

Management of Acute Asthma Exacerbations in the Pediatric Emergency Department

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Abstract

Asthma exacerbations remain one of the most common reasons for pediatric emergency department visits, accounting for approximately 1.6 million ED visits and 183,000 hospitalizations annually in the United States alone. Despite advances in outpatient asthma management, acute exacerbations continue to impose substantial morbidity, healthcare costs, and missed school days on affected children and their families. This narrative review synthesizes current evidence on the assessment and management of acute asthma exacerbations in the pediatric emergency department setting. We conducted a comprehensive literature search of PubMed, MEDLINE, and Cochrane Database of Systematic Reviews for articles published between 2010 and 2024, prioritizing systematic reviews, randomized controlled trials, and clinical practice guidelines from the Global Initiative for Asthma and the National Asthma Education and Prevention Program. Current evidence supports a structured approach beginning with rapid severity assessment using validated clinical scoring systems such as the Pediatric Respiratory Assessment Measure. First-line therapy includes oxygen supplementation as needed, frequent administration of inhaled short-acting beta-agonists during the initial hour, and early systemic corticosteroids. For moderate-to-severe exacerbations, the addition of ipratropium bromide has demonstrated benefit, while intravenous magnesium sulfate shows efficacy in severe cases unresponsive to initial treatment. High-flow nasal cannula therapy has emerged as a promising adjunctive intervention, though evidence in the emergency department setting continues to evolve. A systematic approach emphasizing early corticosteroids and appropriate escalation for refractory cases can reduce admission rates and improve outcomes. Ongoing research into adjunctive therapies and phenotype-specific treatment strategies may further refine emergency department management in the coming years.

Keywords: *pediatric asthma, acute exacerbation, emergency department, management, children, bronchodilators, corticosteroids*

Introduction

Asthma is the most common chronic disease affecting children worldwide, with an estimated 262 million people living with asthma globally according to the Global Burden of Disease Study 2019, and childhood cases representing a substantial proportion of this burden [1,2]. In the United States alone, approximately five million children are currently living with asthma, representing roughly 6.5% of the pediatric population under age 18 [3]. The disease disproportionately affects children aged 5 to 9 years, where prevalence peaks at approximately 10-15% in this vulnerable age group [3,4]. While overall global prevalence rates among children and adolescents have shown a gradual decline over the past

three decades, asthma remains among the top 20 causes of disability-adjusted life years in children of all ages and ranks among the top 10 causes in children aged 5 to 14 years [5,6].

The emergency department serves as the frontline of care for children experiencing acute asthma exacerbations. Each year, asthma accounts for approximately 1.6 million ED visits and 183,000 hospitalizations in the United States, with children bearing a disproportionate share of this burden [7,8]. Recent data indicate that pediatric patients are more than twice as likely as adults to present to the ED for asthma-related complaints and nearly nine times more likely to require hospitalization following an ED visit [9]. Preschool-aged children are particularly vulnerable, with younger children more likely to present with moderate-to-severe exacerbations than their older counterparts [10,11]. The persistence of high ED utilization rates underscores both the severity of acute exacerbations and the ongoing challenges in achieving optimal disease control in the outpatient setting.

Beyond its clinical implications, pediatric asthma imposes a substantial economic burden on families, healthcare systems, and society at large. The total annual cost of asthma in the United States exceeds \$80 billion, encompassing medical expenses, mortality, and productivity losses [12]. For pediatric patients specifically, direct healthcare costs amount to approximately \$5.9 billion annually, with ED visits and hospitalizations representing major cost drivers [13,14]. The average cost per pediatric asthma hospitalization has risen to nearly \$6,900 in recent years, reflecting both disease severity and the intensity of required interventions [15]. Indirect costs compound this burden, as children with asthma miss an estimated 7.9 million school days annually, while parents and caregivers lose additional workdays to care for affected children [13,16]. These figures likely underestimate the true burden, as they do not capture costs related to transportation, caregiver stress, or diminished quality of life.

Significant disparities exist in asthma outcomes across demographic groups. Non-Hispanic Black children experience hospitalization rates three to four times higher than non-Hispanic White children, a disparity that has persisted despite overall declines in hospitalization rates across all groups [8,17]. Children from lower socioeconomic backgrounds face increased risks of severe exacerbations, more frequent ED visits, and poorer long-term outcomes [18,19]. These disparities reflect complex interactions among environmental exposures, access to preventive care, medication adherence, and social determinants of health. Addressing these inequities requires not only improvements in acute management but also sustained efforts to enhance disease education, environmental interventions, and access to guideline-based outpatient care [20].

The ED encounter represents a critical intervention point in the trajectory of an acute exacerbation. Prompt recognition of severity, timely initiation of appropriate therapy, and sound disposition decisions can prevent disease progression, reduce the need for hospitalization, and decrease morbidity [21]. Conversely, delays in treatment or failure to recognize severe disease can result in respiratory failure, intensive care admission, or death. Over the past two decades, management of asthma exacerbations in the ED has evolved considerably, with updated guidelines from the Global Initiative for Asthma (GINA) and the National Asthma Education and Prevention Program (NAEPP) providing evidence-based frameworks for assessment and treatment [22,23]. Recent advances in adjunctive therapies, including high-flow nasal cannula oxygen and intravenous magnesium sulfate, have expanded the therapeutic armamentarium available to emergency clinicians [24,25].

This review aims to provide a comprehensive synthesis of current evidence on the assessment and management of acute asthma exacerbations in the pediatric ED setting. We examine the pathophysiological basis of acute exacerbations, review validated severity assessment tools, discuss

first-line and adjunctive pharmacological therapies, and address disposition decision-making. Our goal is to offer clinicians a practical, evidence-based framework for optimizing care during this critical window of intervention.

1. Pathophysiology Of Acute Exacerbations

Asthma is fundamentally a chronic inflammatory disorder of the airways characterized by complex interactions among inflammatory cells, structural cells, and a wide array of mediators that collectively produce the clinical syndrome of variable airflow obstruction [26]. Understanding the pathophysiological mechanisms underlying acute exacerbations is essential for clinicians managing these events in the emergency department, as it provides the rational basis for therapeutic interventions and helps explain why certain treatments are effective while others are not.

