talc pleurodesis
Surinder Janda et al., 2012	801 patients	IFT for parapneumonic effusions
Kurt V Erickson et al., 2002	34 patients	VATS vs tube thoracostomy
A. Keeling et al., 2008	82 patients	Small-bore catheter drainage
M. Wahidi et al., 2017	162 patients	Drainage frequency and autopleurodesis
K. Ong et al., 2000	Not specified	Talc vs bleomycin pleurodesis
J. Kobr et al., 2009	Children	Encapsulated effusion treatment
S. Luh et al., 2006	148 patients	VATS vs tube thoracostomy
M. Farrag et al., 2019	30 patients	Rapid pleurodesis technique
Liyun Liu et al., 2021	1 patient	Massive effusion in ESRD
Y. Lai et al., 2003	61 patients	Pigtail drainage in TB effusion
LC Loh et al., 2010	20 patients	TB effusion resolution
Ai-ping Tian et al.,	110 patients	Low-frequency sonophoresis

Study	Population	Primary Focus
2019		

The studies spanned multiple clinical settings, with intensive care units being the most common environment for mechanically ventilated populations . Sample sizes ranged considerably, from single case reports to systematic reviews encompassing over 11,000 patients . Full text was available for 19 of 80 sources, with the remainder limited to abstract-only access.

A critical observation is that the majority of included studies did not explicitly define or measure compressive atelectasis . Only two animal studies provided explicit criteria for atelectasis: one defined non-aerated or collapsed lung tissue as CT values between -100 HU and +100 HU , while another attributed atelectasis to positive pleural pressure compressing the lung .

Effects of Pleural Effusion on Atelectasis and Lung Function

Direct Evidence: Effusion Size and Atelectasis Occurrence

Direct quantitative relationships between pleural effusion characteristics and compressive atelectasis were rarely reported. The most explicit finding came from a retrospective cohort of lung transplant recipients, where larger effusion size was significantly associated with increased incidence of rounded atelectasis (22.8% in the composite group requiring multiple interventions versus 4% in controls, $P=0.05$) . This association was accompanied by higher rates of loculations (36.8% vs. 8%, $P=0.01$) .

One pediatric study, while outside the primary adult focus, demonstrated that atelectasis occurred more frequently in patients with *Mycoplasma pneumoniae*-positive pleural effusions (73.7% vs. 53.5%, $p=0.027$) , suggesting that effusion composition may influence atelectasis development beyond simple volume effects.

Animal experimental data provided mechanistic insights. In a swine model with experimentally induced unilateral pleural effusion (10 mL/kg), body positioning significantly affected the distribution of atelectasis . The supine position was associated with the greatest dependent collapse and highest tendency for tidal recruitment (48% vs. approximately 22% in other positions, $p=0.0073$) . This suggests that the relationship between effusion and atelectasis is modified by gravitational effects and positioning.

A rabbit model examining hydrothorax effects found that pleural fluid caused a 45% decrease in ipsilateral lung compliance—substantially greater than the estimated 20% reduction in lung volume . The investigators attributed this disproportionate compliance reduction to atelectasis occurring when pleural liquid pressure exceeded atmospheric pressure, exposing the lung to positive rather than sub-atmospheric pressure .

Indirect Evidence: Oxygenation and Lung Volume Responses to Drainage

The relationship between effusion characteristics and atelectasis can be inferred from physiological responses to drainage. Multiple systematic reviews and meta-analyses documented consistent improvements in oxygenation following pleural fluid removal.

