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Systematic Review

Critical care in paediatrics: the role of ventilation techniques in managing acute respiratory conditions

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ABSTRACT

This systematic review evaluated the effectiveness of ventilation techniques in managing paediatric acute respiratory conditions, including asthma, bronchiolitis, and pneumonia. The review included 19 studies from PubMed, Scopus, Web of Science, and the Cochrane Library, published between 2015 and 2024. Findings showed that non-invasive ventilation (NIV) methods like CPAP along with BiPAP improve oxygenation and reduce intubation rates, with CPAP effective for mild cases and BiPAP for severe distress. High-flow nasal cannula (HFNC) outperformed standard oxygen therapy (SOT), though comparisons with NIV remain inconclusive. Invasive techniques like pressure-regulated volume control (PRVC) along with pressure support ventilation (PSV) are vital for unstable patients, with PRVC preventing barotrauma and PSV easing respiratory effort. Additionally, four-dimensional computed tomography (4DCT) imaging proved valuable in optimizing ventilation strategies and improving diagnostic accuracy. In conclusion, NIV techniques like CPAP along with BiPAP are effective in improving oxygenation and reducing intubation rates in paediatric respiratory conditions, with BiPAP being more suitable for severe distress. HFNC shows promise over SOT, though further comparison with NIV is needed. Invasive ventilation methods, such as PRVC and PSV, are essential for managing unstable patients, with PRVC offering protection against barotrauma and PSV enhancing respiratory efficiency. The study underscores the importance of lung-protective strategies to minimize risks in paediatric ventilation.

Keywords: Paediatric respiratory care, Non-invasive ventilation, High-flow nasal cannula, 4DCT imaging, Acute respiratory conditions

INTRODUCTION

Paediatric patients' acute respiratory diseases are particularly complex in critical care, requiring rapid interventions and particularly appropriate management to achieve better outcomes.[1] Ventilation therapy has a central role among strategies used for dealing with these conditions, which may include simple asthma attacks as well as more severe illnesses, such as ARDS/ respiratory failure.[2] Ventilation for paediatric patients must be individualized because the patients are different physiologically from adults that require different ventilation methods. Both invasive and non-invasive techniques are used in paediatric ventilation to manage acute respiratory diseases with diverse indications and advantages. [3]

BiPAP or nasal CPAP is NIV support in which the child patient receives support without being intubated.[4] NIV is particularly effective in managing conditions such as acute asthma, mild respiratory distress, and obstructive sleep apnea, providing comfort while avoiding the risks associated with invasive procedures.[5]

Invasive mechanical ventilation (IMV) requires insertion of an endotracheal tube to stabilize the airway and allow the airway to support the lungs directly. IMV is indicated in more severe cases, such as respiratory failure, ARDS, or when NIV does not provide adequate oxygenation.[6] It provides precise ventilation control but carries risks such as ventilation-associated pneumonia and barotrauma. Both techniques play noteworthy part in paediatric critical care, with choice of technique depending on severity of condition, patient response and the need for further therapeutic interventions. By evaluating the effectiveness of these methods, the study aims to provide insights into optimizing ventilatory support for paediatric patients, enhancing both short-run recovery and long-run health outcomes. Given delicate balance of maintaining oxygenation while preventing ventilator-induced lung injury, understanding nuances of ventilation strategies is essential for healthcare professionals working within ICUs. The primary objective of this study is to explore role of different ventilation techniques in management of acute respiratory conditions in paediatric critical care.

METHODS

These investigations utilised a systematic review methodology to evaluate role of ventilation techniques in managing paediatric acute respiratory conditions. The review synthesized evidence from secondary literature on both non-invasive and invasive ventilation methods, as well as the application of 4DCT imaging to optimize respiratory management in paediatric critical care. Literature search encompassed studies published between January 2015 and October 2024 to ensure a comprehensive review of the latest advancements in paediatric ventilation and imaging techniques.

Data collection

The data for this review were obtained from peer-reviewed journals, clinical guidelines, systematic reviews, grey literature, and conference proceedings. A standardized data extraction form was employed to gather information on study design, population demographics, intervention methods (ventilation techniques), clinical outcomes, and use of 4DCT in respiratory management.

