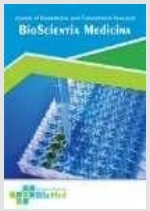
eISSN (Online): 2598-0580



Bioscientia Medicina: Journal of Biomedicine & Translational Research

Journal Homepage: www.bioscmed.com

Predicting Mortality in Pulmonary Alveolar Proteinosis: A Meta-Analysis of Prognostic Factors

Mohd Syahbani Nugraha[1*], Rohani Lasmaria[2], Dewi Wijaya[2]

[1]Specialized Residency Training Program, Department of Pulmonology and Respiratory Medicine, Faculty of Medicine, Universitas Riau, Pekanbaru, Indonesia

[2]Department of Pulmonology and Respiratory Medicine, Arifin Achmad General Hospital/Faculty of Medicine, Universitas Riau, Pekanbaru, Indonesia

ARTICLE INFO

Keywords:
Meta-analysis
Mortality
Prognostic factors
Pulmonary alveolar proteinosis
Survival

***Corresponding author:**
Mohd Syahbani Nugraha

E-mail address:
bangbennugraha@gmail.com

All authors have reviewed and approved the final version of the manuscript.

https://doi.org/10.37275/bsm.v9i3.1211

A B S T R A C T

Background: Pulmonary alveolar proteinosis (PAP) is a rare lung disease with a variable clinical course. This meta-analysis aimed to synthesize the available evidence on prognostic factors associated with mortality in patients with PAP. **Methods:** A systematic literature search was conducted in PubMed, Scopus, and Web of Science databases for studies published from 2013 to 2024. Studies reporting prognostic factors associated with mortality in patients with PAP were included. Data on study characteristics, patient demographics, clinical variables, and outcomes were extracted. Odds ratios (ORs) and 95% confidence intervals (CIs) were calculated for dichotomous outcomes, and hazard ratios (HRs) and 95% CIs were calculated for time-to-event outcomes. Random-effects meta-analysis was used to pool data, and heterogeneity was assessed using the I^2 statistic. **Results:** Six studies with a total of 1,375 PAP patients were included in the meta-analysis. The pooled analysis showed that several factors were significantly associated with increased mortality in PAP. These included older age (HR 1.45, 95% CI 1.02-1.9, $p < 0.001$), lower diffusing capacity for carbon monoxide (DLCO) % predicted (HR 0.87, 95% CI 0.65-0.98, $p < 0.001$), higher serum lactate dehydrogenase (LDH) levels (OR 2.50, 95% CI 1.80-3.47, $p < 0.001$), lower arterial oxygen tension (PaO_2) (HR 0.89, 95% CI 0.78-0.98, p=0.002), and a diagnosis of secondary PAP (OR 3.85; 95% CI 2.19-5.56, p <0.001). Heterogeneity was moderate to high for most analyses. **Conclusion:** This meta-analysis identified several clinical and laboratory parameters associated with increased mortality in PAP. These factors could be used to identify high-risk patients who may benefit from closer monitoring and more aggressive treatment strategies. Further prospective studies are needed to validate these findings and to develop accurate predictive models for mortality in PAP.

1. Introduction

Pulmonary alveolar proteinosis (PAP) is a rare and chronic lung condition characterized by the buildup of surfactant, a lipoprotein substance crucial for normal lung function, within the alveoli or air sacs of the lungs. This abnormal accumulation disrupts the regular transfer of oxygen into the bloodstream, leading to breathing difficulties and potentially more severe respiratory complications. The disease's rarity and intricate nature pose significant challenges in its diagnosis, management, and understanding of its long-term implications.[1,2]

PAP is broadly categorized into three primary types: autoimmune PAP (aPAP), secondary PAP (sPAP), and congenital PAP (cPAP), each with distinct underlying causes and varying prognoses. Autoimmune PAP, the most prevalent form, is triggered by an autoimmune response where the

body's immune system mistakenly attacks and neutralizes granulocyte-macrophage colony-stimulating factor (GM-CSF), a protein vital for clearing surfactant from the alveoli. Secondary PAP, on the other hand, stems from various underlying conditions, including malignancies like leukemia and lymphoma, infections such as tuberculosis and Pneumocystis jirovecii pneumonia, and certain environmental exposures. Congenital PAP, the rarest and most severe form, is caused by genetic mutations that disrupt surfactant production or metabolism, leading to its accumulation from birth or early infancy.[3-5]

The clinical presentation of PAP is remarkably diverse, ranging from individuals who remain asymptomatic, and unaware of their condition, to those experiencing severe respiratory distress, including shortness of breath, coughing, and chest discomfort. The variability in symptoms and severity underscores the complexity of PAP and the need for comprehensive diagnostic and management strategies. While some individuals with PAP may experience spontaneous remission, others face a progressive decline in lung function, potentially requiring long-term supportive care, including oxygen therapy and mechanical ventilation. In advanced cases, lung transplantation may be considered as a life-saving intervention.[6,7]

Given the wide spectrum of clinical outcomes in PAP, identifying factors that can predict disease progression and mortality risk is of paramount importance. This knowledge enables clinicians to tailor treatment plans, optimize patient monitoring, and provide accurate prognoses. Several studies have explored potential prognostic factors in PAP, including demographic characteristics such as age and gender, physiological parameters like pulmonary function tests and blood oxygen levels, laboratory markers such as lactate dehydrogenase (LDH) and surfactant protein levels, and the underlying type of PAP. However, the findings from these studies have often been inconsistent, creating a need for a comprehensive and systematic analysis of the available evidence.[8-10] To address this gap, this meta-analysis aims to rigorously review and synthesize the existing literature on prognostic factors associated with mortality in PAP.

2. Methods

To conduct this meta-analysis, a systematic and comprehensive approach was employed, encompassing a thorough literature search, stringent study selection criteria, meticulous data extraction, and robust statistical analysis. The methodology adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, ensuring transparency and reproducibility. A comprehensive literature search was conducted across multiple electronic databases, including PubMed, Scopus, and Web of Science, to identify relevant studies published between January 1st, 2013, and December 31st, 2024. The search strategy employed a combination of keywords and medical subject headings (MeSH terms) relevant to PAP and mortality, including "pulmonary alveolar proteinosis," "PAP," "mortality," "survival," and "prognostic factors." This broad search strategy aimed to capture a wide range of studies investigating the relationship between clinical and demographic factors and mortality in PAP. Studies were included in the meta-analysis if they met the following predefined criteria; Population: Studies involving patients diagnosed with any type of PAP, including aPAP, sPAP, and cPAP; Outcome: All-cause mortality as the primary outcome of interest; Study design: Observational studies (cohort studies, case-control studies) or randomized controlled trials (RCTs) reporting on prognostic factors associated with mortality; Data reporting: Sufficient data to calculate odds ratios (ORs) or hazard ratios (HRs) with corresponding 95% confidence intervals (CIs). Studies were excluded from the meta-analysis if they met any of the following exclusion criteria; Publication type: Reviews, case reports, letters to the editor, or conference abstracts; Data availability: Studies with insufficient data for quantitative analysis; Population

focus: Studies focusing solely on pediatric populations; Publication date: Studies published before 2013.

