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Paper Accepted*

ISSN Online 2406-0895

Review Article / Прегледни рад

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Application of fiberoptic bronchoscopy in the diagnosis and treatment of pneumonia in children

Примена фиброптичке бронхоскопије у дијагнози и лечењу пнеумоније код деце

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Received: April 24, 2025
Revised: September 4, 2025
Accepted: September 5, 2025
Online First: September 29, 2025
DOI: https://doi.org/10.2298/SARH250424078Z

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SUMMARY
Pneumonia is a leading cause of morbidity and mortality in children, caused by various pathogens such as bacteria, viruses, mycoplasma, and fungi, each with distinct clinical manifestations. Fiberoptic bronchoscopy (FOB) is an invaluable tool for visualizing the airway, collecting lower respiratory tract specimens, and diagnosing and treating pediatric pneumonia. This review explores the role of FOB in managing pneumonia caused by different etiologies, including mycoplasma, adenovirus, and aspiration pneumonia. It also addresses the complications and precautions associated with FOB, emphasizing the importance of careful patient selection and the need for timely referrals to specialized centers, particularly in primary healthcare settings where access to FOB may be limited. The review concludes with a discussion on the future development of FOB, focusing on advancements in technology, such as improved imaging, multi-modal functions, and artificial intelligence integration, which will enhance diagnostic accuracy and treatment efficacy for pneumonia.
Keywords: fiberoptic bronchoscopy; pneumonia; diagnosis; treatment; children

САЖЕТАК
Пнеумонија је водећи узрок морбидитета и морталитета код деце, узрокована разним патогенима као што су бактерије, вируси, микоплазме и гљивице, од којих свака има своје особене клиничке манифестације. Фиберооптичка бронхоскопија (ФОБ) је непроцењив алат за визуализацију дисајних путева, прикупљање узорака из доњих дисајних путева и дијагностиковање и лечење педијатријске пнеумоније. Овај преглед истражује улогу ФОБ-а у управљању пнеумонијом узрокованом различитим етиологијама, укључујући микоплазму, аденовирус и аспирациону пнеумонију. Такође се бави компликацијама и мерама опреза везаним за ФОБ, наглашавајући значај пажљивог одабира пацијената и потребу за правовременим упућивањем у специјализоване центре, посебно у примарној здравственој заштити где приступ ФОБ-у може бити ограничен. Рецензија се завршава расправом о будућем развоју ФОБ-а, са фокусом на напредак у технологији, попут побољшаног сликања, мулти-модалних функција и интеграције вештачке интелигенције, што ће побољшати дијагностичку тачност и ефикасност лечења пнеумоније.
Кључне речи: фиберооптичка бронхоскопија; пнеумонија; дијагноза; лечење; деца

INTRODUCTION

Pneumonia is an inflammation of the pulmonary alveoli and interstitium, commonly seen in pediatrics – defined as individuals from birth to 18 years of age-and a leading cause of childhood mortality. The World Health Organization estimates that nearly two million children under the age of five die from pneumonia annually [1]. The disease is caused by various pathogens, including bacteria, viruses, mycoplasma, and fungi, with symptoms such as fever, cough, dyspnea, and chest pain [2, 3]. Epidemiological studies indicate that viruses are the most common cause of pediatric pneumonia, accounting for approximately 60–70% of cases in young children, with respiratory syncytial virus and influenza viruses being predominant [4].

Bacterial pathogens, particularly Streptococcus pneumoniae, are responsible for about 20–30% of cases, often in conjunction with or secondary to viral infections [5]. *Mycoplasma pneumoniae* (MPP) is increasingly recognized as a significant pathogen in school-aged children, contributing to 10–40% of community-acquired pneumonia cases in this age group [5]. Diagnosing and treating pneumonia requires a comprehensive approach, including medical history, clinical signs, laboratory tests, and imaging. However, diagnosis can be challenging, and treatment failures are frequent, particularly in primary healthcare settings, where limited resources hinder early detection and effective management [6–9].