2.1 The Inflammatory Cascade

At its core, an acute asthma exacerbation represents an amplification of the chronic inflammatory processes that define the disease. In children with asthma, the airways are primed with increased populations of inflammatory cells even during periods of apparent clinical stability [27]. Upon exposure to a triggering stimulus, these inflammatory cells, along with hyperactive structural bronchial cells, produce an excess of inflammatory mediators that initiate a cascade of events culminating in acute airflow obstruction [28].

The key cellular players in this inflammatory response include mast cells, eosinophils, T-helper type 2 (Th2) lymphocytes, basophils, neutrophils, and airway epithelial cells [26,29]. Following allergen inhalation in sensitized individuals, cross-linking of allergen-specific immunoglobulin E (IgE) antibodies on mast cell surfaces triggers rapid degranulation and release of preformed mediators including histamine, tryptase, and leukotrienes [30]. These mediators act directly on airway smooth muscle to induce bronchoconstriction while simultaneously increasing vascular permeability and promoting mucus secretion.

The cytokine profile of asthmatic airway inflammation is dominated by Th2-derived cytokines, particularly interleukin-4 (IL-4), IL-5, and IL-13 [29,31]. IL-4 promotes IgE synthesis and Th2 cell differentiation; IL-5 is critical for eosinophil recruitment, activation, and survival; and IL-13 contributes to mucus hypersecretion, airway hyperresponsiveness, and airway remodeling. More recently, the role of epithelial-derived cytokines, including IL-25, IL-33, and thymic stromal lymphopoietin (TSLP), has been recognized as important in initiating and amplifying type 2 inflammation, particularly in response to viral infections and other epithelial insults [32].

1.2 Mechanisms of Airflow Obstruction

The acute airflow obstruction that characterizes an asthma exacerbation results from three interconnected mechanisms: bronchospasm, mucosal edema, and mucus plugging [27,33].

Bronchospasm represents the most rapidly reversible component of airflow obstruction and results from contraction of airway smooth muscle in response to inflammatory mediators. Histamine, leukotrienes, and prostaglandins released from mast cells and other inflammatory cells act directly on smooth muscle receptors to induce contraction [26]. This early-phase response typically occurs within minutes of trigger exposure and is the primary target of bronchodilator therapy.

Mucosal edema develops as inflammatory mediators increase vascular permeability, allowing plasma proteins and fluid to extravasate into the airway wall [33]. This edema contributes to airway wall thickening and further narrows the airway lumen. Unlike bronchospasm, mucosal edema responds

more slowly to treatment and is primarily addressed through anti-inflammatory therapy with corticosteroids.

Mucus hypersecretion and the formation of mucus plugs represent perhaps the most challenging component of airflow obstruction in severe exacerbations [34]. Goblet cell hyperplasia and increased mucus production, combined with impaired mucociliary clearance and epithelial cell sloughing, can lead to complete obstruction of small airways. Pathological studies of fatal asthma cases consistently demonstrate extensive mucus plugging of conducting airways with cellular debris [35]. This component of obstruction is poorly responsive to bronchodilators and requires time for resolution, even with appropriate anti-inflammatory treatment.

1.3 Physiological Consequences

The physiological consequences of acute airflow obstruction are substantial and explain many of the clinical findings observed during an exacerbation. Increased airway resistance leads to decreased expiratory flow rates, and as expiration becomes prolonged and incomplete, air trapping and dynamic hyperinflation develop [33,36].

Hyperinflation serves as a compensatory mechanism that helps maintain airway patency by increasing airway caliber through radial traction [26]. However, this compensation comes at a significant cost. As the lungs become hyperinflated, tidal breathing occurs near the top of the pulmonary compliance curve where the lungs are stiff and require greater inspiratory effort. The work of breathing increases substantially, and the diaphragm is flattened to a mechanically disadvantaged position [36].

Ventilation-perfusion mismatch resulting from regional variations in airway obstruction leads to hypoxemia, which is typically the first blood gas abnormality observed in an acute exacerbation [27,37]. In the early stages of an exacerbation, the hypoxic drive stimulates hyperventilation, leading to a decrease in arterial carbon dioxide tension (PaCO_2) and respiratory alkalosis. As the exacerbation progresses and the work of breathing increases, respiratory muscle fatigue may develop, and the ability to maintain adequate alveolar ventilation becomes compromised [37]. A rising or even normal PaCO_2 in a patient with a severe exacerbation is an ominous sign indicating impending respiratory failure and the need for immediate intervention.

The cardiovascular system is also affected during severe exacerbations. Dynamic hyperinflation increases intrathoracic pressure, which can impede venous return and reduce cardiac preload [36]. Simultaneously, the marked negative pleural pressures generated during forceful inspiration increase left ventricular afterload. Hypoxemia and the stress response increase heart rate and myocardial oxygen demand. These combined effects can lead to pulsus paradoxus, an exaggerated fall in systolic blood pressure during inspiration, which serves as a clinical marker of severe airflow obstruction.

1.4 Why Children Are Different

Several anatomical and physiological factors render children more susceptible to severe airflow obstruction during asthma exacerbations compared to adults [38,39]. Understanding these differences is crucial for clinicians managing pediatric patients.

The principle described by Poiseuille's Law dictates that resistance to airflow through a tube is inversely proportional to the fourth power of the radius [38]. Because children have smaller baseline airway diameters than adults, even modest reductions in airway caliber from mucosal edema or bronchospasm produce proportionally greater increases in airway resistance. A 1-mm reduction in airway radius that might cause minimal symptoms in an adult can produce severe obstruction in an infant or young child.

Infants and young children also have more compliant chest walls, which predisposes them to chest wall collapse during the negative intrathoracic pressures generated to overcome increased airway resistance [39]. This dynamic chest wall collapse further compromises ventilation and increases the work of breathing. Additionally, young children have fewer collateral ventilation pathways between alveoli, making them more susceptible to atelectasis when small airways become completely obstructed [40].

The respiratory muscles of young children are also less developed than those of older children and adults, with a lower proportion of fatigue-resistant type I muscle fibers in the diaphragm [39]. This predisposes infants and young children to earlier respiratory muscle fatigue during prolonged exacerbations. Finally, young children have higher baseline metabolic rates and oxygen consumption, which means that hypoxemia develops more rapidly when ventilation is compromised.