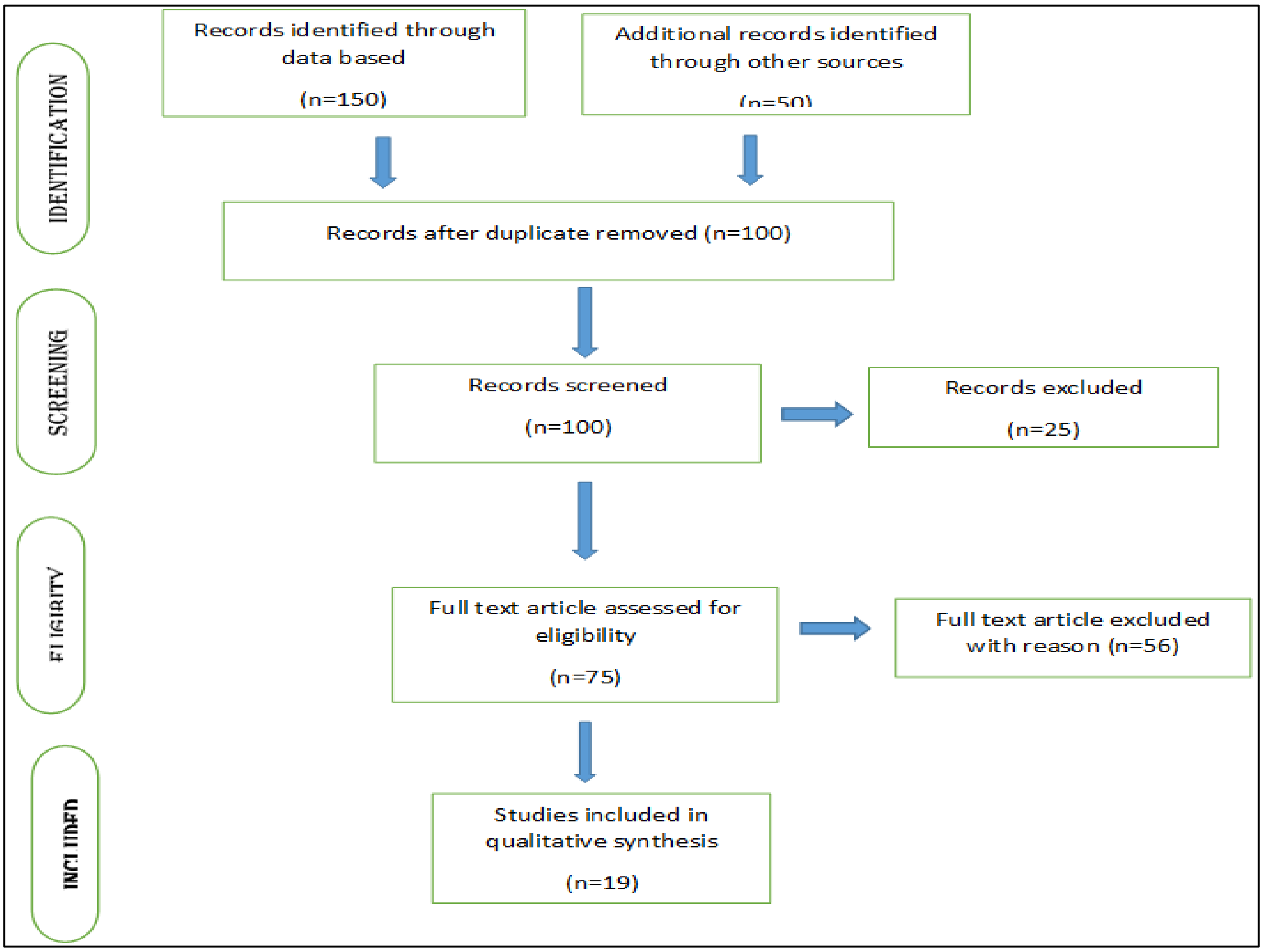

Figure 1: PRISMA flow diagram depicting the systematic selection process of studies for the qualitative synthesis.

Inclusion and exclusion criteria

Inclusion criteria focused on studies involving paediatric populations (0-17 years) with acute respiratory conditions requiring mechanical ventilation. Studies discussing non-invasive techniques-CPAP and BiPAP, invasive methods such as PRVC and clinical utility of 4DCT imaging were included. Key outcomes of interest were oxygenation improvement, reduction in complications, and changes in clinical decision-making. Exclusion criteria ruled out studies involving adult populations, unrelated respiratory conditions, case reports, editorials, and non-English publications without available translations.