Fiberoptic bronchoscopy (FOB) is a crucial tool for visualizing the airway and collecting specimens from the lower respiratory tract, playing a vital role in diagnosing and treating pediatric respiratory diseases [10, 11]. Developed by Japanese thoracic surgeon Shigeto Ikeda, FOB has become a cornerstone of modern pulmonary medicine [12]. In pediatric care, FOB is primarily used for airway inspection, removal of secretions or foreign bodies, sample collection, and placement of devices or drugs [13]. In primary healthcare settings, particularly in community hospitals with limited access to FOB, clinicians must understand its indications and recognize when referral to specialized centers is necessary. Timely referral can significantly improve the diagnosis and management of conditions like pneumonia. While several reviews have addressed bronchoscopy in pediatric respiratory diseases, this review is distinct in its focused evaluation of FOB's role across a broad pediatric age range, its emphasis on specific pneumonia etiologies such as mycoplasma, adenovirus, and aspiration, and its integration of recent technological advancements – including improved imaging, multi-modal functions, and AI-driven diagnostics – offering updated insights for both clinical practice and future research. This review highlights the importance of FOB in pediatric care and emphasizes its value in primary care settings. Understanding when to refer patients for FOB is essential for clinicians to improve the care of pediatric respiratory patients.

DIAGNOSTIC VALUE OF FOB IN PEDIATRIC PNEUMONIA

FOB allows direct observation of airway structure, identifying abnormalities such as stenosis, inflammation, and tumors. It also facilitates lower respiratory tract sample collection through bronchial irrigation, bronchoalveolar lavage (BAL), and biopsy. These samples support microbiological testing for bacteria, viruses, mycoplasma, fungi, and tuberculosis, enhancing diagnostic accuracy for pediatric pneumonia. In primary care, FOB is often used for repeated or unresolved pneumonia, unclear etiology, and suspected foreign body aspiration, prompting referrals for specialized care.

Evaluation of inflammatory response and immune status of the lungs

FOB, through BAL fluid (BALF), is essential for evaluating the inflammatory response and immune status of the lungs. Indicators such as cellular components, cytokines, and immunoglobulins in BALF reflect the degree of inflammation and immune responses. For example, an increased proportion of neutrophils suggests bacterial pneumonia, while lymphocyte dominance points to viral or tuberculous pneumonia. Elevated eosinophil counts indicate allergic or fungal pneumonia, and reduced pulmonary surfactant proteins are associated with alveolar surfactant deficiency, contributing to atelectasis and respiratory failure [14, 15, 16].

Assessment of lung structure and function

FOB also provides a detailed assessment of lung structure and function through bronchoscopic imaging. Key parameters, such as airway diameter, length, branching, angle, and wall thickness, are used to evaluate airway integrity and detect abnormalities like stenosis, deformity, inflammation, bleeding, or tumors. These findings are crucial for determining the location, extent, and severity of pneumonia, as well as airway damage. For instance, a reduction

in airway diameter and length may suggest stenosis or collapse, while changes in branching or angle could indicate deformities. An increase in wall thickness may point to inflammation or tumors, and the presence of secretions or foreign bodies suggests obstruction or infection [17, 18, 19].

IDENTIFYING DIFFERENT TYPES OF PNEUMONIA

Unresolved or recurrent pneumonia:

In pediatric pneumonia cases that do not improve with antibiotics or where the etiology remains unclear, FOB is essential for identifying rare causes such as atypical pathogens or complications like pleural effusion or lung abscesses. Early referral to a bronchoscopy-equipped facility ensures timely diagnosis and better outcomes.

Mycoplasma pneumonia, caused by MPP, accounts for 10–40% of pediatric pneumonia cases [20]. It typically presents with low fever, cough, sore throat, and headache, with patchy infiltrates on chest X-rays. Extrapulmonary symptoms, including erythema multiforme and myocarditis, are common [21]. Diagnosis relies on serology and molecular tests, though serology may suffer from cross-reactivity and molecular tests may yield false results [22]. FOB with BALF improves specificity, avoiding contamination. Cytological and pathological analysis of BALF enhances detection, and bronchoscopic imaging can identify mucous emboli, characteristic of severe mycoplasma pneumonia [23, 24].