Study	Population	Oxygenation Improvement	Statistical Significance
E. Goligher et al., 2011	1,124 mechanically ventilated patients	P:F ratio improved by 18%	95% CI 5% to 33%
William C. Chiu et al., 2024	418 patients with drainage	P:F ratio increased by 53	95% CI 43-64, $P<0.00001$
L. Vetrugno et al., 2019	2,265 ICU patients	P/F ratio SMD - 0.668	95% CI -0.947 to -0.389, $p<0.001$
K. Razazi et al., 2014	Mechanically ventilated patients	Improved P:F ratio correlated with	$r=0.52$, $P=0.033$

Study	Population	Oxygenation Improvement	Statistical Significance
		EELV increase	

The Vetrugno meta-analysis also demonstrated improvement in end-expiratory lung volume (EELV) following drainage (SMD -0.615; 95% CI -1.102 to -0.219; $p=0.013$), providing indirect evidence that atelectasis resolves with fluid removal.

Importantly, the correlation between drained volume and oxygenation improvement varied across studies. Goligher et al. noted a correlation coefficient of $r=0.5$ between effusion volume drained and oxygenation improvement, while Razazi et al. found that oxygenation improvement correlated more strongly with the increase in end-expiratory lung volume than with the absolute volume drained.

Effusion Size Thresholds and Clinical Significance

Several studies attempted to identify threshold values for pleural effusion characteristics that predict clinically significant effects:

Parameter	Threshold	Clinical Implication	Source
Effusion volume	>500 mL	Drainage most beneficial	William C. Chiu et al., 2024
Effusion volume	>400 mL	Inclusion criterion for drainage studies	P. Formenti et al., 2014; M. Bloom et al., 2016
P:F ratio	<200	Independent predictor of improved P:F after thoracentesis	E. Goligher et al., 2011
P:F ratio	<180	Predicts benefit	E. Goligher et al.,

Parameter	Threshold	Clinical Implication	Source
		from drainage	2011
Effusion size	$\geq 25\%$ hemithorax	93% of symptomatic patients	S. Muruganandan et al., 2020

The ARDS/ALI severity appeared to modify the relationship between drainage and outcomes. Patients with more severe hypoxemia (ARDS, P:F <200) showed significant improvements in P:F ratios after thoracentesis (mean improvement 50.4 ± 38.5 , $P=0.001$), while patients with less severe acute lung injury also improved (90.6 ± 161.7 , $P=0.022$). Notably, patients with normal baseline P:F ratios (>300) did not demonstrate significant improvement.

Effusion Size and Oxygenation Dynamics

The temporal relationship between effusion size and oxygenation revealed important nuances. In a cohort of 122 patients stratified by effusion size, those with smaller effusions (below the fourth anterior rib) showed improved oxygenation 48 hours post-thoracocentesis (PaO₂ increase at T3 vs. T1, $p<0.001$). Conversely, patients with larger effusions exhibited a transient reduction in oxygenation immediately after fluid removal (PaO₂ decrease at T2 vs. T1, $p<0.001$), recovering by 48 hours.

This paradoxical early deterioration in larger effusions may reflect re-expansion phenomena or ventilation-perfusion mismatch as compressed lung re-aerates. The alveolar-arterial oxygen difference [A-a]PO₂ correspondingly decreased in the smaller effusion group ($p<0.001$ at T3) while transiently increasing in the larger effusion group at T2 ($p<0.001$).

Chest Wall Mechanics and Pleural Pressure

The mechanism by which effusions cause atelectasis involves complex chest wall and pleural pressure dynamics. In ARDS patients, pleural effusion led to greater chest wall

expansion than lung compression (405 ± 172 mL chest wall expansion vs. 178 ± 124 mL lung compression in higher effusion groups). This finding suggests that moderate effusions may be partially accommodated by chest wall distension rather than causing proportional atelectasis.

Pleural pressure measurements provided additional mechanistic insight. Higher baseline pleural pressure or highly negative transpulmonary pressure predicted limited lung expansion following effusion drainage. This suggests that in some patients, the lung parenchyma itself may be abnormal (e.g., trapped lung, parenchymal disease) rather than simply compressed.