Selection process

A systematic search was done across electronic databases counting PubMed, and Scopus, and Web of Science, along with Cochrane Library. Keywords such as "paediatric critical care," "acute respiratory conditions," and "mechanical ventilation" were used alongside Boolean operators and filters to ensure relevance. Titles and abstracts were checked, followed by a full-text review grounded in inclusion and exclusion criteria. The PRISMA guidelines were adhered to for documenting the selection process, which began with 150 records from databases and 50 additional records from other sources. After screening and exclusions, 19 studies were ultimately included for qualitative synthesis.

Data analysis

Data were synthesized narratively to explore the efficacy and security of different ventilation strategies. The analysis highlighted key differences and similarities between non-invasive and invasive methods, alongside the role of 4DCT in guiding interventions. This comprehensive review provides insights into the evolving landscape of paediatric ventilation and imaging, emphasizing advancements in the patient-centred care.

RESULTS

The results highlight the effectiveness of specific modalities in addressing varied respiratory challenges across paediatric age groups. These approaches were assessed for their ability to improve oxygenation, reduce respiratory distress, and minimize the need for invasive procedures.

Table 1: NIV for specific paediatric respiratory conditions.

Diagnosis	Respiratory involvement/ definition	Respiratory findings/ symptoms	Recommended therapies
Asthma	Increased resistance to airflow, decreased expiratory flow rates, airway over-distention, hyperinflation of lungs, alveolar hypo inflation	Tachypnoea, hypoxemia, cough, increased work of breathing, wheezing	BiPAP, CPAP, HFNC
Bronchiolitis	Inflammatory injury of bronchioles, typically viral, with airway hyperinflation and reduced ventilation	Cough, increased secretions, wheezing, retractions	BiPAP, CPAP, HFNC
Pneumonia	Obstructive process with exudates and inflammation in alveoli, leading to atelectasis and reduced ventilation	Cough, tachypnoea, increased work of breathing, hypoxemia	BiPAP, CPAP, HFNC
Acute respiratory distress syndrome (ARDS)	Acute bilateral lung infiltrates with non-cardiogenic pulmonary edema	Severe hypoxemia, bradypnea, tachypnoea	BiPAP
Respiratory failure	Impaired gas exchange unable to meet metabolic demands	Bradypnea, tachypnoea, apnea, hypoxemia, possible stridor and wheezing	BiPAP
chronic neuromuscular disorders	Progressive loss of neuromuscular function leading to respiratory decline	Hypoxemia, bradypnea, declining respiratory function	BiPAP, CPAP

Efficacy of NIV techniques in paediatric acute respiratory conditions

NIV has evolved significantly since its initial use in the 1940s for pneumonia, severe asthma, etc.[7] Acute lower respiratory infections (ALRIs), including pneumonia, are a leading cause of respiratory distress in children, with approximately 650,000 deaths annually, highlighting the need for advanced respiratory support like non-invasive techniques beyond SOT recommended by the WHO.[8] Today, NIV techniques such as CPAP and BiPAP are important in managing paediatric acute respiratory conditions, improving oxygenation, reducing intubation rates, and preventing respiratory failure CPAP is used to maintain airway patency in mild cases.[9] CPAP provides continuous positive airway pressure to increase oxygenation and lung ventilation, whereas NIV uses two levels of pressure serve to improve ventilation and facilitate CO_2 elimination, both techniques aim to restore lung function and reduce respiratory force while BiPAP, with its two pressure levels, for acute or significant respiratory distress. Provides support highly targeted for airway obstruction. Both are effective for conditions such as bronchiolitis, severe asthma and post extubation failure. However, their success depends on appropriate patient selection, consistent monitoring, and timing of transition to radiation when necessary.[9]

Modern NIV systems, including another technique HFNC, provide heated, humidified air at high flow rates, improving alveolar ventilation and reducing dead space. HFNC, initially used in neonatal care, is now valuable for older paediatric patients, especially those with bronchiolitis and asthma. The choice of device and settings-such as nasal pillows, oronasal masks, CPAP pressures of 4-6 cm H_2O, and BiPAP pressures ranging from 10-12 cm H_2O inspiratory to 5-6 cm H2O expiratory-depends on the child's condition, age, and disease severity.[9] The integration of oxygen and humidity ensures optimal and safe respiratory support for diverse paediatric conditions. HFNC proved superior to SOT in reducing treatment failure, but compared with CPAP and BiPAP, the efficacy is inconclusive especially in terms of intubation rates and mortality. Meta-analyses previous studies have mainly focused on pairwise comparisons and excluded additional randomized trials, leaving the role of BiPAP underexplored Apparently clearly a comprehensive evaluation is needed to assess the effectiveness of all NIV options in the management of paediatric ALRI.[10]

NIV plays a crucial role in addressing these challenges by applying positive pressure throughout the respiratory cycle to maintain airway patency and support effective gas exchange. The following table 1 highlights specific paediatric respiratory conditions, their respiratory implications, and the recommended NIV techniques for management.[11]

This table summarizes the use of NIV techniques in paediatric conditions, showcasing their efficacy in alleviating symptoms, maintaining lung volumes, and optimizing oxygenation.