Adenovirus pneumonia, responsible for 10-20% of pediatric pneumonia, particularly in children under 5, presents with high fever, cough, dyspnea, and chest pain, with patchy infiltrates and pleural effusion on chest X-rays [25, 26]. Diagnosis depends on virological and molecular tests, but these can produce false results [27]. FOB enhances diagnostic accuracy by

reducing upper respiratory contamination through BALF, enabling better immune response assessment. Bronchoscopic imaging can reveal airway abnormalities such as inflammation and necrosis [28, 29].

Aspiration Pneumonia

Aspiration pneumonia, caused by inhaling gastric contents, vomit, or foreign bodies, is common in children with neurological impairments or swallowing difficulties, accounting for 5–15% of pediatric cases, particularly in newborns and infants [30]. It presents with wheezing, shortness of breath, and cyanosis, with chest X-rays showing patchy infiltrates and pleural effusion [31]. Diagnosis typically involves medical history, clinical signs, chest X-rays, and bronchoscopy, although sample quality may affect accuracy [32]. FOB is essential for diagnosis and management, as BALF helps identify aspirated material, improving specificity. Cytological and pathological analyses of BALF assess inflammatory responses, and bronchoscopy can directly visualize aspirated substances, characteristic of aspiration pneumonia [27, 33].

Timing of FOB in pediatric pneumonia

The timing of FOB is crucial for maximizing diagnostic yield and therapeutic benefit in pediatric pneumonia. For MPP pneumonia, particularly severe or refractory cases, FOB is recommended within 7–10 days of symptom onset, especially if there is no clinical improvement after 48–72 hours of appropriate antimicrobial therapy. Early bronchoscopy during this window allows for effective removal of mucus plugs and mucous casts, which are prone to form during the peak inflammatory phase, thereby preventing bronchiolar obstruction and atelectasis [23, 24]. In adenovirus pneumonia, which often progresses rapidly and may lead to airway necrosis and post-infectious bronchiolitis obliterans, FOB should be performed earlier – ideally within the first 5–7 days of hospitalization – if there is clinical deterioration,

persistent hypoxia, or radiological progression despite supportive care. This enables timely pathogen confirmation via BALF and intervention to clear necrotic debris [28, 29]. For aspiration pneumonia, FOB is most beneficial when performed acutely, within 24–48 hours of the suspected aspiration event, to directly visualize and remove aspirated material, reduce bacterial load, and prevent secondary chemical pneumonitis or infection. In chronically aspirating children, such as those with neurodevelopmental disorders, semi-elective FOB may be scheduled to evaluate recurrent pulmonary infiltrates or persistent symptoms, even in the absence of an acute event [32, 33]. Overall, the decision to perform FOB should balance the urgency of intervention with procedural risks, and close monitoring during the initial phase of illness is essential to identify the optimal time window for intervention.

THERAPEUTIC VALUE OF FOB IN PEDIATRIC PNEUMONIA

The therapeutic application of FOB in pediatric pneumonia should be guided by the stage of disease progression. Interventions differ significantly between the acute and recovery phases, with distinct priorities in each.

Acute phase interventions (first 1–2 weeks of illness)

During the acute phase, the primary goals of FOB are to restore airway patency, manage life-threatening obstructions, and support gas exchange. This phase is characterized by intense inflammation, mucus hypersecretion, and potential airway plugging—particularly in severe mycoplasma, adenovirus, and aspiration pneumonias. FOB is indicated for the immediate removal of viscous secretions, mucus plugs, necrotic debris, or aspirated material via suction, irrigation, or forceps extraction [34, 35]. In children with respiratory distress, hypoxemia, or atelectasis unresponsive to conventional therapy, such interventions can rapidly improve

ventilation and prevent progression to respiratory failure [36]. Additionally, in cases of bronchial obstruction due to inflammatory casts or foreign bodies, timely FOB-guided clearance is critical to prevent irreversible lung damage. Direct instillation of saline lavage or mucolytic agents during this phase may further aid in breaking down tenacious secretions [37].

