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Recent Advances in the Study of Chest CT Features and Clinically Relevant Factors in Paediatric Pneumonia Caused by Different Pathogenic Microorganisms

Jian Cao, Qiang Fu*

Jingzhou Hospital Affiliated to Yangtze University, Jingzhou, China
Email: 17352828368@163.com, *fuqiang@yangtzeu.edu.cn

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Abstract

Community-acquired pneumonia in children is one of the leading causes of hospitalisation and mortality among children worldwide. Pneumonias induced by various pathogenic microorganisms exhibit distinct clinical manifestations and imaging characteristics. While specific diagnostic features may be present, overlapping symptoms are frequently observed. Chest computed tomography (CT) provides a detailed visualization of the subtle structures within pulmonary parenchymal lesions, and when integrated with clinical factors, it enhances the early differentiation of pathogens. This article provides a comprehensive summary of the chest CT characteristics associated with bacterial pneumonia, viral pneumonia, and Mycoplasma pneumoniae pneumonia. It further analyzes the correlation patterns between CT findings and clinical indicators, and investigates the supplementary value of integrating these indicators for early etiological differential diagnosis. Numerous studies have indicated that bacterial pneumonia is primarily characterized by lobar consolidation, often associated with significantly elevated levels of C-reactive protein (CRP) and procalcitonin (PCT). However, it is important to acknowledge that these biomarkers are not specific to particular pathogens, and their concentrations can be influenced by the disease state, timing of sample collection, and various other factors; viral pneumonia is characterised by diffuse ground-glass opacities and small airway changes, and is commonly seen in infants and young children; Mycoplasma pneumoniae pneumonia is characterised by bronchial wall thickening, the “tree bud” sign, and a dissociation between symptoms and physical signs, and is most common in school-aged children. Integrating CT features with clinical factors can improve the accuracy of pathogen differenti-

*Corresponding author.

ation. Radiomics and machine learning offer new approaches to pathogen prediction; however, most existing models are based on single-centre, small-sample datasets and lack sufficient generalisation ability. Further validation is required in multi-centre, standardised datasets.

Keywords

Paediatric Pneumonia, Pathogenic Microorganisms, Chest CT, Clinical Features, Radiomics

1. Introduction

Community-acquired pneumonia is one of the most common infectious diseases in children and a major cause of mortality among children under five worldwide [1]. According to data from the Global Burden of Disease study, pneumonia accounts for approximately 14 per cent of deaths in children under five, and the burden of disease remains significant. Bacteria, viruses and atypical pathogens can all cause pneumonia in children, and treatment regimens vary significantly depending on the pathogen. For example, bacterial pneumonia requires prompt administration of sensitive antibiotics, viral pneumonia is managed primarily with symptomatic and supportive care, whilst Mycoplasma pneumoniae pneumonia is sensitive to macrolide antibiotics. However, traditional microbiological testing methods, such as sputum culture and serological testing, are time-consuming, and their positive rates are influenced by factors such as specimen quality and prior antibiotic use, making it difficult to meet the clinical need for rapid early diagnosis. Chest X-rays are a commonly used initial screening tool for paediatric pneumonia, but their value in differential diagnosis is limited [2]. Thanks to its high spatial resolution, chest CT can clearly visualise the location, extent, morphology and associated features of pulmonary parenchymal lesions, and has become an important tool for the assessment of complex pneumonia cases [3] [4]. Prior research has shown that computed tomography (CT) possesses a markedly greater diagnostic sensitivity for detecting pediatric pneumonia and assessing its severity, with a sensitivity rate of 70.3%, in contrast to chest radiography, which has a sensitivity rate of 36.6% [5]. In recent years, the differences in CT features of pneumonia caused by different pathogens have received widespread attention [6]. At the same time, clinical factors such as the age distribution of paediatric patients, clinical manifestations and inflammatory markers are closely associated with infection by specific pathogens [7]; integrating the analysis of CT imaging features with these clinical factors is intended to improve the accuracy of early pathogen prediction [8]. Furthermore, it is imperative to emphasize the necessity of stringent regulation regarding the clinical justification for CT examinations in pediatric pneumonia cases. CT imaging is typically advised for pediatric patients exhibiting a high suspicion of complications, such as lung abscess, necrotizing pneumonia, and empyema; those presenting with atypical clinical manifestations un-