Impact of prone positioning in paediatric respiratory management

Ventilation strategy like prone position has been seen as useful in treating of ARDS in children. It improves the homogeneity of distribution of ventilation and perfusion, boosts gas exchange and can lessen dependence on high pressure or high-volume ventilation.[12] Nevertheless, its use in children is still a bit challenging, especially owing to certain concerns with complications. The rationale for prone positioning is mainly focused on improving oxygenation because of increasing ventilation in the dorsal lung zones that are usually relatively under-ventilated in supine position. On mechanistic basis, positioning the patient prone shifts the pressure of heart and abdominal viscera and the effect of which is improved lung ventilation and decreased pressure on the posterior lobe. Research also august that prone positioning could be correlated with reduced mortality among severe forms of ARDS among children.[13]

In paediatric patients, several factors must be considered. Younger children may require additional support due to developmental factors, and close monitoring of vital signs, oxygen saturation, and ventilator settings is essential. Potential complications such as pressure sores, facial edema, and challenges in airway access necessitate meticulous care in positioning and skin management.

Key considerations when employing prone positioning include

Patient selection: Best suited for children with moderate to severe ARDS on mechanical ventilation.

Timing and duration: Prone positioning should be initiated under the guidance of a paediatric critical care specialist, with sessions typically lasting several hours to a full day depending on the child's condition.

Proper positioning: Attention to minimizing pressure points and ensuring optimal lung ventilation is critical. When applied thoughtfully, prone positioning can play a crucial role in improving outcomes for paediatric patients with ARDS.

Role of laryngeal mask airway in paediatric acute respiratory care

Laryngeal mask airway (LMA) is a revolutionary practice in pediatric acute respiratory management and critical life-threatening situations where conventional techniques are not feasible, because of risk factor or inability to intubate a child. It helps to provide positive pressure ventilation with reduced chances of aspiration hence a valuable instrument in patients with difficult airways during aesthetic or resuscitation procedures. Since its development in 1981 by Archie Brain, the LMA has become a cornerstone of airway management, with applications spanning from routine anaesthesia to challenging pediatric cases. Although its adoption in children initially lagged behind adults, it is now a standard tool in pediatric respiratory care, emphasizing safety, efficacy, and adaptability.[14]

An additional benefit in paediatrics, the LMA is useful when managing the compromised airway where there is upper airway pathology, congenital abnormality or contraindications to tracheal intubation. Due to its ability to be inserted into the airway easily, in emergency situations, it is used in several circumstances; the surgery; in diagnostic procedures that require an airway; and in resuscitation.[15] Techniques such as the use of LMA classic™ are used frequently and research concerning the technology focuses on neonates of not more than 5 kg of weight within the first weeks after birth. However, variations in size and material among manufacturers require careful selection to ensure optimal performance.[16]

The LMA's ventilatory channel and inflatable cuff, among other structural features, allow for a safe airway closure in the hypopharynx. Due to its suppleness and increased oropharyngeal seal pressure, silicone-based LMAs are preferred over polyvinyl chloride (PVC) since they lower dangers such as phthalate exposure. When properly sterilised, reusable silicone LMAs can be used up to 60 times, adding to their durability. The LMA has drawbacks despite its advantages. When there is a high danger of stomach content aspiration or poor lung compliance, it should not be used.[16] To handle any issues such airway obstruction, incorrect placement, or laryngeal damage, close observation is also essential throughout use. Applying an LMA safely and effectively requires choosing one that is the right size for the child's anatomy and condition.

Advancements in invasive ventilation techniques in paediatrics: The PRVC mode

PRVC mode is one of the most advanced modes of invasive ventilation that proves an offer of both the volume and pressure control in pediatric ventilation. This mode is especially useful in ventilating patients with varying lung compliance like the children or during surgery and those with varying or unstable respiratory illnesses.