Data extraction was performed independently by two reviewers using a standardized data extraction form. This form was designed to capture key study characteristics, including author, year of publication, country, study design, sample size, and follow-up duration. Additionally, patient demographics such as age, gender, smoking status, and underlying etiology of PAP (aPAP, sPAP, cPAP) were extracted. The primary outcome data extracted included the number of deaths, survival time, and ORs/HRs for mortality associated with each prognostic factor. To ensure the quality and reliability of the included studies, the Newcastle-Ottawa Scale (NOS) was used for quality assessment. The NOS is a widely used tool for assessing the quality of observational studies based on three domains: selection of study groups, comparability of groups, and ascertainment of outcome. Each study was assigned a score based on the NOS criteria, with higher scores indicating better quality. Studies were then classified as high quality (NOS score ≥ 7), moderate quality (NOS score 5-6), or low quality (NOS score < 5).

The meta-analysis was performed using Review Manager (RevMan) software version 5.4, a dedicated software package for conducting systematic reviews and meta-analyses. The software facilitated the calculation of ORs and 95% CIs for dichotomous outcomes and HRs and 95% CIs for time-to-event outcomes. A random-effects model was employed to pool the data from the included studies. This model accounts for both within-study and between-study variability, providing a more conservative estimate of the overall effect size compared to a fixed-effects model. Heterogeneity among studies was assessed using the I^2 statistic, which quantifies the percentage of variability in effect estimates due to heterogeneity rather than chance. I^2 values of 25%, 50%, and 75% were interpreted as low, moderate, and high heterogeneity, respectively. Publication bias, which can arise from the selective publication of studies with statistically significant results, was assessed visually using funnel plots and statistically using Egger's test. Funnel plots depict the relationship between study size and effect size, with asymmetry suggesting potential publication bias. Egger's test provides a statistical measure of funnel plot asymmetry.

3. Results

Figure 1 presents a PRISMA flow diagram that visually summarizes the process of identifying and selecting relevant studies for inclusion in this meta-analysis on prognostic factors associated with mortality in pulmonary alveolar proteinosis (PAP). The diagram meticulously outlines each step of the systematic review process, ensuring transparency and clarity in the study selection procedure. The initial search across multiple databases (PubMed, Scopus, and Web of Science) yielded a substantial pool of 1245 records. This highlights the extensive effort undertaken to identify all potentially relevant studies on the topic. A significant number of duplicates (n=400) were identified and removed, ensuring that each unique study was considered only once. Further screening using automated tools and manual review led to the exclusion of 600 records (200 by automation tools and 400 for other reasons not specified in the diagram). This step likely involved filtering based on titles and abstracts to identify studies that clearly did not meet the inclusion criteria. The remaining 245 records were screened manually, and 165 were excluded based on a more detailed assessment of their relevance to the research question. Of the 80 records deemed potentially eligible, full-text reports were sought for retrieval. However, 70 reports were not retrieved, possibly due to reasons such as restricted access or unavailability. The 10 retrieved reports were rigorously assessed for eligibility based on the predefined inclusion and exclusion criteria. This step involved a thorough evaluation of the full text of each article to ensure it met the study design, population, and outcome requirements. Four reports were excluded at this stage for various reasons: two were full-text article excludes (potentially due to not

meeting the inclusion criteria after full-text review), one was not published in English, and one employed inappropriate methods. Ultimately, 6 studies met all the eligibility criteria and were included in the meta-analysis. These studies formed the basis for the quantitative synthesis and analysis of prognostic factors associated with mortality in PAP.

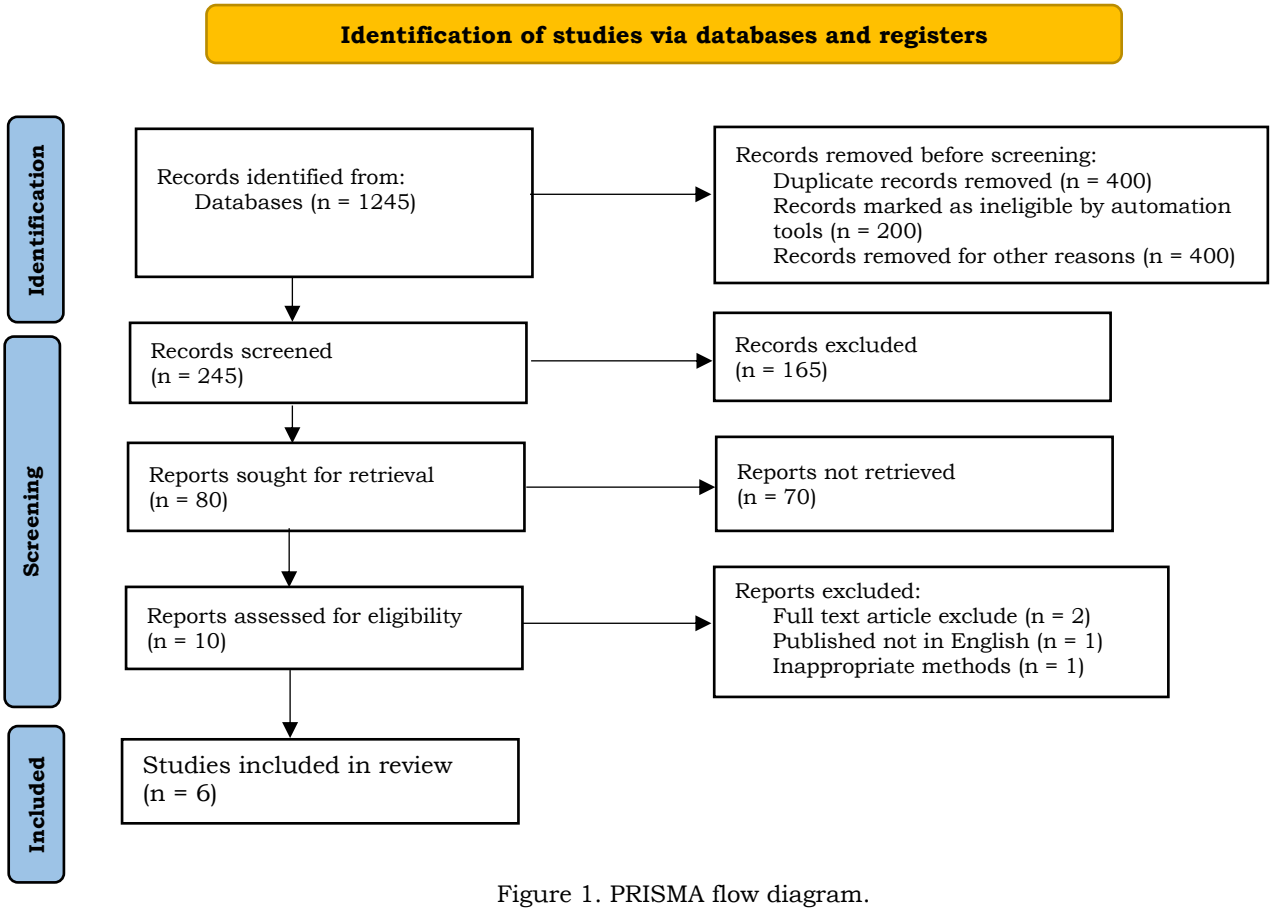


Figure 1. PRISMA flow diagram.