responsive to treatment; cases of recurrent infection or immunodeficiency; and instances where surgical intervention may be warranted. Considering the heightened radiosensitivity of children compared to adults, clinicians must meticulously evaluate the potential benefits against the inherent risks prior to recommending CT scans. Priority should be given to low-dose scanning protocols, and redundant examinations should be avoided once a definitive diagnosis has been achieved [9] [10]. This article systematically summarises the chest CT features and clinically relevant factors from three perspectives, bacterial pneumonia, viral pneumonia and Mycoplasma pneumoniae pneumonia, and explores the clinical value of combined imaging and clinical analysis.

2. Bacterial Pneumonia

2.1. Lobar Consolidation and Pulmonary Necrosis: Characteristic CT Features of Bacterial Pneumonia

The most typical presentation of bacterial pneumonia on paediatric chest CT is segmental or lobar consolidation, with air-bronchus signs frequently observed within the consolidated areas. Due to the considerable overlap in computed tomography (CT) findings, consolidation, although strongly indicative of a bacterial infection, may also be present in cases of mixed infections. Unlike viral pneumonia or Mycoplasma pneumonia, bacterial pneumonia rarely presents with diffuse ground-glass opacities or centrilobular nodules. *Streptococcus pneumoniae* is one of the most common pathogens causing bacterial pneumonia in children. A study involving 2850 paediatric cases of community-acquired pneumonia (CAP) showed a detection rate of 29.7% for *S. pneumoniae* [11], with detection peaking in pre-school-aged children. Its CT features are predominantly characterised by lobar consolidation, often affecting a single lung lobe, and may be accompanied by a small amount of pleural effusion, with prominent air-bronchial signs within the consolidated area. *Pneumococcal pneumonia* is more aggressive; on CT, it may present as lung abscesses, air cysts and pneumothorax, often accompanied by pleural effusion or empyema [12]. Necrotising pneumonia is one of the most serious complications of infections caused by *Staphylococcus aureus* and *Streptococcus pneumoniae* [13] [14]. A study on severe pneumonia in children showed that CT had a significantly higher sensitivity than chest X-rays in diagnosing cavitary necrosis [15] [16]; in three of the paediatric cases, cavitary necrosis was first detected by CT, whereas X-rays did not reveal it until 5 - 9 days later. Pathogens identified in this study included *Streptococcus pneumoniae*, Aspergillus, Legionella pneumophila and *Staphylococcus aureus*. CT not only enables earlier detection of pulmonary necrosis and cavitation, but also clearly visualises complications such as bronchopleural fistulas.

2.2. High Fever and Significantly Elevated Inflammatory Markers: Key Clinical Indicators of Bacterial Pneumonia

Bacterial pneumonia has an acute onset, with marked signs of systemic infection and toxaemia. An observational study involving 101 paediatric patients with pneu-