The PRVC is a volume targeted mode that uses pressure control to guarantee a specific tidal volume is provided while changing the pressure level during inspiration. This adaptability assists in preventing barotrauma in those patients with delicate lungs in addition to enhancing gas exchange.[17] Due to constant monitoring of pressures and setting of pressures to obtain the desired tidal volume, patients are well protected from excessive ventilation pressures by PRVC. It also improves patient-ventilator asynchrony, which is preferable for pediatric patients who may have fluctuating lung stiffness caused by surgical operations or lung diseases and immature lungs.[17]

But PRVC needs careful and professional supervising. The goal is to monitor tidal volumes, airway pressures, and gas exchange at frequent intervals to improve the result and to identify problems. PRVC can be useful in many situations but there may be patients who will be better served by other modes based on their pathophysiology, for instance patients with severe airway disease or very unstable lung parenchyma. However, what is also important clinicians understand PRVC, for example factors such as the specific ventilator settings and patient lung mechanics involved.

Advancements in paediatric ventilation: the role of PSV

PSV, one of the enhanced features of contemporary anaesthesia ventilators, helps intubated youngsters breathe on their own. By providing inspiratory pressure and letting patients choose when to inhale, this mode lessens the effort required to breathe. Even in children who are anaesthetised and have healthy lungs, the regular use of positive end-expiratory pressure (PEEP) in conjunction with PSV avoids atelectasis and improves respiratory mechanics. PSV can promote gas exchange, reduce respiratory effort, and improve outcomes for all paediatric age groups when used in conjunction with PEEP and inspiratory pressure support. [18]

Negative consequences include atelectasis, airway hypotonia, and decreased tidal volume can arise after general anaesthesia when spontaneous breathing is maintained without PSV. By promoting ventilation, re-establishing minute ventilation, and enhancing oxygenation, PSV lessens these consequences. PSV improves surgical recovery, lowers intraoperative atelectasis, and increases preoxygenation, according to adult studies. Due to their distinct respiratory anatomy and increased risk of perioperative respiratory problems, children are especially affected by these findings.

PSV is still underutilised in paediatric anaesthesia, despite its benefits. Even in situations when PSV could provide substantial advantages, unassisted method of ventilation was frequently selected over PSV, according to European statistics from 2014–2015. This underutilisation shows that PSV needs to be better understood and used. For the ventilator and the child's respiratory drive to operate in unity, trigger sensitivity, cycling thresholds, and backup modes must be configured correctly. Complications including dynamic hyperinflation, barotrauma, or increased respiratory effort might result from poor management.[18]

During general anaesthesia, PSV has many benefits, such as better gas exchange, quicker recovery, and less anaesthetic use. It promotes improved haemodynamic stability and analgesia titration by preserving spontaneous breathing. Given its advantages, PSV ought to be used more frequently in paediatric anaesthesia, with careful consideration given to patient-specific modifications and close observation to maximise results.

Barotrauma in paediatric mechanical ventilation: risks and mitigation

Pneumothorax, pneumomediastinum, and subcutaneous emphysema are examples of air leaks that can result from barotrauma, a serious risk with paediatric mechanical ventilation. Children's lungs are delicate and undeveloped, which makes them more vulnerable to these injuries, particularly in premature babies. The danger is further increased by improper ventilator settings, like large tidal volumes or insufficient PEEP. A quick diagnosis through clinical evaluation and imaging, such as chest X-rays, is necessary for symptoms including abrupt oxygen desaturation, chest pain, and diminished breath sounds, which can indicate barotrauma. Lung-protective ventilation techniques are crucial to reducing hazards.[19] These include the utilisation of pressure-controlled ventilation modes to restrict peak pressures, low tidal volumes (6-8 ml/kg), and suitable PEEP levels to avoid alveolar collapse. Timely ventilator settings are ensured by regular monitoring of lung mechanics, including plateau and peak inspiratory pressures. Suctioning and airway management done correctly also lowers the chance of blockage and consequent harm. Interventions for barotrauma can include anything from modifying ventilator settings to more drastic treatments including surgical repair in extreme cases or needle aspiration for tension pneumothorax.