1.5 Common Triggers in Pediatric Populations

Viral respiratory infections are by far the most common trigger for acute asthma exacerbations in children, accounting for approximately 85% of cases [41,42]. Human rhinovirus (HRV) is the predominant pathogen identified, responsible for up to 76% of virus-associated wheezing episodes in school-age children [43,44]. Respiratory syncytial virus (RSV), influenza, parainfluenza, human metapneumovirus, and adenovirus are also commonly implicated [41].

The mechanisms by which viral infections trigger exacerbations are complex and involve both direct epithelial damage and amplification of underlying airway inflammation [45]. Viral infection of airway epithelial cells triggers the release of epithelial-derived cytokines (IL-25, IL-33, TSLP) that activate innate lymphoid cells and Th2 lymphocytes, promoting type 2 inflammation [32,46]. Additionally, evidence suggests that children with asthma may have impaired interferon responses to viral infection, leading to increased viral replication, more severe illness, and prolonged airway inflammation [47].

Beyond viral infections, other common triggers in pediatric populations include aeroallergens (dust mites, animal dander, mold, pollen), environmental tobacco smoke, air pollution, exercise, cold air exposure, and strong odors or irritants [26,48]. Importantly, these triggers often act synergistically, for example, allergen exposure during a viral infection substantially increases the risk of a severe exacerbation compared to either exposure alone [49]. Poor baseline asthma control significantly increases the likelihood that exposure to any of these triggers will result in a clinically significant exacerbation [50].

2. Initial Assessment And Severity Classification

Rapid and accurate assessment of exacerbation severity is the cornerstone of effective emergency department management of pediatric asthma. The initial evaluation serves multiple purposes: it identifies children who require immediate intervention, guides the intensity of initial therapy, establishes a baseline against which response to treatment can be measured, and ultimately informs disposition decisions [51]. This section reviews the clinical assessment of the child presenting with an acute asthma exacerbation, validated severity scoring systems, and the appropriate use of ancillary testing.

3.1 Initial Clinical Assessment

The assessment of a child with suspected acute asthma begins the moment the patient enters the emergency department. Experienced clinicians can often gauge severity within seconds by observing the child's general appearance, work of breathing, and ability to speak [52]. However, this initial gestalt must be supplemented by a systematic evaluation to avoid missing subtle signs of severe disease.

The primary survey should focus on identifying children with impending respiratory failure who require immediate intervention. Signs of severe distress include an altered level of consciousness, inability to speak in sentences or phrases, severe retractions, cyanosis, and a quiet chest with poor air entry [51,53]. Paradoxically, the absence of wheezing in a child with significant respiratory distress is an ominous sign, as it suggests airflow is so severely limited that turbulent flow cannot be generated. These children require immediate treatment and should not be left waiting for a complete history or diagnostic testing.

For children who are not in extremis, a focused history and physical examination should be conducted concurrently with initiation of therapy. The history should establish the diagnosis of asthma (or identify first-time wheezers who may require broader differential consideration), characterize the current episode, and identify risk factors for severe or fatal asthma [54].

Key historical elements include the time of symptom onset and progression, potential triggers (viral illness, allergen exposure, exercise), current medications and recent use of rescue bronchodilators, prior response to similar episodes, and any recent courses of systemic corticosteroids. The child's baseline asthma severity and level of control should be ascertained, as poorly controlled asthma is a risk factor for severe exacerbations [50].

Several historical features identify patients at increased risk for life-threatening exacerbations and should prompt heightened vigilance [54,55]. These include prior intubation or intensive care admission for asthma, hospitalization or ED visit for asthma within the past year, current or recent use of systemic corticosteroids, history of rapid-onset severe exacerbations, poor perception of airflow obstruction, significant psychiatric disease or psychosocial problems, and poor adherence to asthma medications. Children with any of these risk factors warrant aggressive initial therapy and careful observation regardless of initial presentation severity.

3.2 Physical Examination Findings

The physical examination provides critical information about exacerbation severity and response to treatment. Key parameters include vital signs, oxygen saturation, work of breathing, auscultatory findings, and mental status [51,56].

Tachypnea is nearly universal in acute exacerbations and correlates with severity, though the degree of tachypnea must be interpreted in the context of the child's age. Heart rate elevation typically accompanies tachypnea and may be further increased by beta-agonist therapy. Pulsus paradoxus, a decline in systolic blood pressure of more than 10 mmHg during inspiration, reflects the large intrathoracic pressure swings generated to overcome airway obstruction and, when present, indicates moderate-to-severe disease [57]. However, pulsus paradoxus may be difficult to measure in young children and may diminish with respiratory muscle fatigue, limiting its clinical utility.

Oxygen saturation measured by pulse oximetry provides objective data on gas exchange and should be obtained early in the evaluation. Room air oxygen saturation below 92% generally indicates significant ventilation-perfusion mismatch and moderate-to-severe disease [51]. However, clinicians should recognize that hypoxemia is a relatively late finding in asthma exacerbations, and normal oxygen saturation does not exclude significant airway obstruction.

Assessment of work of breathing includes evaluation of respiratory rate, use of accessory muscles, presence of retractions (subcostal, intercostal, suprasternal, supraclavicular), nasal flaring, and the ability to speak [56]. Suprasternal and scalene muscle retractions are particularly indicative of severe obstruction. The child's position of comfort is also informative: children who insist on sitting upright, lean forward, or assume a tripod position are demonstrating air hunger and severe distress.

Auscultation of the chest assesses air entry and the presence of wheezing. Wheezing, a high-pitched musical sound caused by turbulent airflow through narrowed airways, is the hallmark of asthma but must be interpreted carefully [51]. The intensity of wheezing does not reliably correlate with severity; indeed, improving wheezing may simply reflect improved airflow, while diminishing wheezing in the setting of worsening distress suggests critical obstruction. Prolonged expiratory phase, reflecting difficulty expelling air through obstructed airways, is another useful finding. Assessment should note whether findings are symmetric or asymmetric, as focal findings may suggest alternative diagnoses such as foreign body aspiration, mucus plugging, or pneumonia.