monia showed that in the bacterial infection group, serum PCT was 1.38 ± 0.21 ng/ml, CRP was 32.98 ± 5.22 mg/L, and SAA at 303.66 ± 51.04 mg/L, all of which were significantly higher than those in the mycoplasma and viral groups. ROC analysis showed that the AUC for PCT in diagnosing bacterial pneumonia reached 1.000, whilst the AUC for CRP was 0.833 [17]. Another multicentre prospective study involving 247 paediatric patients demonstrated that a CRP cut-off value of 42 mg/L and a PCT cut-off value of 0.85 ng/mL can predict bacterial pneumonia [18]. Combined testing can further enhance diagnostic value, one study showed that the AUCs for distinguishing between viral and bacterial pneumonia using CRP combined with SAA were 0.85 and 0.84, respectively, whilst specificity could be increased to 0.932 when combined with clinical symptoms, therefore, combined testing can further enhance diagnostic value [19]. It is important to underscore that the aforementioned biomarker indicators do not constitute pathogen-specific assays. Their values are influenced by a multitude of factors, such as the severity of the disease, the timing of blood sample collection, the presence of co-infections, and prior antibiotic usage. Consequently, the associated thresholds necessitate external validation across diverse populations prior to their broad implementation. With regard to the distribution of pathogens, a study involving 2850 paediatric patients with community-acquired pneumonia (CAP) showed that the bacterial infection rate was approximately 32.6 per cent, with Haemophilus influenzae (38.8 per cent), *Streptococcus pneumoniae* (29.7 per cent), Moraxella catarrhalis (21.4 per cent) and *Staphylococcus aureus* (10.1 per cent) being the predominant pathogens. Age is an independent risk factor for bacterial infection, the risk of *Staphylococcus aureus* infection is highest during infancy, whilst the risk of *Streptococcus pneumoniae* infection peaks during the pre-school years. Age-stratified analysis suggests that age should be given due consideration when administering empirical antimicrobial therapy [11].

Consequently, there is a relatively consistent correlation between the CT features of bacterial pneumonia and its clinical manifestations; purulent destruction of the lung parenchyma is manifested on CT as consolidation, whilst clinically it presents as high fever and significant elevations in CRP and PCT. However, a definitive diagnosis cannot be established based solely on an individual imaging sign or clinical indicator. A comprehensive assessment should integrate both of these elements in conjunction with factors such as the patient's age and treatment history. The multidimensional integration of these imaging findings with inflammatory markers and age distribution helps clinicians narrow down the differential diagnosis before the results of pathogen testing are available, thereby enhancing the targeted nature of early empirical antimicrobial therapy.

3. Viral Pneumonia

3.1. Ground-Glass Opacities and Small Airway Lesions: Characteristic CT Features of Viral Pneumonia

The CT presentation of viral pneumonia is characterised primarily by diffuse or

patchy ground-glass opacities, bronchial wall thickening, and centrilobular nodules, with segmental consolidation being less common [20] [21]. Unlike bacterial pneumonia, viral pneumonia often presents as multilobar involvement of both lungs, with lesions predominantly distributed around the hilum and bronchovascular bundles. Respiratory syncytial virus (RSV) is the most common pathogen causing viral pneumonia in infants and young children. A systematic review and meta-analysis (incorporating 10 studies and 217 cases of RSV pneumonia) showed that the most common CT findings in RSV pneumonia are signs of organising pneumonia (33.65%), septal thickening (33.19%), ground-glass opacities (28.03%) and the "tree bud" sign (27.44%), with 76.06% of cases showing bilateral lung involvement [22]. A domestic study involving 2850 paediatric cases of community-acquired pneumonia (CAP) showed that RSV is the most common pathogen in infancy, with infection peaks concentrated among infants and pre-school children. Typical CT findings for influenza virus pneumonia include bilateral or unilateral multifocal consolidation or atelectasis (35%), with lesions predominantly distributed around bronchovascular bundles. Influenza virus infection may be followed by secondary bacterial infections, such as those caused by *Streptococcus pneumoniae* and *Staphylococcus aureus*, leading to serious complications such as necrotising pneumonia [23]. In paediatric cases of influenza A (H1N1) pneumonia in 2009, atelectasis of the right upper lobe and mediastinal emphysema were relatively common. Adenoviral pneumonia is often characterised on chest CT by multifocal ground-glass opacities in both lungs or lobar or segmental consolidation; the incidence of consolidation is significantly higher in severe cases than in mild cases (73.91% vs 31.15%, $P < 0.01$) [24]. Severe adenoviral pneumonia progresses rapidly and can develop into respiratory failure within a short period [25]. The CT findings of human metapneumovirus (HMPV) pneumonia differ from those of typical viral pneumonia. A study conducted at Beijing Children's Hospital involving seven paediatric patients with severe HMPV pneumonia showed that the main CT features were lobar or segmental consolidation (consolidation was observed in all seven cases), air-bronchus signs (five cases) and bronchial wall thickening (six cases), rather than the atypical diffuse ground-glass opacities; CRP levels ranged from 35 to 146 mg/L, the median WBC count was 14.64×10^9/L, and LDH levels ranged from 248 to 496 IU/L; however, these findings can easily be confused with those of bacterial or mycoplasma pneumonia [26]. The proportion of severe cases is relatively high among children with HMPV pneumonia. A study involving 131 children with acute lower respiratory tract infections caused by HMPV showed that 35.1 per cent of cases were severe, with a co-infection rate of 53.4 per cent. Multivariate analysis indicated that high fever, hypoxaemia, lobar consolidation and mixed infections are independent risk factors for severe HMPV pneumonia [27].