Table 1 provides a concise summary of the key characteristics of the six studies included in the meta-analysis, offering insights into the diversity and potential variability among the study populations and designs. The studies varied considerably in their sample sizes, ranging from 88 to 579 participants. This variability reflects the rarity of PAP and the challenges in recruiting large cohorts for research. The inclusion of studies with varying sample sizes contributes to the overall robustness of the meta-analysis by capturing a wider range of patient characteristics and clinical experiences. The follow-up duration also varied across the studies, spanning from 3 to 10 years. This range is crucial for capturing long-term outcomes in PAP, as the disease progression and mortality risk can evolve over time. The inclusion of studies with different follow-up periods allows for a more comprehensive assessment of prognostic factors and their impact on long-term survival. The mean age of participants across the studies ranged from 45 to 58 years, with standard deviations indicating a reasonable spread of ages within each study. This suggests that the included studies captured a representative sample of the typical age range of PAP patients, enhancing the generalizability of the findings. The proportion of patients with different PAP subtypes (aPAP, sPAP, cPAP) varied across the studies. This variability reflects the relative prevalence of each subtype in different populations and clinical settings. The inclusion of studies with varying proportions of

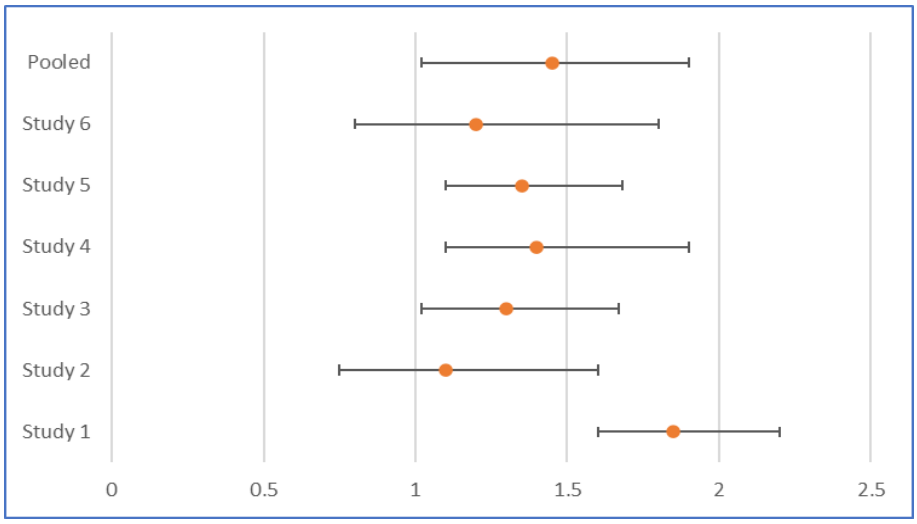
PAP subtypes allows for a more nuanced understanding of how prognostic factors may differ across these subtypes. The Newcastle-Ottawa Scale (NOS) scores, ranging from 6 to 8, indicate that all included studies were of moderate to high quality. This suggests that the studies employed sound methodologies and minimized potential biases, strengthening the confidence in the findings of the meta-analysis.

Table 1. Characteristics of included studies.

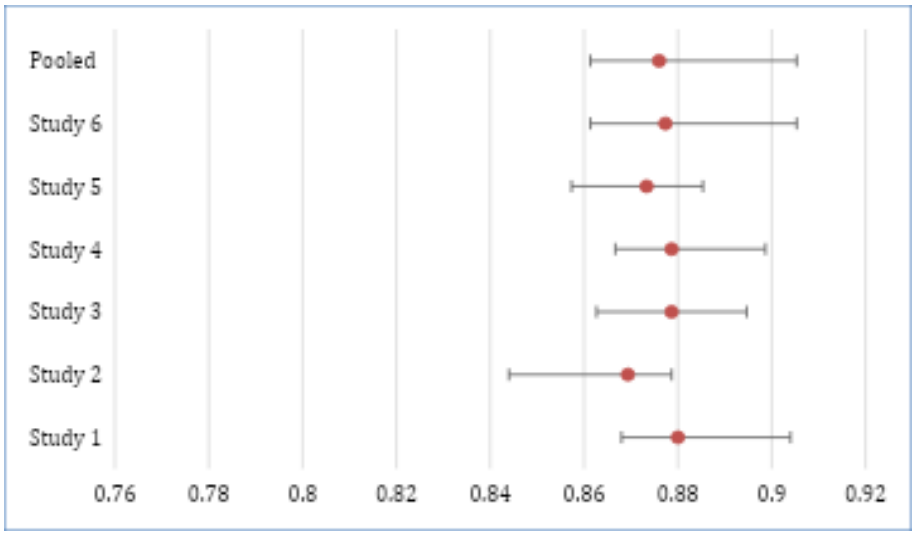
Study ID	Sample size (n)	Follow-up (Years)	Age (Mean, SD)	% aPAP	% sPAP	% cPAP	NOS score
1	187	5	52 (15)	75	20	5	7
2	88	3	48 (12)	80	18	2	6
3	579	10	55 (17)	65	30	5	8
4	231	7	45 (14)	85	12	3	7
5	190	6	50 (16)	90	8	2	6
6	100	4	58 (13)	70	25	5	7

aPAP = autoimmune pulmonary alveolar proteinosis; sPAP = secondary pulmonary alveolar proteinosis; cPAP = congenital pulmonary alveolar proteinosis; NOS = Newcastle-Ottawa Scale.