Mental status changes, including agitation, confusion, or lethargy, are late findings indicating severe hypoxemia, hypercarbia, or exhaustion and demand immediate intervention [53].

3.3 Severity Scoring Systems

Several validated clinical scoring systems have been developed to standardize severity assessment in pediatric asthma exacerbations. These instruments provide a reproducible, objective measure of disease severity that facilitates communication among providers, guides treatment protocols, enables tracking of response to therapy, and supports disposition decision-making [58].

The Pediatric Respiratory Assessment Measure (PRAM) is one of the most widely validated and utilized scoring systems. Originally developed for preschool children by Chalut and Ducharme, it was subsequently validated across the full pediatric age range (2-17 years) [59,60]. The PRAM incorporates five clinical findings: oxygen saturation, suprasternal retractions, scalene muscle contraction, air entry, and wheezing, with scores ranging from 0 to 12 [59]. Scores of 0-3 indicate mild exacerbation, 4-7 indicate moderate exacerbation, and 8-12 indicate severe exacerbation. The PRAM has demonstrated good internal consistency, inter-rater reliability, criterion validity against respiratory resistance measured by forced oscillometry, and strong predictive validity for hospital admission [60,61]. Studies have shown that triage PRAM scores are strongly associated with admission rates and can help predict which patients will require hospitalization despite intensive therapy [62].

The Pediatric Asthma Severity Score (PASS) was developed by Gorelick and colleagues and validated in children aged 1-18 years [63]. The PASS comprises three clinical components: wheezing, work of breathing, and prolonged expiration, each scored on a three-point scale (1-3) yielding total scores from 3-9. The PASS demonstrated good inter-observer reliability (kappa 0.72-0.83) and showed both discriminative and responsive properties in validation studies [63]. Its relative simplicity (three items versus five for PRAM) may offer practical advantages in busy clinical settings.

The Pulmonary Index Score (PIS) and its modifications represent another family of scoring instruments that incorporate respiratory rate, wheezing, inspiratory-to-expiratory ratio, accessory muscle use, and oxygen saturation [64]. Various modified versions have been developed and implemented in different institutions.

Comparative studies have generally found similar performance characteristics among these scoring systems for predicting outcomes such as hospitalization [65,66]. The choice of which instrument to use may depend on institutional familiarity, ease of implementation, and local protocol requirements. Regardless of which scoring system is selected, the key is consistent application by all team members, physicians, nurses, and respiratory therapists, to enable meaningful tracking of response to treatment.

3.4 Pulmonary Function Testing in the ED

Pulmonary function testing, specifically measurement of forced expiratory volume in one second (FEV₁) by spirometry or peak expiratory flow rate (PEFR), provides objective assessment of airflow obstruction and is recommended by guidelines for assessing severity and response to treatment in

acute exacerbations [23,51]. However, several practical limitations restrict the utility of these measurements in the pediatric emergency department.

Spirometry requires trained personnel, specialized equipment, and patient cooperation, all of which may be limited in the acute setting. Most children under 5-6 years of age cannot reliably perform the forced expiratory maneuvers required for valid spirometry, and even older children in respiratory distress may be unable or unwilling to cooperate [67]. PEFR measurement is simpler but shares similar age and cooperation limitations and has been shown to be less reliable than spirometry, particularly during acute exacerbations [68].

Consequently, many pediatric emergency departments have moved away from routine pulmonary function testing during acute exacerbations and instead rely on clinical severity scoring systems combined with assessment of response to therapy [67,69]. This approach is supported by studies demonstrating that clinical scores have criterion validity comparable to spirometry for assessing severity and may be more sensitive to clinical change during treatment [70]. When pulmonary function testing is available and the patient can cooperate, FEV₁ or PEFR less than 40% of predicted generally indicates severe obstruction, 40-69% indicates moderate obstruction, and 70% or greater indicates mild obstruction [23].

3.5 Role of Ancillary Testing

A key principle in emergency department management of pediatric asthma is that diagnostic testing should not delay initiation of treatment. For the child with a known diagnosis of asthma presenting with a typical exacerbation, laboratory studies and imaging are generally unnecessary and should be obtained selectively based on specific clinical indications [51,71].

Chest radiography is not recommended as a routine component of ED evaluation for acute asthma exacerbations [71,72,73]. Studies have consistently demonstrated that chest radiographs infrequently reveal findings that change management in children with known asthma presenting with typical exacerbations. Common findings on chest radiographs during acute exacerbations, including hyperinflation, peribronchial thickening, and subsegmental atelectasis, are expected consequences of the disease process and do not alter treatment [74]. Furthermore, atelectasis is frequently misinterpreted as pneumonia, leading to unnecessary antibiotic prescriptions [79].

Specific indications for chest radiography include: clinical suspicion for pneumonia (focal findings on examination, high fever, failure to respond to appropriate therapy), concern for pneumothorax or pneumomediastinum (sudden onset of pleuritic chest pain, subcutaneous emphysema), suspected foreign body aspiration (unilateral findings, history suggestive of aspiration), first episode of wheezing without clear asthma history, and following endotracheal intubation [71,75]. Outside these circumstances, routine chest radiography adds cost, increases radiation exposure, delays treatment, and may lead to inappropriate antibiotic use.

Arterial blood gas (ABG) analysis provides objective assessment of oxygenation, ventilation, and acid-base status but is rarely necessary in the ED management of pediatric asthma [73,75]. With the widespread availability of pulse oximetry for continuous oxygenation monitoring and end-tidal CO₂ monitoring as a noninvasive surrogate for ventilation, invasive blood gas sampling can generally be reserved for patients with severe exacerbations who are deteriorating despite aggressive therapy or who have impending respiratory failure [75]. Importantly, respiratory failure is a clinical diagnosis that should prompt immediate intervention; treatment should never be delayed to await blood gas results. A normal or rising PaCO₂ in the setting of clinical deterioration is an ominous sign, but the

decision to escalate therapy or intubate should be based on clinical assessment rather than laboratory values alone.

Other laboratory studies are also not routinely indicated. Complete blood count and inflammatory markers are nonspecific and do not guide acute management. Serum electrolytes may be reasonable in patients receiving high-dose continuous beta-agonist therapy (which can cause hypokalemia) or those with prolonged symptoms and poor oral intake, but routine testing is not necessary [78]. Viral testing may be of epidemiological interest but does not change acute management.