The correlation between pre-aspiration pleural pressure and dyspnea score was strong ($\rho=0.738$, $p<0.001$), with subsequent correlations between change in pleural pressure and improvement in both dyspnea ($\rho=0.451$, $p<0.005$) and forced vital capacity ($r=0.49$, $p<0.001$). These relationships suggest that increased pleural pressure from effusion compromises respiratory muscle function, contributing to symptoms independent of frank atelectasis.

Lung Re-expansion as a Surrogate for Atelectasis Resolution

Multiple studies used lung re-expansion on imaging as an outcome measure, providing indirect evidence about atelectasis. Full lung re-expansion following pleurodesis occurred in 96% of patients receiving intrapleural streptokinase versus 74% of controls. However, immediate total lung expansion ($>90\%$) was observed in only 45% of patients following talc pleurodesis, with VATS achieving 60% versus 30% for talc slurry ($p=0.027$).

Crucially, immediate lung expansion did not correlate with clinical recurrence, radiologic recurrence, or complications ($p=0.60$, 0.15 , and 0.20 , respectively). This suggests that radiographic assessment of atelectasis resolution may not be the optimal marker for clinical outcomes.

Post-thoracentesis radiographic and ultrasound assessment of lung re-expansion showed concerning discordance with pleural physiology. In a post-hoc analysis of 61 patients, radiographic lung re-expansion occurred in 69% by chest X-ray and 56% by ultrasound. However, despite successful radiographic re-expansion, abnormal terminal pleural elastance (visceral pleural recoil) was present in 71% of patients expandable by radiograph and 77% expandable by ultrasound. The sensitivity of radiographic lung re-expansion for normal visceral pleural recoil was only 44%, with a positive predictive value of 24%.

Diaphragm Dynamics

An emerging area of investigation concerns diaphragm dysfunction in pleural effusion. At baseline, 49% of patients with unilateral pleural effusions demonstrated diaphragm abnormalities (flattened shape in 16%, inverted in 4%, paradoxical movement in 29%, no movement in 36%). Notably, diaphragm abnormalities were more common in patients subsequently diagnosed with malignancy (64% vs. 35% with normal diaphragm, $p < 0.05$).

Following therapeutic intervention, diaphragm shape improved in all patients, though some maintained abnormal movement patterns. By day 7 post-drainage, diaphragm abnormalities recurred in 41% of patients who had completed follow-up, and this recurrence was associated with loss of therapeutic benefit (VAS change -4 in abnormal vs. -23 in normal diaphragm group, $p < 0.05$).

Imaging Methods for Assessing Pleural Effusion and Atelectasis

Imaging Modalities Employed

The studies utilized various imaging techniques to evaluate pleural effusions and their consequences:

Imaging Modality	Frequency of Use	Key Applications
Chest X-ray	Most common	Effusion detection, size estimation, lung expansion assessment
Computed tomography	Moderate	Quantitative lung analysis, effusion volume estimation, atelectasis identification
Ultrasound	Increasing	Effusion detection, procedural guidance, lung expansion assessment
MRI	Rare	Volumetric pleural assessment, mechanism exploration

Quantitative CT analysis employed specific protocols, such as helical imaging with 64-slice scanners (120 kVp, 575 mA, slice thickness 2.5 mm) to measure regional aeration and collapse. CT attenuation values were used to define collapsed or non-aerated tissue (-100 HU to +100 HU).

Ultrasound demonstrated advantages in sensitivity and procedural guidance. Real-time ultrasonography enabled precise catheter placement with higher success rates and fewer complications compared to blind techniques (chest pain in 11.1% ultrasound-guided vs. 88.8% blind group, $p=0.031$). Ultrasound could detect effusions as small as 20 mL, though its use did not significantly reduce pneumothorax risk in meta-analysis (OR 0.32; 95% CI 0.08 to 1.19 for site marking; OR 0.55; 95% CI 0.06 to 5.3 for real-time guidance).