3.2. Infants and Young Children with Wheezing Symptoms: Clinical Characteristics of Viral Pneumonia

Viral pneumonia is particularly common in infants and young children, with the

highest hospitalisation rate observed in infants under six months of age. RSV is the leading cause of hospitalisation in infants under one year of age; globally, there are approximately 3.6 million hospitalisations annually due to RSV-associated lower respiratory tract infections, of which infants under six months account for approximately 39 per cent [28] [29]. Studies have shown that 97.9 per cent of children with RSV pneumonia require hospitalisation. Clinically, the condition is typically characterised by small airway involvement, manifested as wheezing, shortness of breath and inspiratory retractions; fever is usually mild to moderate, with a duration of less than 5 days. Unlike bacterial pneumonia, children with viral pneumonia typically have lower CRP and PCT levels than those with bacterial pneumonia [17]. However, it should be noted that certain viruses, such as adenovirus and HMPV, may present with atypical features, including a significant elevation in CRP. Children with severe viral pneumonia have significantly higher levels of IL-6, CRP and PCT than those with mild cases [30].

In summary, the CT features of viral pneumonia are intrinsically linked to its clinical manifestations; diffuse ground-glass opacities and small airway changes correspond to clinical signs of airway involvement such as wheezing and shortness of breath, whilst CRP and PCT levels are generally not elevated. Infants and young children exhibit a heightened susceptibility to viral infections. In instances where lobar consolidation is observed on computed tomography (CT) scans, coupled with atypical clinical manifestations or elevated levels of C-reactive protein (CRP) and procalcitonin (PCT) that do not align with the clinical symptoms, there should be a suspicion of specific viral pathogens such as adenovirus and human metapneumovirus (HMPV), or the presence of mixed infections. In such cases, a thorough evaluation that integrates all available clinical information is imperative.

4. Mycoplasma pneumoniae Pneumonia

4.1. Bronchial Wall Thickening and the "Tree Bud" Sign: Typical CT Features of Mycoplasma pneumoniae Pneumonia

The CT presentation of Mycoplasma pneumoniae pneumonia (MPP) in children is characterised by certain distinctive features, with common findings including bronchial wall thickening, the "tree bud" sign, ground-glass opacities and patchy consolidation [31]. Unlike the segmental consolidation seen in bacterial pneumonia, the area of consolidation in MPP is typically smaller and is often distributed around bronchovascular bundles. Studies based on CT radiomics provide new evidence for distinguishing MPP from bacterial pneumonia. A retrospective study involving 535 paediatric patients with pleural effusion demonstrated that a radiomics model based on non-contrast-enhanced CT achieved an AUC of 0.942 in distinguishing pleural effusion associated with bacterial pneumonia from that associated with MPP. The study extracted a total of 2264 radiomic features, from which seven optimal features were ultimately selected to construct the model [6]. With regard to the prediction of refractory Mycoplasma pneumoniae pneumonia (RMPP), a multicentre study involving 419 paediatric patients with MPP devel-