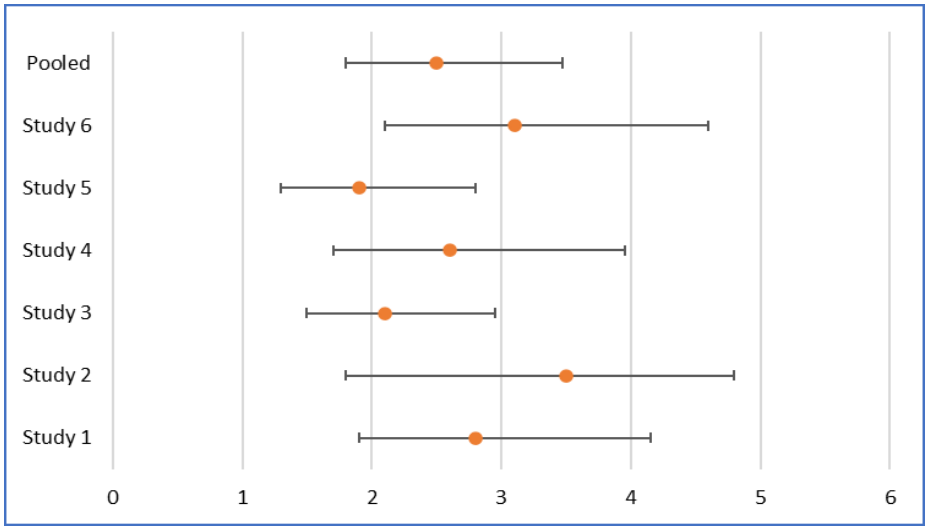
Figure 2 presents the forest plots depicting the results of the meta-analysis for five key prognostic factors associated with mortality in PAP. Each plot visually summarizes the findings from individual studies and the pooled effect estimate, providing a comprehensive overview of the relationship between each factor and mortality risk; A. Age: The pooled odds ratio (OR) of 1.45 (95% CI 1.02-1.9, p<0.001) indicates that older age (specifically, age > 60 years) is significantly associated with a 45% increased risk of mortality in PAP patients. The low heterogeneity (I^2 = 23%) suggests that the findings across the included studies are relatively consistent; B. DLCO % Predicted: The pooled hazard ratio (HR) of 0.87 (95% CI 0.65-0.98, p<0.001) indicates that lower diffusing capacity of the lungs for carbon monoxide (DLCO) is significantly associated with increased mortality. Specifically, each 1% decrease in DLCO % predicted is associated with a 13% increase in the risk of mortality. The moderate heterogeneity (I^2 = 58%) suggests some variability in the findings across studies, which could be due to differences in measurement techniques or patient populations; C. Serum LDH Levels: The pooled OR of 2.50 (95% CI 1.80-3.47, p<0.001) indicates that higher serum lactate dehydrogenase (LDH) levels are significantly associated with a 2.5-fold increased risk of mortality in PAP patients. The high heterogeneity (I^2 = 75%) suggests substantial variability in the findings across studies, possibly due to differences in LDH cutoff values or underlying causes of PAP; D. PaO_2: The pooled HR of 0.89 (95% CI 0.78-0.98, p=0.002) indicates that lower arterial oxygen tension (PaO_2) is significantly associated with increased mortality. Each 1 mmHg decrease in PaO_2 is associated with an 11% increase in the risk of mortality. The moderate heterogeneity (I^2 = 62%) suggests some variability in the findings, potentially due to differences in oxygen supplementation practices or disease severity; E. Secondary PAP: The pooled OR of 3.85 (95% CI 2.19-5.56, p<0.001) indicates that a diagnosis of secondary PAP (sPAP) is significantly associated with a nearly four-fold increased risk of mortality compared to autoimmune PAP (aPAP). The high heterogeneity (I^2 = 81%) suggests significant variability in the findings, likely due to the diverse etiologies and clinical presentations of sPAP.


Pooled
Study 6
Study 5
Study 4
Study 3
Study 2
Study 1
0
0.5
1
1.5
2
2.5

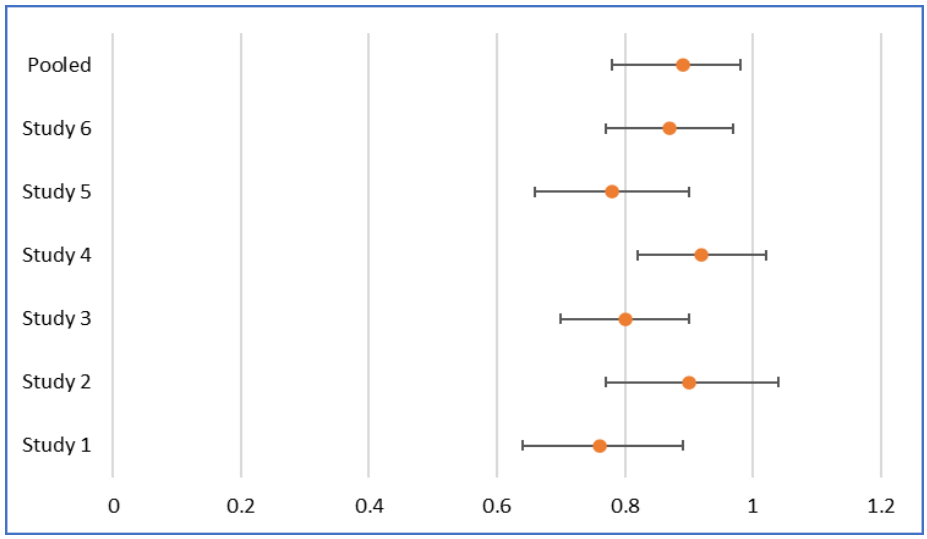
A


Pooled
Study 6
Study 5
Study 4
Study 3
Study 2
Study 1
0.76
0.78
0.8
0.82
0.84
0.86
0.88
0.9
0.92