Recovery phase interventions (beyond two weeks or in persistent/recurrent cases)

In the recovery phase, FOB shifts from emergency intervention to diagnostic and rehabilitative roles. Persistent radiological infiltrates, prolonged oxygen dependence, or failure to thrive may indicate unresolved atelectasis, bronchial stenosis, or evolving airway complications such as bronchiectasis or bronchiolitis obliterans – particularly following severe adenovirus or mycoplasma infections [28, 29]. FOB during this phase allows for reassessment of airway integrity, clearance of residual secretions, and targeted delivery of anti-inflammatory agents (e.g., corticosteroids) or antibiotics directly to affected segments, enhancing local efficacy while minimizing systemic exposure [36, 37]. Furthermore, FOB enables the placement of airway stents or balloon dilation in cases of acquired bronchostenosis, thereby improving long-term pulmonary function and reducing the risk of recurrent infections [38, 39]. Serial BAL in the recovery phase may also be used to monitor inflammatory markers and microbiological clearance, guiding the duration of therapy.

COMPLICATIONS AND PRECAUTIONS OF FOB

Despite the advantages of FOB in the diagnosis and treatment of pneumonia in children, FOB is associated with risks and complications. FOB-related complications are described below.

Anesthesia and sedation-related complications

Anesthesia and sedation are required in FOB, which may lead to anesthesia and sedation-related complications such as respiratory depression, arrhythmia, hypotension, and allergic reactions [36]. In order to reduce the incidence of these complications, it is necessary to fully evaluate the patients before the procedure, select appropriate anesthesia and sedatives, monitor the vital signs of patients, and promptly find out and handle abnormal conditions [40].

Airway-related complications

FOB is operated through the airway and may lead to airway-related complications, such as laryngospasm, bronchospasm, airway bleeding, airway injury, and pneumothorax [36]. It is important to select an appropriate bronchoscope model, avoid excessive operation, control the pressure of the airway, keep the airway moist, and promptly find out and handle abnormal conditions to reduce the incidence of these complications [35].

Infection-related complications

The bronchoscope may contact with the secretions or tissues of the lower respiratory tract during the process of FOB, and may consequently cause infection-related complications, such as the spread of bacteria, viruses, mycoplasmas, and fungi, leading to cross-infection and nosocomial infections [36]. In order to reduce the incidence of these complications, it is essential that aseptic operation is strictly followed, bronchoscope and necessary instruments are thoroughly cleaned and disinfected, children are pre-treated with appropriate antibiotics for preventive purposes, and abnormal conditions are detected and handled promptly [41].

CONSIDERATIONS FOR FOB IN PEDIATRIC PNEUMONIA

Several issues need to be noted when FOB is used in the diagnosis and treatment of pneumonia in children, as described below.

Indications and contraindications of FOB

It is essential to understand the indications and contraindications of FOB when diagnosing and treating pneumonia in children to minimize risks. Indications include pneumonia with unclear etiology or treatment failure; severe pneumonia with complications like respiratory failure, difficult weaning, or organ dysfunction; pneumonia with airway blockages due to secretions or foreign bodies; pneumonia with airway abnormalities such as stenosis, deformities, inflammation, bleeding, or tumors; and cases requiring drug instillation or device placement in the airway [42]. Contraindications include severe systemic conditions like shock, coma, and massive bleeding; cardiovascular diseases such as heart failure, arrhythmia, and pericardial tamponade; coagulation dysfunction like thrombocytopenia; severe airway or lung abnormalities, including laryngeal edema, tracheal or esophageal fistulas, pleural effusion, and pneumothorax; and serious anesthesia or sedation risks, such as allergies and drug interactions [43].

