



Pulmonary and Respiratory Trauma in Infants and Children: A State-of-the-Art Review of Mechanisms, Diagnosis, Contemporary Management, and Outcomes

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ABSTRACT

Background

Pulmonary and respiratory trauma remains a major cause of morbidity and mortality in infants and children worldwide. Although blunt thoracic trauma accounts for most injuries, important causes include birth-related trauma, ventilator-associated barotrauma, child abuse, penetrating injuries, blast injuries, aviation disasters, and iatrogenic complications. Unique anatomical and physiological characteristics of children result in injury patterns that differ substantially from those observed in adults.



Objective

To review the epidemiology, mechanisms, pathophysiology, diagnosis, imaging, contemporary management, and long-term outcomes of pulmonary and respiratory trauma in infants and children.

Data Sources

A narrative review of contemporary literature indexed in PubMed, Scopus, Embase, and major pediatric trauma, respiratory, and critical care journals published between 2020 and 2026.

Results

Pulmonary contusion remains the most common pediatric thoracic injury and frequently occurs in the absence of rib fractures owing to increased chest wall compliance. Advances in trauma imaging, point-of-care ultrasonography, low-dose computed tomography, bronchoscopy, thoracoscopy, and extracorporeal membrane oxygenation have significantly improved diagnostic accuracy and clinical outcomes. Ventilator-induced lung injury, child abuse-related thoracic trauma, blast injury, and iatrogenic respiratory trauma continue to present major management challenges. Contemporary care increasingly emphasizes multidisciplinary management, lung-protective ventilation, minimally invasive intervention, and individualized treatment strategies.

Conclusions

Early recognition, appropriate imaging, and multidisciplinary management are critical for optimizing outcomes following pediatric pulmonary trauma. Emerging technologies including artificial intelligence-assisted imaging, advanced ventilatory monitoring, and international pediatric trauma registries are expected to further improve diagnosis and evidence-based care.

Keywords: pediatric thoracic trauma; pulmonary contusion; ventilator-induced lung injury; blast lung injury; child abuse; pulmonary barotrauma; respiratory trauma; pediatric critical care.

STRENGTHS AND LIMITATIONS OF THIS REVIEW

Strengths

- This review provides a comprehensive overview of pulmonary and respiratory trauma across the full pediatric age spectrum, encompassing neonates, infants, children, and adolescents.
- Multiple mechanisms of injury are addressed, including blunt trauma, penetrating trauma, ventilator-associated barotrauma, birth-related injury, child abuse, blast injury, aviation-related trauma, and iatrogenic complications.
- Contemporary diagnostic approaches are reviewed, including point-of-care ultrasonography, low-dose computed tomography, CT angiography, bronchoscopy, and advanced trauma imaging pathways.
- Current evidence regarding ventilator-induced lung injury, blast lung injury, pediatric trauma imaging, and modern critical care management has been incorporated.
- The manuscript integrates perspectives from pediatric pulmonology, emergency medicine, intensive care, pediatric surgery, trauma surgery, radiology, and respiratory medicine.
- Practical clinical algorithms and summary tables are included to facilitate translation of evidence into clinical practice.
- Particular emphasis is placed on developmental anatomy and the unique physiological characteristics that distinguish pediatric thoracic trauma from adult injury patterns.



Limitations

- High-quality randomized controlled trials are uncommon in pediatric thoracic trauma, and much of the available evidence is derived from retrospective studies, trauma registries, institutional experiences, and expert consensus.
- Significant heterogeneity exists in injury classification systems, imaging protocols, treatment thresholds, and outcome reporting between institutions and countries, limiting direct comparison of published studies.
- Many severe injury mechanisms, including blast injury, air-crash trauma, and major tracheobronchial disruption, are rare, resulting in a predominance of case series and observational reports.
- Long-term respiratory outcomes, pulmonary function, exercise tolerance, neurodevelopmental consequences, and health-related quality-of-life data remain inadequately reported for many pediatric trauma populations.
- Evidence regarding optimal management of ventilator-induced lung injury, child abuse-related thoracic trauma, and rare airway injuries continues to evolve.
- Emerging technologies including artificial intelligence-assisted imaging, advanced ventilatory monitoring, and precision trauma medicine have shown promise but currently lack robust pediatric outcome data.

Key Message

Despite advances in imaging, critical care, and minimally invasive interventions, pediatric pulmonary and respiratory trauma remains an area where clinical practice is frequently guided by observational evidence and expert consensus. Continued multicenter collaboration, prospective registries, and long-term outcome studies are essential to strengthen the evidence base and improve outcomes for injured children.