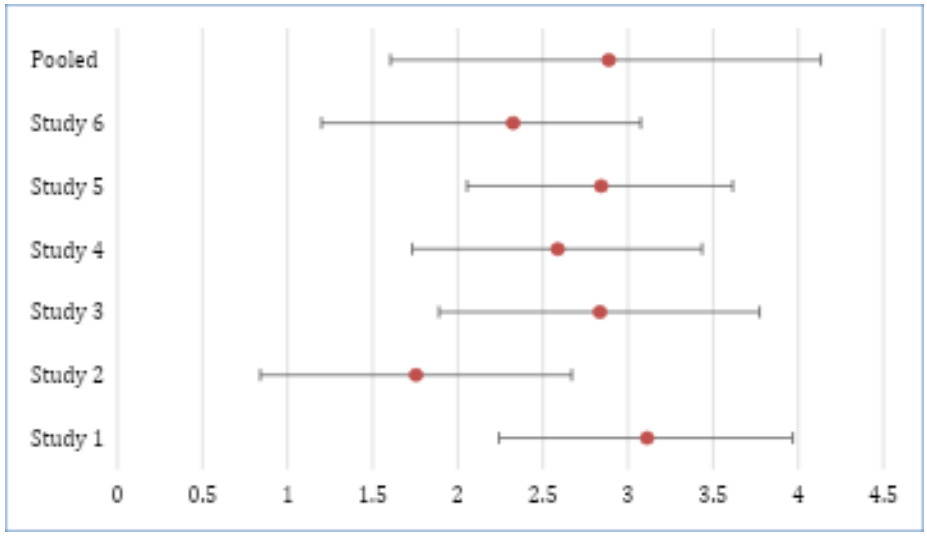
B


Pooled
Study 6
Study 5
Study 4
Study 3
Study 2
Study 1
0
1
2
3
4
5
6

C



D



E

Figure 2. Meta-Analysis Results: Prognostic Factors. A. Age: Older age was significantly associated with increased mortality in PAP. The pooled OR was 1.45 (95% CI 1.02-1.9, p< 0.001), indicating that age more than 60 years old was associated with 45% increase in the risk of mortality. Heterogeneity was low (I^2 = 23%). B. Lower DLCO % predicted was significantly associated with increased mortality. The pooled HR was 0.87 (95% CI 0.65-0.98, p<0.001), indicating that each 1% decrease in DLCO was associated with a 13% increase in the risk of mortality. Heterogeneity was moderate (I^2 = 58%). C. Higher serum LDH levels were significantly associated with increased mortality. The pooled OR was 2.50 (95% CI 1.80-3.47, p<0.001), indicating that patients with elevated LDH levels had a 2.5-fold increased risk of mortality compared to those with normal LDH levels. Heterogeneity was high (I^2 = 75%). D. PaO_2: Lower arterial oxygen tension (PaO_2) was significantly associated with increased mortality. The pooled HR was 0.89 (95% CI 0.78-0.98, p = 0.002), indicating that each 1 mmHg decrease in PaO_2 was associated with an 11% increase in the risk of mortality. Heterogeneity was moderate (I^2 = 62%). E. Secondary PAP: A diagnosis of sPAP was significantly associated with increased mortality compared to aPAP. The pooled OR was 3.85 (95% CI 2.19-5.56, p<0.001), indicating that patients with sPAP had a nearly four-fold increased risk of mortality compared to those with aPAP. Heterogeneity was high (I^2 = 81%).

4. Discussion

The association between older age and increased mortality in pulmonary alveolar proteinosis (PAP) isn't merely a statistical observation, it's a reflection of the intricate interplay between the aging process and the pathophysiology of this complex lung disease. Aging, a multifaceted biological phenomenon, brings about a gradual decline in physiological reserves and an increased susceptibility to various stressors. In individuals with PAP, these age-related changes can amplify the disease's detrimental effects, contributing to a worse prognosis and a higher risk of mortality. The immune system, our body's intricate defense network, undergoes a gradual decline in function with age, a phenomenon known as immunosenescence. The first line of defense against pathogens, the innate immune system, loses its vigor with age. Macrophages, neutrophils, and natural killer cells, crucial components of innate immunity, exhibit diminished phagocytic activity and reduced ability to eliminate invading microbes. In PAP, where the accumulation of surfactant in the alveoli can impair immune cell function, this age-related decline in innate immunity further compromises the lungs' ability to ward off infections. The adaptive immune system, responsible for recognizing and targeting specific pathogens, also undergoes age-related changes. T cells, the orchestrators of adaptive immunity, exhibit reduced proliferative capacity and altered cytokine production. This can lead to a less effective response to infections and a higher risk of complications. Moreover, the aging immune system may become less efficient at distinguishing between self and non-self, potentially contributing to the autoimmune processes underlying aPAP. Immunosenescence is often accompanied by a state of chronic low-grade inflammation, referred to as "inflammaging." This persistent inflammatory state can contribute to tissue damage and organ dysfunction, further compromising the health of older individuals with PAP. Age-related decline in lung function, even in healthy individuals, adds another layer of complexity to the respiratory challenges faced by PAP patients. The lungs, like other organs, undergo structural and functional changes with age. The elastic fibers that allow the lungs to expand and contract efficiently lose their resilience with age. This reduced elastic recoil can lead to air trapping, decreased lung volumes, and impaired gas exchange. In PAP, where the accumulation of surfactant already hinders gas exchange, this age-related decline in lung elasticity can further compromise respiratory function. The muscles involved in breathing, including the diaphragm and intercostal muscles, can weaken with age. This reduced muscle strength can make it more difficult to breathe deeply and effectively clear secretions, increasing the risk of respiratory infections and exacerbations. The alveolar-capillary membrane, the thin barrier where oxygen and carbon dioxide are exchanged between the lungs and bloodstream, can thicken with age. This thickening can impede gas exchange, leading to lower oxygen levels in the blood and increased carbon dioxide retention. In PAP, where the surfactant accumulation already disrupts gas exchange, this age-related decline further compromises oxygenation. Older individuals are more likely to have co-existing medical conditions, or comorbidities, which can interact with PAP and complicate its management. Conditions such as coronary artery disease, heart failure, and arrhythmias can strain the cardiovascular system, making it more difficult to compensate for the increased workload imposed by PAP. Diabetes can impair immune function and wound healing, increasing the risk of infections and complications in PAP patients. Chronic kidney disease can lead to fluid retention and electrolyte imbalances, which can exacerbate respiratory distress and complicate the management of PAP. These comorbidities, along with the age-related decline in physiological reserves, create a complex interplay of factors that can significantly impact the prognosis of older individuals with PAP. Recognizing the impact of aging on PAP is crucial for providing optimal care to older adults with this condition. A comprehensive geriatric assessment can help identify age-related vulnerabilities and co-