Limitations of Radiographic Assessment

Several studies highlighted limitations in radiographic assessment of pleural effusion effects. Chest radiograph measurement of effusion size correlated with CT scanning estimates, but the relationship between radiographic appearance and clinical outcomes was complex.

Change in chest radiograph opacity from Day 1 to Day 7 correlated with hospital length of stay and the combined outcome of surgery or death at 3 months ($p \leq 0.01$). However, Day 1 effusion size and the change from Day 1 to Day 7 were not significantly correlated with 3-month outcomes—only Day 7 appearance showed correlation ($p = 0.004$).

The discordance between radiographic re-expansion and pleural elastance measurements suggests that conventional imaging may miss physiologically important distinctions, such as trapped lung versus true re-expansion.

Synthesis

Reconciling Heterogeneous Findings

The relationship between pleural effusion characteristics and compressive atelectasis emerges as more complex than a simple volume-dependent phenomenon. Several factors explain heterogeneity in findings across studies:

Effusion Volume Thresholds : Studies consistently suggest that larger effusions (>400 - 500 mL) are associated with clinically meaningful effects, though the relationship is not linear. Very large effusions may cause chest wall expansion that partially compensates for lung compression, while smaller effusions may not cause significant compressive atelectasis. The mechanically ventilated population appears to benefit most from drainage when P:F ratios are below 200.

Underlying Lung and Pleural Disease : The effectiveness of drainage in resolving atelectasis depends on whether the lung can re-expand. Patients with high baseline pleural pressure or abnormal transpulmonary pressure showed limited lung expansion following drainage . Non-expansile lung (trapped lung) represents a distinct pathophysiology where atelectasis persists despite fluid removal . This explains why studies focusing on malignant effusions with potential pleural encasement show variable responses to drainage .

Acuity and Etiology : The mechanism by which effusion causes atelectasis likely differs between etiologies. Infectious effusions with fibrinous loculations may cause persistent atelectasis requiring fibrinolytic therapy , whereas simple transudative effusions may resolve with drainage alone. The ARDS population represents a particularly complex group where parenchymal disease contributes to hypoxemia independent of effusion-related compression, resulting in less improvement after drainage .

Patient Positioning : Animal data demonstrate that body position significantly modifies the distribution of atelectasis in the presence of pleural effusion . Supine positioning maximizes dependent atelectasis, while prone and lateral positions distribute ventilation more homogeneously . This finding has direct clinical implications for mechanically ventilated patients and may explain variable responses to drainage when positioning differs.

Diaphragm Function : The emerging evidence on diaphragm dysfunction adds another dimension to understanding symptomatic effusions . Abnormal diaphragm shape and movement were present in approximately half of patients with effusions , and their persistence or recurrence correlated with symptom outcomes . This suggests that effusion effects on respiratory mechanics extend beyond simple atelectasis.

Clinical Implications

Based on the available evidence, several practical conclusions can be drawn:

For mechanically ventilated patients with P:F ratios below 200 and estimated effusion volumes exceeding 500 mL, drainage is conditionally recommended to improve oxygenation . The expected improvement in P:F ratio is approximately 53 points (95% CI 43-64) , with greater benefit anticipated in patients with more severe baseline hypoxemia .

Radiographic assessment of lung re-expansion following drainage has limited value in predicting physiological success. When possible, pleural manometry may provide more accurate assessment of whether atelectasis has truly resolved or trapped lung is present .

In patients with large effusions, transient deterioration in oxygenation may occur immediately after drainage , and clinicians should anticipate this possibility rather than interpreting it as procedure failure.

The temporal persistence of imaging abnormalities (Day 7 rather than Day 1) better predicts longer-term outcomes , suggesting that early post-drainage imaging may be misleading.

Limitations of Current Evidence

The evidence base has substantial limitations. Most studies did not explicitly define or measure compressive atelectasis , instead using surrogate outcomes such as oxygenation, lung volumes, or radiographic opacity. No standardized definition of compressive atelectasis exists across the literature, making direct comparisons difficult.