3.6 Red Flags and Indications for Immediate Intervention

Throughout the assessment process, clinicians must remain vigilant for signs indicating severe, potentially life-threatening asthma requiring immediate aggressive intervention. These red flags include [51,53,75]:

- Altered mental status (agitation, confusion, lethargy)
- Inability to speak in phrases or sentences
- Oxygen saturation less than 90% on room air
- Silent chest with poor air entry despite respiratory effort
- Severe retractions with accessory muscle fatigue
- Cyanosis
- Peak flow less than 25% predicted (if measurable)
- Failure to improve with initial bronchodilator therapy
- History of prior intubation for asthma

Children presenting with any of these features should receive immediate treatment, close monitoring, and early involvement of senior clinicians and intensive care services as appropriate.

3. First-Line Pharmacological Management

The pharmacological management of acute asthma exacerbations centers on three pillars: rapid bronchodilation with short-acting beta-agonists (SABAs), reduction of airway inflammation with systemic corticosteroids, and augmented bronchodilation with anticholinergics in moderate-to-severe cases. The goal of initial therapy is to rapidly reverse airflow obstruction, prevent progression, and facilitate safe disposition. Table 1 summarizes recommended dosing for first-line medications.

4.1 Short-Acting Beta-Agonists

Inhaled SABAs, primarily albuterol (salbutamol), remain the cornerstone of acute asthma management. These agents act within minutes by relaxing airway smooth muscle through beta-2 adrenergic receptor stimulation [80].

Delivery Method: Multiple systematic reviews and meta-analyses have demonstrated that metered-dose inhalers (MDIs) with spacers are at least as effective as nebulizers for mild-to-moderate exacerbations, with comparable hospitalization rates and clinical improvement [81-83]. MDIs offer advantages including faster administration, fewer systemic side effects (tachycardia, tremor), and shorter ED length of stay [84]. Current guidelines recommend MDI with spacer as the preferred delivery method for mild-to-moderate exacerbations, reserving nebulization for severe cases, young children who cannot coordinate MDI technique, or when continuous therapy is required [23,80].

Dosing Strategy: Initial treatment consists of repeated SABA administration, typically three doses given every 20 minutes during the first hour. For MDI delivery, 4-8 puffs (depending on age and weight) are administered through a valved holding chamber; for nebulization, weight-based dosing of

0.15 mg/kg (minimum 2.5 mg) is used [23,80]. Patients with severe exacerbations may require continuous nebulization at 0.5 mg/kg/hour (maximum 10-20 mg/hour) [85].

4.2 Systemic Corticosteroids

Early administration of systemic corticosteroids is essential for all but the mildest exacerbations. Corticosteroids reduce airway inflammation, decrease mucus production, and enhance beta-agonist responsiveness. Evidence consistently demonstrates that early corticosteroid administration (within the first hour) reduces hospitalization rates, prevents relapse, and shortens recovery time [86,87].

Route and Timing: Oral administration is preferred given equivalent efficacy to intravenous dosing and less invasive delivery [23]. Corticosteroids should ideally be administered within 60 minutes of ED arrival; nurse-initiated protocols at triage have been shown to improve ED efficiency without adverse effects [88].

Choice of Agent: Dexamethasone has emerged as an attractive alternative to prednisone/prednisolone based on its longer half-life (36-72 hours vs. 12-36 hours), better palatability, reduced vomiting rates, and improved compliance [89-91]. A meta-analysis of 10 studies (3,208 patients) found significantly lower vomiting rates with dexamethasone (RR 0.29) and no differences in hospitalization, ED revisits, or symptom resolution [92]. Single-dose or two-dose dexamethasone regimens are now widely adopted, simplifying outpatient management compared to traditional 5-day prednisone courses [93].

4.3 Ipratropium Bromide

Ipratropium bromide, an inhaled anticholinergic, provides additive bronchodilation through a mechanism complementary to SABAs, blocking muscarinic receptors to reduce vagally mediated bronchoconstriction. A landmark trial by Qureshi et al. demonstrated that adding ipratropium to albuterol reduced hospitalization rates by 25% in children with moderate-to-severe exacerbations [94]. Subsequent meta-analyses confirmed that combined ipratropium-albuterol therapy reduces hospitalizations (RR 0.73) and improves lung function compared to SABA alone in moderate-to-severe exacerbations [95]. However, benefit appears limited to the initial ED treatment phase; continued ipratropium use after admission does not improve outcomes [96]. Current guidelines recommend ipratropium for moderate-to-severe exacerbations during the first 1-3 hours of ED treatment, combined with SABA therapy [23].

Table 1. First-Line Medications for Pediatric Acute Asthma Exacerbations

Medication	Delivery	Dosing	Frequency	Notes
Albuterol (Salbutamol)				
MDI + spacer	Mild-moderate	4-8 puffs (100 mcg/puff)	q20min × 3, then q1-4h PRN	Preferred for mild-moderate; use mask for age <4 years
Nebulizer	Moderate-severe	2.5 mg (<20 kg) or 5 mg (≥20 kg)	q20min × 3, then q1-4h PRN	0.15-0.3 mg/kg per dose
Continuous nebulization	Severe/refractory	0.5 mg/kg/hr (max 10-20 mg/hr)	Continuous	For severe exacerbations unresponsive to intermittent therapy
Ipratropium Bromide				
MDI + spacer	Moderate-severe	4-8 puffs (17-	q20min × 3	ED use only; no

		21 mcg/puff)	doses	benefit after admission
Nebulizer	Moderate-severe	250 mcg (<20 kg) or 500 mcg (≥20 kg)	q20min × 3 doses	Often combined with albuterol ("DuoNeb")
Systemic Corticosteroids				
Dexamethasone	PO/IV/IM	0.6 mg/kg (max 16 mg)	Once or daily × 2 days	Preferred; better taste, less vomiting
Prednisone/Prednisolone	PO	1-2 mg/kg/day (max 60 mg)	Daily × 3-5 days	Alternative if dexamethasone unavailable
Methylprednisolone	IV	1-2 mg/kg (max 60 mg)	q6h	For patients unable to tolerate PO