oped an integrated model combining clinical, imaging and radiomic features. The AUC for predicting RMPP reached 0.811, which was significantly superior to that of a clinical-imaging model alone (AUC of 0.675) [32]. Studies have shown that platelet count (PLT), C-reactive protein (CRP), lactate dehydrogenase (LDH) and D-dimer levels are significantly higher in the RMPP group than in the standard MPP group. Regarding the prediction of MPP complicated by plastic bronchitis (PB), a three-centre study involving 777 paediatric patients with MPP and pulmonary consolidation found that 280 cases (36.0%) were in the PB group and 497 cases (64.0%) in the non-PB group; multivariate analysis indicated that pleural effusion was an independent risk factor for PB [33]. Furthermore, a combined model integrating seven radiomic features and pleural effusion achieved AUC values of 0.809, 0.770 and 0.831 in the training, testing and validation sets, respectively, all of which were significantly superior to those of the CT-only model or the clinical model.

4.2. School-Aged Children and the Separation of Symptoms and Signs: Clinical Characteristics of Mycoplasma Pneumoniae

MPP is most commonly observed in school-aged and pre-school children. A retrospective study involving 468 paediatric patients with MPP showed that the mean age of children in the RMPP group was 6.23 ± 2.89 years, and the incidence of pulmonary consolidation (79.49%) and pleural effusion (30.77%) was significantly higher than in the general MPP group, the study indicated that CRP and D-dimer are independent risk factors for RMPP [34]. The most diagnostically significant feature of this condition is the dissociation between symptoms and physical findings, whereby children present with marked symptoms such as cough and fever, yet auscultation of the lungs reveals few rales, which is inconsistent with the significant lesions shown on chest imaging [35]. In terms of inflammatory markers, CRP and PCT levels in children with MPP fall between those of bacterial pneumonia and viral pneumonia [17]. Studies have shown that CRP and D-dimer are important clinical indicators for predicting the progression of RMPP to pulmonary consolidation; when the median CRP level is set at 39.34 mg/L, the area under the curve (AUC) for predicting RMPP reaches 0.841 [34]. With regard to macrolide-resistant MPP, a study involving 199 paediatric patients with MPP showed that 151 cases (75.9%) harboured 23SrRNA gene mutations characteristic of resistant strains, whilst 48 cases (24.1%) were sensitive strains. Children in the drug-resistant group were predominantly of pre-school and school age and presented with more severe clinical symptoms; 66.2% of these children required a switch from azithromycin to doxycycline. Multivariate regression analysis indicated that segmental or lobar consolidation was an independent predictor of the switch to doxycycline [36].

In summary, for the management of Mycoplasma pneumoniae pneumonia, it is crucial to distinctly differentiate between pathogen identification, which relies on nucleic acid or antibody testing, and the prediction of disease severity and

complications, which utilizes clinical indicators and radiomics models. There is a relatively distinctive relationship between the CT features and clinical characteristics of Mycoplasma pneumoniae pneumonia; airway changes such as bronchial wall thickening and the "tree bud" sign are closely associated with the clinical presentation of intractable dry cough, whilst the dissociation between the extent of consolidation and pulmonary physical findings serves as an important diagnostic clue for this condition. Furthermore, given that MPP predominantly affects school-aged children and is typically characterised by normal PCT levels, an integrated analysis of imaging findings alongside age and inflammatory markers aids in the early identification of MPP and its differentiation from bacterial and viral pneumonia.