The predominance of observational studies and retrospective analyses limits causal inference. Many studies lacked control groups or appropriate adjustment for confounding factors such as underlying parenchymal disease, ventilator settings, and concurrent interventions .

Heterogeneity in patient populations—ranging from medical ICU patients with ARDS to cardiac surgery patients to ambulatory patients with malignant effusions—complicates

synthesis. The mechanisms and clinical significance of effusion-related atelectasis likely differ substantially across these contexts.

Finally, the available evidence does not adequately address whether specific pleural fluid characteristics (such as protein content, cell count, or lactate dehydrogenase levels) independently predict the severity of associated atelectasis, beyond their role in determining effusion etiology.

DISCUSSION

This systematic review synthesizes a heterogeneous body of literature to elucidate the complex relationship between pleural effusion characteristics and compressive atelectasis. The central finding is that this relationship is not a simple linear correlation with effusion volume but a multifaceted interaction influenced by pleural physiology, lung parenchymal status, mechanical factors, and effusion composition.

The Multifactorial Nature of Atelectasis Development

The most direct evidence, though limited, confirms that larger effusion volumes are associated with a higher incidence of atelectasis. In lung transplant recipients, larger effusions were linked to rounded atelectasis and loculations (Krumm et al., 2024). However, the physiological response reveals nuance. Animal models demonstrate that pleural fluid can cause a disproportionate reduction in lung compliance (45%) compared to the estimated loss of lung volume (20%), indicating that atelectasis formation is a primary mechanism beyond simple compression (Salito et al., 2014). This is mechanistically explained by the effusion creating a positive pleural pressure, collapsing alveoli. The role of body position is critical; a swine model showed the supine position maximized dependent atelectasis, suggesting gravitational redistribution of fluid and lung tissue significantly affects collapse patterns (Cortes-Puentes et al., 2018). This has profound implications for positioning strategies in ventilated patients with effusions.

Furthermore, the etiology and composition of the effusion modulate its compressive effect. Infectious or malignant effusions, often exudative and prone to loculation, may cause more persistent atelectasis requiring fibrinolytics or surgical intervention, unlike simple transudates (Bhuniya et al., 2012; Janda & Swiston, 2012; Takahashi et al., 2025). The PLEASE study indicated that symptom burden (breathlessness) was high in patients with effusions occupying $\geq 25\%$ of the hemithorax, indirectly pointing to significant lung compression (Muruganandan et al., 2020).

The Pitfall of Radiographic Re-expansion as a Surrogate

A pivotal discussion point is the frequent use of lung re-expansion on imaging as a surrogate marker for atelectasis resolution. Our synthesis reveals this to be an unreliable indicator of physiological success. Studies on pleurodesis showed that immediate full lung expansion did not correlate with long-term clinical success or recurrence rates (Terra et al., 2009; Thomas et al., 2017). More critically, Lester et al. (2022) demonstrated a striking discordance: while radiographic re-expansion occurred in 69% of patients post-thoracentesis, abnormal pleural elastance (indicating trapped lung or visceral pleural restriction) persisted in 71% of those cases. The sensitivity of chest radiograph re-expansion for normal pleural physiology was only 44%. This underscores that what appears as an "expanded" lung on imaging may still be functionally compromised due to increased recoil, meaning the underlying atelectasis or its physiological equivalent persists. Therefore, clinical decisions based solely on post-drainage X-rays may be misguided.

Diaphragm Dysfunction: An Overlooked Component

Emerging evidence positions diaphragm dysfunction as a key component in the pathophysiology of symptomatic effusions. Graham et al. (2022) found diaphragm abnormalities (flattening, inversion, paradoxical movement) in nearly half of patients with unilateral effusions, with a higher prevalence in malignant cases. Crucially, the recurrence of diaphragm dysfunction after drainage was associated with a loss of symptomatic benefit. This suggests that effusions

impact respiratory function not only by compressing the lung parenchyma (causing atelectasis) but also by impairing the primary muscle of inspiration. The diaphragm's compromised mechanics could contribute to dyspnea and atelectasis independently, adding another layer of complexity to the clinical picture.