MDI = metered-dose inhaler; PO = oral; IV = intravenous; IM = intramuscular; PRN = as needed

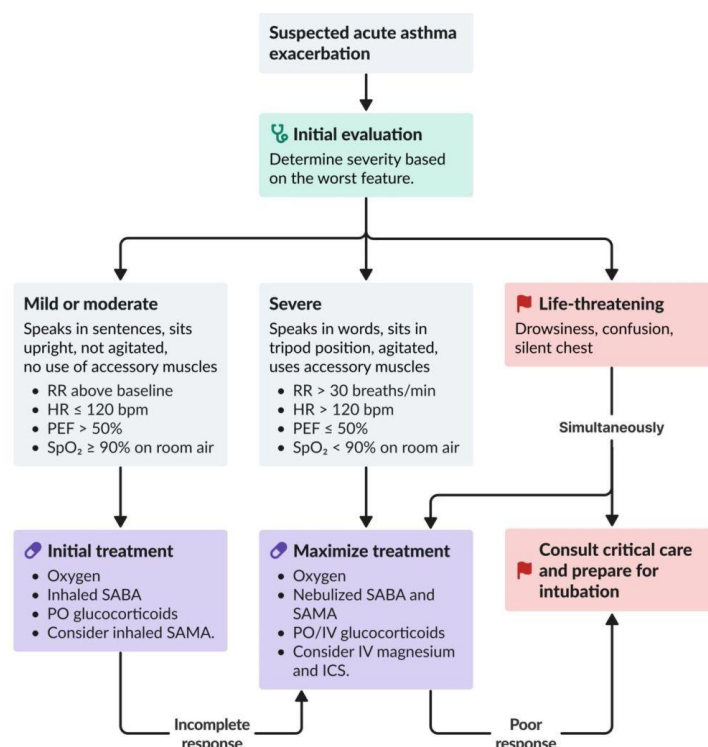


Figure 1 Initial ED Management Algorithm for Pediatric Acute Asthma

4. Management Of Severe And Refractory Cases

Children who fail to respond adequately to first-line therapy require escalation to second-line agents and advanced respiratory support. This section addresses evidence-based approaches for severe and refractory asthma, with emphasis on therapies available in the ED setting. Table 2 summarizes dosing for escalation therapies.

5.1 Intravenous Magnesium Sulfate

Magnesium sulfate acts as a bronchodilator through calcium channel antagonism and smooth muscle relaxation. A 2016 Cochrane review found that IV magnesium reduced hospital admissions by 68% (OR 0.32, 95% CI 0.14-0.74) in children with moderate-to-severe exacerbations unresponsive to first-line therapy [97]. A more recent systematic review (2024) demonstrated approximately 85% reduction in hospitalization odds and improved peak expiratory flow rates compared to placebo [98].

Current guidelines recommend IV magnesium sulfate for children with severe exacerbations who have not responded to initial bronchodilator therapy [23,99]. The standard dose is 25-75 mg/kg (maximum 2 g) administered over 15-30 minutes. Higher doses (50-75 mg/kg) may provide greater benefit in severe cases [100]. Side effects are generally mild and include flushing, hypotension, and nausea; monitoring of blood pressure during infusion is recommended [101].

5.2 Continuous Albuterol Nebulization

For children with severe exacerbations who remain symptomatic despite intermittent bronchodilator therapy, continuous albuterol nebulization provides sustained bronchodilation. Typical dosing is 0.5 mg/kg/hour (range 10-20 mg/hour) [102]. While continuous nebulization is associated with more pronounced side effects (tachycardia, hypokalemia, tremor), it avoids the peaks and troughs of intermittent dosing and is particularly useful in patients requiring frequent treatments [103]. Electrolyte monitoring is advisable during prolonged continuous therapy.

5.3 High-Flow Nasal Cannula Oxygen Therapy

High-flow nasal cannula (HFNC) has emerged as an intermediate respiratory support option between standard oxygen therapy and noninvasive positive pressure ventilation. HFNC provides heated, humidified oxygen at flows of 1-2 L/kg/min, generating low levels of positive airway pressure, washing out nasopharyngeal dead space, and reducing work of breathing [104].

Evidence for HFNC in pediatric asthma remains limited. A pilot RCT found that HFNC produced greater reduction in respiratory distress within 2 hours compared to standard oxygen therapy [105], though subsequent observational studies have shown mixed results [106]. Current evidence suggests HFNC is safe and feasible but should not delay escalation to noninvasive positive pressure ventilation (NIPPV) when indicated [107]. Clinicians should be aware that bronchodilator delivery may be suboptimal during HFNC therapy.

5.4 Noninvasive Positive Pressure Ventilation

NIPPV (BiPAP) provides more substantial respiratory support than HFNC and has demonstrated efficacy in severe pediatric asthma. By unloading respiratory muscles and recruiting collapsed airways, NIPPV can prevent intubation in children with impending respiratory failure [108]. Typical initial settings are IPAP 8-12 cm H₂O and EPAP 5-6 cm H₂O, titrated to clinical response. NIPPV is particularly valuable as a bridge while waiting for pharmacologic therapies to take effect.

5.5 Additional Escalation Therapies

Epinephrine: Subcutaneous or intramuscular epinephrine (0.01 mg/kg, maximum 0.3-0.5 mg) provides rapid bronchodilation and may benefit children with severe exacerbations, particularly those with poor air entry limiting inhaled medication delivery [109].

Terbutaline: IV terbutaline (loading dose 10 mcg/kg over 10 minutes, then 0.1-10 mcg/kg/min infusion) is an alternative for refractory cases, typically in the ICU setting with continuous cardiac monitoring [110].

Aminophylline/Theophylline: Once a mainstay of asthma therapy, IV aminophylline is now reserved for severe cases unresponsive to other therapies due to its narrow therapeutic index and significant side

effects. When used, a loading dose of 5-6 mg/kg is followed by continuous infusion at 0.5-1 mg/kg/hour with serum level monitoring [111].

Ketamine: This dissociative anesthetic has bronchodilatory properties and may be useful as an induction agent if intubation becomes necessary, or as sedation for NIPPV. Typical dosing is 0.5-2 mg/kg IV bolus [112].