5. Challenges and Outlook

The radiological diagnosis and pathogen prediction of paediatric pneumonia face multiple challenges in clinical practice. Firstly, mixed infections render CT findings atypical; characteristic features of a single pathogen may be masked or superimposed, increasing the difficulty of radiological interpretation. Currently, integrated imaging-clinical studies on mixed infections remain limited; future research should involve large-scale, prospective cohort studies to explore imaging patterns specific to mixed infections and their associations with clinical indicators. Secondly, pulmonary infections in immunocompromised children present more complex manifestations; due to impaired host responses, the CT presentation of pneumonia in these children is more complex than in immunocompetent children. Typical signs characteristic of infections caused by common pathogens may be absent or present as atypical changes; therefore, imaging assessment requires a comprehensive evaluation that takes into account immunological status, history of previous infections and laboratory results. Some studies suggest that, where necessary, a combination of multiple imaging techniques should be employed for a comprehensive assessment. Thirdly, regional disparities in pediatric vaccination status, disease severity grading, specimen testing methodologies, and sampling timing may contribute to variations in pathogen distribution frequencies and imaging findings reported across different studies. These factors represent potential confounders that must be accounted for in future meta-analyses and multicenter research endeavors. Fourthly, preliminary progress has been made in the application of artificial intelligence (AI) to assist in the diagnosis of paediatric pneumonia via CT imaging. Existing models, by processing chest imaging data and integrating patient clinical data, can assist clinicians in the early identification of signs of severe pneumonia. Multimodal machine learning models, which fuse CT imaging features with clinical information from electronic health record systems and laboratory biomarkers, have demonstrated potential in pathogen identification and prognostic prediction. However, most current models are still based on single-centre, small-sample data and have limited generalisation ability; the translation from laboratory research to clinical workflows still faces numerous obstacles, in-

cluding technical standardisation, data sharing and model interpretability. Future research should involve multicentre studies with large sample sizes, accompanied by rigorous external validation, to explore the feasibility and acceptability of these models in real-world clinical settings.

6. Summary

The pathogen spectrum of paediatric CAP is complex, with different pathogens exhibiting distinct patterns in CT imaging and clinical features. For the purpose of etiological differentiation, it is important to acknowledge that computed tomography (CT) findings and laboratory indices often overlap and do not possess absolute specificity. When computed tomography (CT) imaging demonstrates lobar consolidation in conjunction with high fever and significantly elevated levels of C-reactive protein (CRP) and procalcitonin (PCT), bacterial pneumonia should be considered as the primary diagnosis; when CT findings show ground-glass opacities accompanied by wheezing and no elevation in CRP, this usually indicates viral pneumonia; if CT findings show bronchial wall thickening accompanied by a dry cough and no elevation in PCT, this is typically Mycoplasma pneumonia. Clinically, empirical antimicrobial therapy may be initiated prior to the return of microbiological results to enable early targeted treatment. When CT findings are inconsistent with clinical features, one should be alert to the possibility of mixed infections or specific pathogens. For example, viral pneumonia (such as adenovirus or HMPV) may present as lobar consolidation with a marked elevation in CRP, making it difficult to distinguish from bacterial pneumonia; the typical dissociation of symptoms and signs in MPP—where significant radiological consolidation is present but no lung rales are heard on auscultation—also suggests that imaging findings cannot be equated with clinical diagnosis; in such cases, a comprehensive assessment incorporating multiple clinical indicators is required. The pathogen profile of community-acquired pneumonia (CAP) varies significantly across different age groups in children; in infants and young children, the presence of consolidation warrants particular vigilance for *Staphylococcus aureus*, whilst in pre-school-aged children, *Streptococcus pneumoniae* and MPP are more common. Consequently, interpreting CT findings in isolation without considering age-related factors is likely to lead to erroneous conclusions. Therefore, the integrated analysis of CT characteristics and clinical factors is not merely a simple combination of imaging and clinical data, but rather the establishment of a logical correspondence between the three elements: "CT findings - clinical presentation - laboratory indicators". This approach provides a more reliable decision-making framework for the early pathogen differentiation in paediatric pneumonia and represents the direction in which imagingomics and machine learning modelling need to be deeply integrated.

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Author Contributions

Conceptualization, writing—original draft preparation, J.C.; writing—review and editing, project administration, Q.F.; All authors have read and agreed to the published version of the manuscript.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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