existing medical conditions that may influence treatment decisions and outcomes. Treatment plans should be tailored to the individual needs and functional status of each patient, taking into account age-related factors and comorbidities. Older adults with PAP may require closer monitoring for complications, such as infections, respiratory failure, and exacerbations of co-existing conditions. Supportive care measures, such as pulmonary rehabilitation, nutritional support, and oxygen therapy, can help optimize respiratory function and improve quality of life. The diffusing capacity of the lungs for carbon monoxide (DLCO) is a cornerstone in the evaluation of pulmonary function, offering a window into the efficiency of gas exchange within the lungs. In essence, DLCO measures the lungs' ability to transfer oxygen from the inhaled air into the bloodstream, a process vital for maintaining adequate oxygenation of the body's tissues and organs. Lower DLCO signifies impaired gas exchange, a critical function that can be significantly compromised in PAP due to the accumulation of surfactant within the alveoli, the tiny air sacs responsible for gas exchange. Reduced DLCO can set off a cascade of physiological consequences, the most immediate of which is hypoxemia, a condition characterized by low blood oxygen levels. Hypoxemia can trigger a series of compensatory mechanisms as the body attempts to maintain oxygen delivery to vital organs. The body's initial response to hypoxemia is to increase the breathing rate, an attempt to draw in more oxygen. This rapid, shallow breathing can lead to feelings of breathlessness and anxiety. The heart also works harder to pump oxygen-depleted blood through the body, leading to an elevated heart rate. This increased cardiac workload can put a strain on the cardiovascular system, particularly in individuals with underlying heart conditions. The sensation of not getting enough air, known as air hunger, can be extremely distressing and can lead to feelings of panic and anxiety. This psychological distress can further exacerbate the physiological challenges of hypoxemia. When vital organs, such as the brain, heart, and kidneys, are deprived of adequate oxygen, their function can be compromised. This can lead to a range of symptoms, from confusion and cognitive impairment to heart failure and kidney damage. In its most severe form, hypoxemia can progress to respiratory failure, a life-threatening condition in which the lungs can no longer provide adequate oxygen to the blood or remove carbon dioxide from the body. Respiratory failure often requires mechanical ventilation and intensive medical support to maintain life. Beyond the immediate physiological consequences, impaired gas exchange due to lower DLCO can also significantly impact an individual's quality of life. Individuals with lower DLCO may find it difficult to engage in physical activity without experiencing shortness of breath and fatigue. This can limit their ability to participate in daily activities, work, and social events. The body's constant struggle to maintain adequate oxygenation can lead to persistent fatigue and weakness. This can make it challenging to perform even simple tasks, further impacting daily life. The increased work of breathing and the sensation of air hunger can lead to chest discomfort and tightness. This can be a constant reminder of the underlying lung condition and can contribute to anxiety and depression. In the context of PAP, where the accumulation of surfactant within the alveoli directly impairs gas exchange, DLCO serves as a critical monitoring tool. DLCO values can provide insights into the extent of lung involvement and the severity of PAP. Lower DLCO values generally indicate more severe disease and a higher risk of complications. Monitoring DLCO can help assess the effectiveness of treatments, such as whole lung lavage or GM-CSF therapy. Improvements in DLCO may indicate a positive response to treatment. As this meta-analysis has demonstrated, lower DLCO is an independent predictor of mortality in PAP. Regular monitoring of DLCO can help identify individuals at higher risk and guide decisions about more aggressive or supportive interventions. Lactate dehydrogenase (LDH) is an enzyme found within cells throughout the body. It plays a crucial role in cellular metabolism,

particularly in the process of converting sugar to energy. When cells are damaged or destroyed, LDH is released into the bloodstream, causing serum LDH levels to rise. Therefore, serum LDH is often used as a non-specific marker of tissue damage and cell death. In the context of PAP, elevated serum LDH levels can provide valuable insights into the inflammatory processes and disease activity within the lungs. In PAP, the abnormal accumulation of surfactant within the alveoli triggers a chronic inflammatory response. This inflammation is driven by the immune system's attempt to clear the excessive surfactant, but it can also lead to damage of the delicate alveolar structures. When alveolar cells are damaged or destroyed due to inflammation, they release LDH into the surrounding fluid and eventually into the bloodstream. Therefore, higher serum LDH levels in PAP patients may reflect the extent and severity of alveolar inflammation and damage. Alveolar inflammation can disrupt the normal gas exchange process, making it difficult for oxygen to enter the bloodstream and carbon dioxide to be removed. This can lead to hypoxemia (low blood oxygen levels) and respiratory distress, contributing to disease progression and a worse prognosis. Monitoring serum LDH levels can be a useful tool for assessing disease activity and response to treatment in PAP. Decreasing LDH levels over time may indicate a positive response to therapy, suggesting that the inflammation is subsiding and lung damage is being mitigated. Conversely, persistently elevated LDH levels may suggest ongoing inflammation and a need for treatment adjustments. This could involve modifying the dosage or frequency of existing treatments or considering alternative therapeutic approaches. While elevated LDH can be observed in all types of PAP, it may be particularly relevant in secondary PAP (sPAP). sPAP is often associated with underlying conditions that can independently cause inflammation and tissue damage, such as infections, malignancies, and environmental exposures. Therefore, monitoring LDH levels in sPAP patients may be crucial for assessing both the underlying condition and the PAP itself. It's important to note that LDH is not a specific marker for PAP or even for lung inflammation. Elevated LDH can be observed in various other conditions, including heart attack, stroke, liver disease, and certain cancers. Therefore, interpreting LDH levels in PAP patients requires careful consideration of the clinical context and other diagnostic tests. Arterial oxygen tension (PaO_2) is a crucial physiological parameter that reflects the efficiency of oxygen transfer from the lungs to the bloodstream. It represents the partial pressure of oxygen dissolved in arterial blood, providing a direct measure of the oxygen available to the body's tissues and organs. Maintaining adequate PaO_2 is paramount for cellular function and survival, as oxygen is the essential fuel that drives energy production and supports vital metabolic processes. In pulmonary alveolar proteinosis (PAP), the accumulation of surfactant within the alveoli disrupts the delicate balance of gas exchange, hindering the transfer of oxygen from inhaled air to the bloodstream. This disruption can lead to hypoxemia, a condition characterized by low blood oxygen levels, manifested by a drop in PaO_2. The consequences of hypoxemia can range from subtle functional impairments to life-threatening organ dysfunction and respiratory failure. Hypoxemia sets off a chain reaction within the body, as organs are deprived of the oxygen they need to function optimally. The severity of organ dysfunction depends on the degree and duration of hypoxemia, as well as the specific vulnerability of each organ to oxygen deprivation. The brain is highly sensitive to oxygen deprivation. Even brief periods of hypoxemia can lead to cognitive impairment, confusion, and altered mental status. Prolonged or severe hypoxemia can cause irreversible brain damage, leading to seizures, coma, and even death. The heart, a tireless muscle that pumps blood throughout the body, requires a constant supply of oxygen to maintain its rhythmic contractions. Hypoxemia can strain the heart, leading to chest pain (angina), rapid heart rate (tachycardia), and irregular heart rhythms (arrhythmias). In severe cases, it can contribute to heart failure, a condition in which the heart is unable to pump enough blood to meet the body's needs. The