Heliox: A helium-oxygen mixture (typically 70:30 or 80:20) reduces airway resistance due to helium's lower density. While theoretically appealing, RCTs have not demonstrated consistent benefit, and practical limitations (need for high FiO₂, specialized equipment) restrict its use [113].

5.6 Indications for ICU Admission

Transfer to the pediatric ICU should be considered for children with: persistent severe respiratory distress despite aggressive ED management, oxygen requirement >50% FiO₂, altered mental status, impending respiratory failure (rising PaCO₂), need for continuous albuterol >20 mg/hour, need for IV bronchodilators, or NIPPV requirement [114].

Table 2. Escalation Therapies for Severe/Refractory Pediatric Asthma

Therapy	Dosing	Administration	Key Considerations
IV Magnesium Sulfate	25-75 mg/kg (max 2 g)	Over 15-30 min	Monitor BP; may repeat ×1
Continuous Albuterol	0.5 mg/kg/hr (10-20 mg/hr)	Continuous nebulization	Monitor K ⁺ , HR; wean by 50% increments
HFNC	1-2 L/kg/min (max ~60 L/min)	Heated humidified	May impair nebulizer delivery
NIPPV (BiPAP)	IPAP 8-12, EPAP 5-6 cm H ₂ O	Face/nasal mask	Titrate to WOB; consider sedation
Epinephrine	0.01 mg/kg (max 0.3-0.5 mg)	IM/SC q15-20 min PRN	For severe cases with poor air entry
IV Terbutaline	Load: 10 mcg/kg; Infusion: 0.1-10 mcg/kg/min	IV with cardiac monitoring	ICU setting; monitor for arrhythmias
IV Aminophylline	Load: 5-6 mg/kg; Infusion: 0.5-1 mg/kg/hr	IV with level monitoring	Target level 10-15 mcg/mL
Ketamine	0.5-2 mg/kg bolus	IV	Bronchodilator; useful for intubation

BP = blood pressure; HR = heart rate; WOB = work of breathing; IPAP = inspiratory positive airway pressure; EPAP = expiratory positive airway pressure

5. Disposition Decisions

The decision to admit or discharge a child following ED treatment for an acute asthma exacerbation is among the most consequential determinations in emergency care. Premature discharge risks relapse and potentially life-threatening deterioration at home, while unnecessary admission exposes children to nosocomial risks and imposes significant financial and emotional burdens on families. Evidence-based criteria and systematic assessment can optimize this decision-making process.

6.1 Timing of Disposition Decisions

Most clinical improvement occurs within the first 1-2 hours of treatment, and disposition decisions can generally be made within this timeframe [115,116]. Studies demonstrate that severity scores measured at 1-2 hours after treatment initiation have good predictive validity for hospital admission [117].

Patients who remain severely symptomatic (PRAM ≥ 8 or equivalent) after 1 hour of aggressive therapy are unlikely to be discharged and should be considered for admission and escalation of therapy. Conversely, patients achieving mild severity scores (PRAM ≤ 3) can often be safely discharged after a brief observation period.

6.2 Criteria for Discharge

Children may be considered for discharge when they meet the following criteria [23,115,118]:

Clinical criteria:

- Minimal or no respiratory distress (no retractions, comfortable breathing)
- Minimal or no wheezing, with good air entry
- Oxygen saturation $\geq 92\%$ on room air for at least 60 minutes
- Able to tolerate oral medications and fluids
- Severity score in mild range (e.g., PRAM 0-3) sustained after treatment

Response to treatment:

- Sustained improvement for 60+ minutes after last bronchodilator
- No requirement for supplemental oxygen
- Bronchodilator treatments spaced to every 4 hours or longer

Social/practical factors:

- Caregiver demonstrates understanding of discharge instructions
- Caregiver able to administer medications appropriately
- Access to prescribed medications before leaving ED
- Reliable follow-up arranged within 1-4 weeks
- Access to transportation and ability to return if symptoms worsen

6.3 Criteria for Admission

Hospital admission should be considered when [23,114,119]:

- Persistent moderate-to-severe symptoms despite 1-2 hours of aggressive therapy
- Oxygen requirement to maintain $\text{SpO}_2 \geq 92\%$
- Need for bronchodilator treatments more frequently than every 4 hours
- Incomplete response to systemic corticosteroids
- History of severe/near-fatal asthma, prior intubation, or recent hospitalization
- Significant comorbidities (cardiac disease, immunodeficiency)
- Concern about medication adherence or follow-up
- Social factors precluding safe discharge (inadequate supervision, inability to access care)

ICU admission criteria include: need for continuous nebulization >4 hours with worsening symptoms, respiratory failure or impending failure (altered mental status, rising PaCO_2), need for NIPPV or mechanical ventilation, hemodynamic instability, and inadequate response to IV magnesium [114].

6.4 Risk Factors for Relapse

Certain patient characteristics are associated with increased relapse risk following ED discharge and warrant consideration of lower thresholds for admission or closer follow-up [120,121]:

- Prior hospitalization or ED visit within past 12 months
- Previous ICU admission or intubation for asthma
- Current or recent systemic corticosteroid use
- Poor baseline asthma control or medication non-adherence
- Multiple ED visits ("frequent flyers")

- Lower socioeconomic status or limited healthcare access
- Psychosocial factors (mental health comorbidities, family dysfunction)

6.5 Discharge Planning

Effective discharge planning is essential to prevent relapse and improve long-term outcomes. Key components include [122,123]:

Medications:

- Continue systemic corticosteroids (complete course of dexamethasone or prednisone)
- Provide rescue bronchodilator with clear instructions (albuterol 2-4 puffs every 4-6 hours as needed)
- Initiate or reinforce inhaled corticosteroid therapy for all patients discharged after an exacerbation
- Ensure prescriptions are filled before leaving the ED when possible

Education:

- Review inhaler/spacer technique with return demonstration
- Discuss recognition of worsening symptoms and when to seek care
- Provide written asthma action plan
- Address environmental triggers and avoidance strategies

Follow-up:

- Arrange primary care follow-up within 1-4 weeks
- Consider referral to asthma specialist for patients with: ≥ 2 ED visits or hospitalizations in past year, prior ICU admission, poor baseline control despite appropriate therapy, or diagnostic uncertainty
- Engage social work for high-risk patients with multiple ED visits