Referral recommendations for FOB in primary healthcare settings

Given the limited availability of FOB in primary healthcare facilities, clinicians must recognize when referral to a specialized center is necessary. Referral indications include the following [15, 20, 21, 44]: If a child's pneumonia does not improve despite appropriate antimicrobial therapy or if the etiology remains unclear, FOB should be considered to identify atypical pathogens, foreign body aspiration, or underlying airway abnormalities not detected by routine methods. For severe pneumonia requiring intensive care or mechanical ventilation, FOB allows

for a comprehensive airway assessment and pathogen identification, facilitating targeted treatment and better management of complications such as pleural effusion or bronchial obstruction. In cases of suspected aspiration pneumonia, especially in children with neurological conditions or feeding difficulties, FOB helps identify and remove aspirated material, improving outcomes and preventing further complications. Additionally, when structural airway abnormalities like stenosis or tumors are suspected, FOB provides direct visualization to evaluate the extent of these issues and guide appropriate treatment, including surgical interventions. Finally, for cases requiring therapeutic interventions such as secretion removal, lavage, or device insertion, FOB offers the advantage of simultaneously providing diagnostic and therapeutic procedures, thereby optimizing patient management and outcomes.

Selection of appropriate FOB model and operation mode

When FOB is used in the diagnosis and treatment of pneumonia in children, the selection of an appropriate model and operation mode is required. Appropriate diameter, length, and curvature of fiberoptic bronchoscope should be selected based on factors such as the age, body weight, airway size, and conditions of children, to avoid airway injury and operation difficulties caused by the inappropriate size of the bronchoscope [45]. At the same time, appropriate operation modes, including spontaneous breathing, mechanical ventilation, and high-frequency oscillatory ventilation, are selected according to the factors of the children, such as respiratory pattern, airway pressure, and oxygenation level, to avoid the incidence of intraoperative complications such as dyspnea, hypoxemia and high airway pressure [46].

Age-specific considerations in FOB application

The application of FOB varies significantly across pediatric age groups due to differences in airway anatomy, size, and physiological resilience. Neonates and infants have smaller airway diameters, increased airway compliance, and higher risks of hypoxia, requiring ultra-thin

bronchoscopes (2.0–2.8 mm in diameter) and meticulous sedation management [47]. In contrast, older children and adolescents can tolerate larger scopes (3.0–4.0 mm) and may undergo procedures under moderate sedation with spontaneous breathing. Premature infants and those with underlying lung disease (e.g., bronchopulmonary dysplasia) are at increased risk for complications such as bronchospasm and desaturation. Furthermore, the indications for FOB may differ by age: viral and aspiration pneumonias are more common in infants and toddlers, while MPP predominantly affects school-aged children and adolescents [47]. Therefore, age-stratified approaches to patient selection, procedural planning, and post-procedure monitoring are essential to optimize safety and efficacy.

Combination with other examination and treatment methods

The diagnostic and therapeutic efficacy of FOB is significantly enhanced when integrated into a multimodal clinical strategy. FOB should be used in conjunction with advanced imaging modalities such as chest CT and point-of-care ultrasound, which provide complementary structural and functional information about the extent of pulmonary consolidation, pleural involvement, and airway dynamics [48]. BALF obtained via FOB can be analyzed using rapid molecular techniques—including multiplex PCR and next-generation sequencing (NGS)—to identify pathogens with high sensitivity and specificity, particularly in cases of culture-negative or atypical pneumonia [49]. Furthermore, BALF enables host immune response profiling (e.g., cytokine and cellular analysis), which, when combined with serum biomarkers such as procalcitonin and C-reactive protein, supports differentiation between bacterial, viral, and inflammatory etiologies. Physiological assessments, including pulmonary function tests (when feasible in older children) and pulse oximetry monitoring during and after the procedure, further refine clinical decision-making. This integrative approach – combining FOB with imaging, molecular diagnostics, and systemic biomarkers – facilitates precise etiological

diagnosis, monitors treatment response, and personalizes management strategies in children with complex or refractory pneumonia [50].

FUTURE DEVELOPMENT OF FOB

Remarkable achievements have been made for FOB in the diagnosis and treatment of pneumonia in children. However, there are still limitations and deficiencies in this technique, and further development and improvement are needed. Future developments of FOB are proposed and described below.