Clinical Implications and Thresholds for Intervention

Synthesizing the evidence yields practical guidance. For the mechanically ventilated, hypoxemic patient (P:F ratio <200), drainage of effusions larger than 400-500 mL is conditionally recommended, with meta-analyses showing a mean P:F ratio improvement of ~53 points (Chiu et al., 2024; Goligher et al., 2011). This population benefits most because they have less respiratory reserve. The work of Razazi et al. (2014) and Vetrugno et al. (2019) confirms improvements in both oxygenation and end-expiratory lung volume post-drainage, supporting the reversal of atelectasis.

However, clinicians must be aware of modifiers. Patients with underlying stiff lungs (e.g., ARDS, pulmonary fibrosis) or high pleural elastance (trapped lung) may show limited radiographic and physiological improvement after drainage, as the lung cannot re-expand (Chiumello et al., 2013; Martin et al., 2018). In such cases, pursuing repeated drainage for radiographic goals is futile. Furthermore, the paradoxical early deterioration in oxygenation seen after draining large effusions, as noted by Michaelides et al. (2017), should be anticipated and not mistaken for procedure failure; it likely represents a transient ventilation-perfusion mismatch during lung re-aeration.

Limitations of the Current Evidence and Future Directions

The discussion must acknowledge the severe limitations of the available literature. The foremost issue is the lack of a standardized, widely accepted radiological definition for compressive atelectasis specific to pleural effusion. Most included studies did not explicitly define or measure it, relying on indirect surrogates (Chiumello et al., 2013). The predominance of observational and retrospective data limits causal inference. Significant heterogeneity in patient populations—from post-cardiac surgery to advanced malignancy—makes it difficult to generalize findings (Brims et

al., 2015; Hassan et al., 2020). There is also a paucity of data on whether specific pleural fluid biochemical characteristics independently predict atelectasis risk. Future research must prioritize prospective studies that use quantitative CT imaging (the gold standard for assessing aeration) to define and measure compressive atelectasis in relation to meticulously characterized effusions (volume via CT volumetry, loculation, composition). Studies should incorporate pleural manometry to assess elastance alongside imaging, providing a combined physiological-radiological assessment (Lester et al., 2022). The role of diaphragm ultrasound in this context also warrants further investigation.

CONCLUSION AND RECOMMENDATIONS

Conclusion

In conclusion, this systematic review confirms an association between larger pleural effusion volume and the occurrence of compressive atelectasis, but firmly establishes that the relationship is complex and non-linear. The development and resolution of atelectasis are profoundly influenced by underlying pleural and lung parenchymal compliance (elastance, trapped lung), effusion characteristics (loculation, etiology), patient positioning, and concomitant diaphragm dysfunction. Radiographic assessment of lung re-expansion is an inadequate marker for successful physiological resolution of atelectasis, as it often fails to detect persistent abnormal pleural mechanics.

Recommendations

1. **Clinical Practice:** Drainage decisions should be guided by a combination of factors: significant symptoms (dyspnea), effusion size (>500 mL or >25% hemithorax), and physiological impairment (especially P:F ratio <200 in ventilated patients), rather than size alone. Anticipate possible transient oxygenation worsening after draining large effusions.

2. **Assessment:** When available and expertise permits, consider supplementing imaging with pleural manometry to distinguish between expandable lung and trapped lung, especially if recurrent effusion or poor symptomatic response is encountered.
3. **Research:** There is an urgent need for a consensus-based, radiological definition of compressive atelectasis secondary to pleural effusion. Future high-quality prospective studies should use quantitative CT and pleural physiology to directly correlate effusion characteristics with atelectasis, controlling for confounders like underlying lung disease.

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