Table 3. ED Disposition Decision Framework

Parameter	Discharge Likely	Consider Admission	Admit to ICU
Severity score (post-treatment)	PRAM 0-3	PRAM 4-7	PRAM 8-12
Oxygen saturation	$\geq 92\%$ on RA	90-92% on RA or requiring O ₂	$< 90\%$ despite O ₂
Bronchodilator interval	≥ 4 hours	2-4 hours	Continuous
Work of breathing	None/minimal	Moderate	Severe/fatigue
Response to treatment	Complete	Partial	Poor/worsening
Mental status	Normal	Normal	Altered
Risk factors	None	Present	Multiple/severe

RA = room air; PRAM = Pediatric Respiratory Assessment Measure

6. Special Considerations

7.1 Preschool Wheeze and Diagnostic Uncertainty

Wheezing affects up to 50% of children before age 6, creating significant diagnostic challenges in the ED [124]. Not all preschool wheezers have asthma, and the heterogeneity of wheezing phenotypes complicates management decisions.

Viral-induced wheeze (episodic viral wheeze) is the most common pattern, characterized by wheezing only during viral respiratory infections with symptom-free intervals [125]. This pattern often improves with age as airways grow. In contrast, multiple-trigger wheeze involves symptoms provoked

by various stimuli (exercise, allergens, cold air) in addition to viruses and is more likely to represent true asthma [126].

The modified Asthma Predictive Index (mAPI) helps identify preschoolers at higher risk for persistent asthma. A positive mAPI requires ≥ 4 wheezing episodes in the past year plus either one major criterion (parental asthma, eczema, aeroallergen sensitization) or two minor criteria (food allergen sensitization, wheezing apart from colds, eosinophilia $\geq 4\%$) [127].

Treatment implications: While bronchodilators remain first-line therapy for all preschool wheezers, the role of systemic corticosteroids in viral-induced wheeze is controversial. A large RCT (n=700) found no benefit of oral prednisolone for hospitalized preschoolers with viral-induced wheeze [128]. Current evidence suggests reserving corticosteroids for children with features suggesting true asthma (positive mAPI, multiple-trigger pattern) rather than routine use in all preschool wheezers [129].

7.2 First-Time Wheezers

Children presenting with their first wheezing episode require careful evaluation for alternative diagnoses including bronchiolitis (especially <12 months), foreign body aspiration, and anatomic abnormalities [130]. Key distinguishing features for bronchiolitis include age <12 months, prominent rhinorrhea and cough, crackles on examination, and poor response to bronchodilators. Chest radiography may be warranted in first-time wheezers if the diagnosis is uncertain or response to treatment is poor.

7.3 Obesity

Obese children with asthma represent a distinct phenotype with reduced bronchodilator responsiveness, increased inflammation, and higher rates of severe exacerbations [131]. Standard weight-based dosing should be used, recognizing that some obese children may have symptoms attributable to deconditioning or dyspnea on exertion rather than bronchospasm. Consider broader differential diagnosis and ensure appropriate follow-up for weight management.

7.4 Comorbidities

Allergic rhinitis frequently coexists with asthma and may worsen exacerbations; nasal corticosteroids at discharge may provide benefit [132]. Food allergies are a risk factor for severe and fatal asthma. Anxiety and vocal cord dysfunction can mimic or exacerbate asthma symptoms and should be considered in patients with atypical presentations or poor treatment response.

7.5 Health Disparities

Significant racial and socioeconomic disparities exist in pediatric asthma outcomes, with Black children experiencing 3-4 times higher hospitalization rates and mortality compared to White children [6,7]. Contributing factors include environmental exposures (pollution, allergens, tobacco smoke), reduced access to preventive care, and social determinants of health. ED clinicians should ensure equitable care delivery and connect high-risk families with social services, asthma education, and appropriate follow-up resources.

7. Future Directions

Several emerging areas hold promise for improving acute asthma management:

Precision medicine approaches may eventually allow phenotype-specific treatment. Biomarkers such as blood eosinophils and exhaled nitric oxide could help identify children most likely to respond to corticosteroids, though current ED application is limited [133].

Point-of-care viral testing may inform prognosis and potentially guide therapy, particularly in preschoolers where viral etiology influences treatment response [134].

Biologic therapies (omalizumab, mepolizumab, dupilumab) have transformed management of severe persistent asthma and may eventually have a role in preventing recurrent severe exacerbations, though acute ED use is not currently established [135].

Telemedicine and remote monitoring offer opportunities for post-discharge follow-up and early intervention in evolving exacerbations.

Quality improvement initiatives including standardized clinical pathways, nurse-initiated protocols, and real-time decision support continue to demonstrate benefits in reducing variability and improving outcomes [136].

8. Conclusion

Acute asthma exacerbations remain a leading cause of pediatric emergency department visits and hospitalizations, imposing substantial burden on children, families, and healthcare systems. Effective management requires rapid severity assessment using validated scoring systems, prompt initiation of first-line therapy with inhaled bronchodilators and systemic corticosteroids, and judicious use of escalation therapies for refractory cases.

Key evidence-based principles include: MDI with spacer is preferred over nebulization for mild-to-moderate exacerbations; dexamethasone offers equivalent efficacy to multi-day prednisone courses with improved tolerability; ipratropium bromide provides additive benefit in moderate-to-severe cases during the initial treatment phase; and IV magnesium sulfate reduces hospitalizations in severe exacerbations unresponsive to first-line therapy.

Disposition decisions should integrate clinical severity scores, response to treatment, risk factors for relapse, and social considerations. Effective discharge planning, including completion of corticosteroid courses, initiation of controller therapy, inhaler technique education, and timely follow-up, is essential for preventing relapse and improving long-term outcomes.

Special attention is warranted for preschool wheezers, in whom diagnostic uncertainty and variable treatment response require individualized approaches. Addressing health disparities through equitable care delivery and connection to resources remains a critical priority.

Through systematic application of evidence-based practices, emergency clinicians can optimize outcomes for children presenting with acute asthma exacerbations while minimizing unnecessary interventions, hospitalizations, and healthcare costs.

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