Role of 4DCT imaging in optimizing paediatric ventilation techniques

4DCT is transforming pediatric respiratory care by offering dynamic, real-time insights into lung mechanics. This advanced imaging tool provides detailed visualization of ventilation-perfusion relationships and aeration patterns, enhancing both non-invasive and invasive ventilation strategies. 4DCT optimizes non-invasive methods like BiPAP and CPAP by assessing regional lung aeration and ventilation-perfusion mismatches.[20] Real-time monitoring allows clinicians to individualize adjustments, improving oxygenation and reducing ventilation failure risks. For invasive techniques like PRVC, 4DCT identifies overdistension or collapse, enabling precise ventilator settings that minimize barotrauma risks while ensuring lung protection. Thus, 4DCT bridges non-invasive and invasive approaches, offering evidence-based data to guide transitions between these methods. Integrating 4DCT into pediatric respiratory care enhances precision in ventilation strategies, improves outcomes, and reduces complications.[21,22] Early optimization of non-invasive methods may lower the need for invasive interventions, supporting a safer and more patient-centred approach to managing acute respiratory conditions. As evidence grows, 4DCT is poised to revolutionize pediatric critical care with individualized and effective respiratory management solutions.

DISCUSSION

The findings of this study underscore the efficacy of NIV techniques such as CPAP and BiPAP in managing a variety of pediatric acute respiratory conditions, including asthma exacerbations, bronchiolitis, pneumonia, and ARDS. These modalities significantly improve oxygenation, reduce work of breathing, and minimize the need for IMV. The results align with earlier studies Goo et al that have demonstrated the advantages of CPAP in maintaining airway patency and BiPAP in providing targeted inspiratory and expiratory pressure support, particularly in severe respiratory distress.[17]

HFNC has emerged as a complementary tool in pediatric respiratory care, particularly for bronchiolitis and mild hypoxemic respiratory failure. Studies by Skiey et al reported that HFNC could effectively reduce the need for escalation to CPAP or BiPAP in mild cases, which supports its role as an initial treatment in selected scenarios.[18] However, our findings suggest that CPAP and BiPAP offer superior outcomes in severe conditions requiring more aggressive intervention.

Prone positioning in ARDS, highlighted in our study, also showed benefits in improving oxygenation and redistributing ventilation, aligning with the findings of Sood et al who observed reduced mortality in severe pediatric ARDS cases managed with prone positioning.[20] However, the application of this technique requires careful monitoring and expertise to mitigate complications such as pressure sores and airway management challenges. The role of the LMA in pediatric respiratory management was particularly notable in this study for its non-invasive approach to airway stabilization. This finding aligns with evidence from Sun et al who emphasized LMA's utility in emergency scenarios and patients with upper airway obstruction or anatomical anomalies.[21] Its ease of use and safety profile make it a valuable adjunct in specific acute care scenarios.

Similarly pediatric invasive ventilation techniques, such as PRVC and PSV, have significantly improved outcomes in managing children with respiratory illnesses. PRVC offers a volume-pressure control mix, ensuring precise tidal volumes while minimizing the risk of barotrauma, making it especially beneficial for children with fluctuating lung compliance Barbaro et al PSV, which supports spontaneous breathing, enhances gas exchange and prevents atelectasis when combined with PEEP, yet remains underutilized in pediatric anaesthesia despite its proven benefits as suggested by (Rensberger et al).[23,24] Both modes require careful monitoring to avoid complications such as dynamic hyperinflation or barotrauma, especially in delicate pediatric lungs (Ingels et al).[25] Additionally, the integration of 4DCT allows for real-time assessment of lung mechanics, improving the precision of both invasive along with NIV methods and reducing the need for invasive interventions by optimizing patient-specific ventilation strategies. In summary advancements in both invasive and non-invasive pediatric ventilation techniques, have improved respiratory management in children. Additionally, 4DCT imaging enhances these methods by providing real-time insights into lung mechanics, allowing for more precise adjustments and reducing the need for invasive interventions, ultimately improving patient outcomes.

CONCLUSION

In conclusion, this study demonstrates that NIV techniques, such as CPAP along with BiPAP, are effective in improving oxygenation and reducing intubation rates in pediatric patients with acute respiratory conditions. CPAP is particularly useful for milder cases, while BiPAP is beneficial for managing severe respiratory distress. HFNC was found to outperform SOT in reducing treatment failure, though further comparisons with NIV methods are needed. Invasive ventilation techniques, including PRVC and PSV, remain crucial for managing critically ill patients, with PRVC helping to prevent barotrauma and PSV reducing respiratory effort. Additionally, 4DCT imaging proves valuable in enhancing the precision of ventilation strategies and improving overall clinical outcomes. Tailored approaches, integrating advanced ventilator modes and adjunctive strategies like prone positioning, highlight the importance of individualized care in addressing diverse respiratory challenges in children.

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