Pediatric applicability of advanced imaging technologies

While optical coherence tomography (OCT), endoscopic ultrasound (EUS), fluorescent bronchoscopy (FBS), and magnetic resonance bronchoscopy (MRBS) offer enhanced airway and parenchymal visualization, their application in children remains limited and largely investigational. OCT, which provides high-resolution cross-sectional imaging of airway walls, has shown potential in assessing bronchial inflammation and remodeling in adult chronic lung diseases, but its use in pediatric pneumonia is constrained by the small diameter of pediatric airways and the lack of suitably miniaturized probes compatible with ultra-thin bronchoscopes (2.0–2.8 mm) used in infants and young children [51]. Similarly, EUS-guided bronchoscopy, valuable for evaluating peribronchial lymphadenopathy or parenchymal consolidation, is rarely performed in children due to the size of current echo-bronchoscopes and the complexity of the procedure, which often requires general anesthesia and advanced expertise not widely available in pediatric centers [52]. MRBS, though non-invasive and radiation-free, is currently theoretical and faces significant technical hurdles in real-time airway navigation. Future development must prioritize the design of pediatric-specific probes, rigorous safety studies,

and clinical trials in pediatric populations to determine the diagnostic and therapeutic value of these technologies in childhood pneumonia and other respiratory conditions.

Improving the performance and functions of FOB

The performance and functions of future FOB should be enhanced by increasing the adjustability of related parameters such as the diameter, length, and curvature of the bronchoscope for children of different ages, body weights, and airway sizes, improving the quality of airway observation and diagnosis via increasing the clarity, resolution, and color of the bronchoscope, and enhancing the efficiency of airway operation and treatment via increasing the operability, flexibility, and stability of FOB [53].

Adding functions and accessories to FOB

More functions, such as optical, acoustic, electronic, and magnetic functions, will be added to future FOB for multi-modality imaging and examination, including OCT, EUS, FBS, and MRBS, to improve the structural and functional evaluation of the airways [51]. Meanwhile, accessories for fiberoptic bronchoscopes, such as various pliers, brushes, wires, catheters, stents, and balloons, will be added for multiple airway operations and treatments, including airway dilation, resection, biopsy, perfusion, and placement, to improve airway patency and stability [54].

Combining FOB with artificial intelligence and robotics

Artificial intelligence and robotics will be combined with FOB in the future. For instance, artificial intelligence and machine learning are used to analyze and identify the image and data obtained by FOB to improve the accuracy and objectivity of airway diagnosis and evaluation, for example, the identification of airway stenosis, deformity, inflammation, bleeding, and tumors, and evaluation of airway parameters, including diameter, length, branch, angle, and

wall thickness, which can predict the prognosis and therapeutic effect of airway diseases [55]. In addition, robotic technology is used to optimize and automate the operation and control of fiberoptic bronchoscopes to improve the efficiency and safety of airway operation and treatment, including the accurate positioning, navigation, tracking, operation, and feedback for the airways [56].

In summary, while FOB has proven valuable in diagnosing and managing pediatric pneumonia, its application in primary healthcare settings remains limited due to equipment and expertise constraints. Therefore, it is crucial for clinicians to recognize when referral to specialized centers is necessary. Key indications for referral include unresolved pneumonia despite appropriate treatment, suspected aspiration pneumonia, or when structural airway abnormalities are suspected. Timely referral enables accurate diagnosis, identification of atypical pathogens, and better management of complications, ultimately improving patient outcomes. Further advancements in FOB technology and training are essential to enhance its accessibility and effectiveness in pediatric care.

Ethics: The authors declare that the article was written in accordance with ethical standards of the Serbian Archives of Medicine as well as ethical standards of medical facilities for each author involved

Conflict of interest: None declared.

Author Contributions

Zhang H conception, analyzed the data, and wrote the manuscript;

Wang DX critical review of significant intellectual value, final revision of the manuscript being prepared for publication;

Yu HM obtaining of results or analysis and interpretation of results;

All authors have read and approved the manuscript.

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