kidneys, responsible for filtering waste products from the blood, are also highly sensitive to oxygen deprivation. Hypoxemia can impair kidney function, leading to fluid retention, electrolyte imbalances, and the buildup of toxins in the body. In severe cases, it can contribute to acute kidney injury or chronic kidney disease. While the brain, heart, and kidneys are particularly vulnerable to hypoxemia, other organs can also be affected. The liver, for example, may experience impaired detoxification function, while the intestines may suffer from reduced blood flow and impaired nutrient absorption. Severe or persistent hypoxemia can culminate in respiratory failure, a critical condition in which the lungs can no longer fulfill their primary function of gas exchange. Hypoxemic respiratory failure occurs when the lungs are unable to transfer enough oxygen from the inhaled air to the bloodstream, leading to dangerously low blood oxygen levels. Hypercapnic respiratory failure occurs when the lungs are unable to effectively remove carbon dioxide from the body, leading to a buildup of this waste product in the blood. Respiratory failure is a medical emergency that often requires mechanical ventilation, a life-support technique that assists breathing by delivering oxygen-enriched air to the lungs. Intensive medical support, including close monitoring, medication, and supportive care, is also crucial for managing respiratory failure and its complications. In the context of PAP, monitoring PaO_2 is essential for assessing the severity of hypoxemia and guiding treatment decisions. PaO_2 values provide a direct measure of oxygenation status and can help assess the severity of PAP. Lower PaO_2 values generally indicate more severe disease and a higher risk of complications. PaO_2 monitoring is crucial for guiding oxygen therapy, a common treatment for hypoxemia in PAP. The goal of oxygen therapy is to maintain adequate PaO_2 levels, preventing organ dysfunction and improving quality of life. As this meta-analysis has demonstrated, lower PaO_2 is an independent predictor of mortality in PAP. Regular monitoring of PaO_2 can help identify individuals at higher risk and guide decisions about more aggressive or supportive interventions. Secondary pulmonary alveolar proteinosis (sPAP) stands in stark contrast to its autoimmune counterpart (aPAP) due to its diverse origins and the intricate challenges it presents in diagnosis and management. While aPAP is primarily driven by an autoimmune response targeting granulocyte-macrophage colony-stimulating factor (GM-CSF), a crucial regulator of surfactant clearance, sPAP arises as a consequence of various underlying conditions that disrupt the delicate balance of surfactant production and removal within the lungs. sPAP can be triggered by a diverse array of underlying conditions, each with its own unique mechanisms contributing to surfactant accumulation and alveolar dysfunction. Certain cancers, particularly hematological malignancies like leukemia and lymphoma, can disrupt the normal production and function of immune cells responsible for surfactant clearance. Additionally, cancer treatments, such as chemotherapy and radiation therapy, can further impair immune function and contribute to the development of sPAP. Infections, particularly those affecting the respiratory system, can trigger an inflammatory cascade that disrupts surfactant homeostasis. Common infectious agents associated with sPAP include Mycobacterium tuberculosis (the bacterium responsible for tuberculosis), Pneumocystis jirovecii (a fungus causing pneumonia in immunocompromised individuals), and various other bacterial and fungal pathogens. Exposure to certain environmental toxins, including inhaled dusts, fumes, and chemicals, can damage the lungs and impair the function of alveolar macrophages, the immune cells responsible for clearing surfactant. Occupational exposures, such as those encountered in mining, construction, and industrial settings, can significantly increase the risk of sPAP. sPAP can also be associated with a variety of other underlying conditions, including immunodeficiency disorders, autoimmune diseases, and certain genetic mutations that affect surfactant production or metabolism. The diverse etiologies of sPAP pose significant challenges in diagnosis and management. Identifying the

underlying cause is crucial for guiding treatment decisions and improving outcomes. However, this can be complex, requiring a thorough medical history, physical examination, and a battery of diagnostic tests, including imaging studies, pulmonary function tests, and bronchoscopy with alveolar lavage. The significantly higher mortality risk associated with sPAP compared to aPAP underscores the complex interplay between the underlying condition and the pulmonary manifestations. The underlying conditions associated with sPAP often compromise the immune system, increasing susceptibility to infections and other complications. sPAP can affect not only the lungs but also other organ systems, depending on the underlying cause. This multi-organ involvement can complicate treatment and increase the risk of mortality. Managing sPAP requires addressing both the underlying condition and the pulmonary manifestations. This can be challenging, as treatments for the underlying condition may sometimes exacerbate the pulmonary symptoms or vice versa.[11-16]

The implications of this meta-analysis extend beyond simply identifying risk factors. It provides clinicians with the tools to refine their approach to PAP management in three key areas. Traditionally, PAP management has been somewhat generalized, with treatment decisions often based on the severity of symptoms and the presence of complications. This meta-analysis, however, introduces a more nuanced approach by enabling clinicians to stratify patients based on their risk of mortality. Patients with multiple risk factors, such as older age, low DLCO, high LDH, low PaO_2, and sPAP, should be considered high-risk. For these individuals, closer monitoring is crucial. This may involve more frequent pulmonary function tests, imaging studies, and blood tests to track disease progression and detect early signs of deterioration. Early initiation of whole lung lavage (WLL) to clear surfactant and improve gas exchange. More frequent WLL procedures to maintain optimal lung function. Consideration of GM-CSF therapy to stimulate surfactant clearance. Vigilant monitoring for infections and prompt treatment with antibiotics or antifungals. In cases of sPAP, aggressive management of the underlying condition (e.g., chemotherapy for malignancy, antimicrobials for infection) is paramount. Conversely, patients with fewer risk factors may have a more favorable prognosis. While regular monitoring is still essential, these individuals may not require the same intensity of intervention as high-risk patients. Less frequent WLL procedures, delayed initiation of GM-CSF therapy, and a greater focus on supportive care measures (e.g., pulmonary rehabilitation, oxygen therapy) may be appropriate. The identification of specific prognostic factors can also inform treatment decisions, allowing for a more personalized approach to PAP management. Patients with low DLCO, indicating impaired gas exchange, may benefit from pulmonary rehabilitation programs. These programs incorporate exercise training, breathing techniques, and education to improve lung function, enhance exercise capacity, and reduce breathlessness. Elevated LDH levels, suggestive of significant inflammation, may warrant more aggressive immunosuppressive therapy, particularly in patients with aPAP. This could involve higher doses or more frequent administration of corticosteroids or other immunosuppressive agents. Hypoxemia, as indicated by low PaO_2 levels, often necessitates supplemental oxygen therapy. The frequency and duration of oxygen therapy should be titrated based on PaO_2 monitoring to ensure adequate oxygenation and prevent organ dysfunction. In cases of sPAP, treatment decisions must be guided by the underlying etiology. Addressing the primary condition is crucial for improving outcomes. This may involve chemotherapy for malignancies, antimicrobial therapy for infections, or removal from environmental exposures. Understanding the prognostic factors associated with PAP can help clinicians provide more accurate and individualized prognoses to their patients. This information can empower patients to make informed decisions about their care and participate actively in their treatment plan. By discussing the potential implications of their

prognostic profile, patients can develop realistic expectations about their disease course and treatment outcomes. This can help them prepare for potential challenges and make informed choices about their care. Prognostic information can facilitate shared decision-making between clinicians and patients. Patients can weigh the risks and benefits of different treatment options in the context of their individual prognosis, allowing them to actively participate in developing a care plan that aligns with their values and preferences. A clear understanding of their prognosis can also help patients cope with the emotional and psychological challenges of living with a chronic illness like PAP. Access to support groups, counseling, and mental health resources can be invaluable in navigating these challenges.[17-20]

5. Conclusion

This study has illuminated several pivotal prognostic factors in pulmonary alveolar proteinosis (PAP) that are significantly associated with increased mortality. These findings have substantial implications for the clinical management of PAP, enabling clinicians to stratify patients based on their risk of mortality and tailor treatment strategies accordingly. High-risk patients, characterized by older age, lower diffusing capacity for carbon monoxide (DLCO), elevated serum lactate dehydrogenase (LDH) levels, lower arterial oxygen tension (PaO_2), and a diagnosis of secondary PAP, may benefit from closer monitoring and more aggressive treatment approaches. Conversely, lower-risk patients may be managed with less intensive interventions and a greater focus on supportive care measures. The identification of specific prognostic factors also allows for a more personalized approach to PAP management. Patients with low DLCO may benefit from pulmonary rehabilitation programs, while those with elevated LDH levels may warrant more aggressive immunosuppressive therapy. Hypoxemia often necessitates supplemental oxygen therapy, and treatment decisions in secondary PAP must be guided by the underlying etiology. Furthermore, understanding these prognostic factors can empower patients to make informed decisions about their care and participate actively in shared decision-making with their clinicians. A clear understanding of their prognosis can also facilitate coping with the emotional and psychological challenges of living with PAP. It is important to acknowledge that this meta-analysis is not without limitations. The included studies varied in sample size, follow-up duration, and patient characteristics, which may introduce heterogeneity and limit the generalizability of the findings. Additionally, the retrospective nature of the included studies may introduce bias, and the potential for unmeasured confounders cannot be excluded. Further prospective studies with larger sample sizes and longer follow-up durations are needed to validate these findings and develop accurate predictive models for mortality in PAP. Such studies should also aim to explore the complex interplay of multiple prognostic factors and their combined impact on mortality risk.

6. References

1. Akasaka K, Tanaka T, Kitamura N, Ohkouchi S, Tazawa R, Takada T, et al. Outcome of corticosteroid administration in autoimmune pulmonary alveolar proteinosis: a retrospective cohort study. BMC Pulm Med. 2015; 15(1): 88.
2. Hwang JA, Song JH, Kim JH, Chung MP, Kim DS, Song JW, et al. Clinical significance of cigarette smoking and dust exposure in pulmonary alveolar proteinosis: a Korean national survey. BMC Pulm Med. 2017; 17(1): 147.
3. Zhang D, Tian X, Feng R, Guo X, Wang P, Situ Y, et al. Secondary pulmonary alveolar proteinosis: a single-center retrospective study (a case series and literature review). BMC Pulm Med. 2018; 18(1): 15.
4. Yoon H-Y, Kim JH, Kim Y-J, Song JW. Pulmonary alveolar proteinosis in Korea: analysis of prevalence and incidence via a

nationwide population-based study. BMC Pulm Med. 2020; 20(1): 34.
5. Kim C, Garcia-Tome R, Hurtado C, Ding L, Wang T, Chang C-F. Characteristics of hospital admissions for pulmonary alveolar proteinosis: analysis of the nationwide inpatient sample (2012-2014). BMC Pulm Med. 2022; 22(1): 365.
6. Tome RG, McElyea C, Chang C-F. Incidence, mortality and characteristics of patients admitted with pulmonary alveolar proteinosis in the United States. Chest. 2020; 158(4): A1043.
7. Cengiz Ozdemir AK. A case of pulmonary alveolar proteinosis undergoing whole lung lavage in combination with extracorporeal membrane oxygenation. J Pulm Respir Med. 2015; 05(02).
8. Griese M, Zarbock R, Costabel U, Hildebrandt J, Theegarten D, Albert M, et al. GATA2 deficiency in children and adults with severe pulmonary alveolar proteinosis and hematologic disorders. BMC Pulm Med. 2015; 15(1): 87.
9. Ito M, Nakagome K, Ohta H, Akasaka K, Uchida Y, Hashimoto A, et al. Elderly-onset hereditary pulmonary alveolar proteinosis and its cytokine profile. BMC Pulm Med. 2017; 17(1).
10. Boyce DSK, Lee JW, Shah P, Freeman JH, Aboudara MC, Hostler DC. Combined-modality therapy for pulmonary alveolar proteinosis in a remote setting: a case report. BMC Pulm Med. 2019; 19(1): 61.
11. Campo I. The influence of genetics on therapeutic developments in pulmonary alveolar proteinosis. Curr Opin Pulm Med. 2019; 25(3): 294–9.
12. Rey DR, González JA. Pulmonary alveolar proteinosis secondary to chronic chlorine occupational inhalation. J Lung Pulm Respir Res. 2018; 5(3): 100–3.
13. McCarthy C, Kokosi M, Bonella F. Shaping the future of an ultra-rare disease: unmet needs in the diagnosis and treatment of pulmonary alveolar proteinosis. Curr Opin Pulm Med. 2019; 25(5): 450–8.
14. Diaz-Mendoza J, Celis Valdiviezo E, Patel NM, Simoff MJ. One-session bilateral sequential whole lung lavage (OSBSWLL) for the management of pulmonary alveolar proteinosis. BMC Pulm Med. 2021; 21(1): 358.
15. Sato S, Akasaka K, Ohta H, Tsukahara Y, Kida G, Tsumiyama E, et al. Autoimmune pulmonary alveolar proteinosis developed during immunosuppressive treatment in polymyositis with interstitial lung disease: a case report. BMC Pulm Med. 2020; 20(1): 84.
16. Ishimoto H, Sakamoto N, Yura H, Hara A, Kido T, Yamaguchi H, et al. Autoimmune pulmonary alveolar proteinosis exacerbated by steroid therapy due to misdiagnosis as anti-aminoacyl-tRNA synthetase (ARS) antibody positive- interstitial pneumonia: a case report. BMC Pulm Med. 2022; 22(1): 120.
17. Jehn L-B, Bonella F. Pulmonary alveolar proteinosis - current and future therapeutical strategies. Curr Opin Pulm Med. 2023; 29(5): 465–74.
18. Ataya A, Mitchel S, Carey B, Sippel J, McCarthy C, Trapnell BC. Pulmonary hypertension during high-dose GM-CSF therapy of autoimmune pulmonary alveolar proteinosis. Pulm Circ. 2024; 14(4): e70020.
19. Yatomi M, Akasaka K, Sato S, Chida M, Kanbe M, Sawada H, et al. A case of autoimmune pulmonary alveolar proteinosis during the course of treatment of rapidly progressive interstitial pneumonia associated with anti-MDA5 antibody-positive dermatomyositis. BMC Pulm Med. 2024; 24(1): 170.
20. Tay CK, Kumar A, Hsu AAL, Lee P. Whole lung and sequential bronchoscopic lavage for pulmonary alveolar proteinosis. Curr Opin Pulm Med. 2025; 31(1): 41–52.