INTRODUCTION

Thoracic trauma accounts for approximately 4-8% of pediatric trauma admissions but remains one of the leading causes of trauma-related mortality in children [1]. Unlike adults, children possess a highly compliant chest wall, incompletely ossified ribs, and unique respiratory physiology that allow substantial intrathoracic injury to occur in the absence of obvious external signs. Consequently, pulmonary contusions, airway injuries, and vascular trauma may be underestimated during initial assessment.

The mechanisms of pediatric pulmonary trauma are diverse and include blunt trauma from motor vehicle collisions and falls, penetrating injuries, blast injuries, aviation accidents, birth trauma, ventilator-induced barotrauma, child abuse, and iatrogenic injury. Increasing survival of critically ill neonates and children has also resulted in growing recognition of respiratory trauma associated with mechanical ventilation, bronchoscopy, central venous catheterization, extracorporeal support, and thoracic interventions[2].

Compared with adults, pulmonary contusion is the predominant intrathoracic injury in children, whereas rib fractures are less frequent because the compliant thoracic cage transmits force directly to underlying lung tissue. Recent nationwide data from the Netherlands demonstrated that lung contusions occurred in approximately 40% of pediatric chest trauma cases and were frequently associated with intensive care admission and substantial morbidity [3].

Advances in point-of-care ultrasonography, low-dose computed tomography (CT), bronchoscopy, lung-protective ventilation strategies, extracorporeal membrane oxygenation (ECMO), and minimally invasive thoracic surgery have transformed contemporary management. However, significant challenges remain regarding optimal imaging pathways, prevention of ventilator-associated lung injury, recognition of non-



accidental trauma, management of blast-related pulmonary injury, and long-term respiratory outcomes[4]. This review summarizes current concepts in pediatric pulmonary and respiratory trauma with an emphasis on contemporary diagnostic and therapeutic approaches.

METHODS AND LITERATURE SEARCH STRATEGY

This state-of-the-art narrative review was conducted through a structured search of PubMed/MEDLINE, Embase, Scopus, and Google Scholar databases. Relevant literature published between January 2000 and September 2026 was reviewed, with particular emphasis on studies published between 2020 and 2026.

Search terms included: pediatric thoracic trauma, pulmonary contusion, blunt chest trauma, penetrating thoracic injury, pediatric airway trauma, ventilator-induced lung injury, blast lung injury, neonatal respiratory trauma, ECMO and pediatric trauma, and thoracic imaging in children

Preference was given to systematic reviews, clinical guidelines, multicenter studies, registry analyses, and major pediatric trauma publications. Additional references were identified from article bibliographies and relevant guideline documents.

DEVELOPMENTAL ANATOMY AND PATHOPHYSIOLOGY OF PEDIATRIC PULMONARY TRAUMA

The pediatric thorax differs substantially from that of adults and explains the unique injury patterns observed after chest trauma. Children's ribs are incompletely ossified and highly compliant, allowing transmission of kinetic energy directly to intrathoracic structures without producing obvious rib fractures. Consequently, significant pulmonary contusions may occur despite a normal chest wall examination. Pulmonary contusion remains the most common thoracic injury identified in injured children.

Children also have a smaller functional residual capacity, higher oxygen consumption narrower airways, and reduced physiological reserve. As a result, hypoxemia develops more rapidly following lung injury than in adults. Associated injuries to the head, abdomen, and spine are common and significantly contribute to mortality.

Pulmonary injury occurs through several mechanisms:

Direct Mechanical Injury

Compression, shear forces, and rapid deceleration may produce: Pulmonary contusion, Pulmonary laceration, Pneumothorax, Hemothorax, and Tracheobronchial disruption

Ventilator-Induced Injury

Mechanical ventilation may produce: Barotrauma (excessive pressure), Volutrauma (excessive tidal volume), Atelectrauma (repetitive alveolar collapse and reopening), and Biotrauma (inflammatory mediator release)

These mechanisms collectively contribute to ventilator-induced lung injury (VILI), prolonged respiratory failure, and multisystem inflammatory responses.

Blast Injury

Blast waves produce rapid pressure fluctuations that damage gas-containing organs. The lung is particularly susceptible because of extensive air-tissue interfaces. Primary blast injury causes diffuse alveolar hemorrhage, pulmonary contusion, pneumothorax, air embolism, and acute respiratory failure.

Non-Accidental Trauma

In child abuse, highly compressive chest forces may result in posterior rib fractures, pulmonary contusion, hem



-othorax, and airway injury. Respiratory symptoms may be the first clinical manifestation of occult abuse.

CLASSIFICATION OF PEDIATRIC PULMONARY AND RESPIRATORY TRAUMA

Pediatric pulmonary and respiratory trauma encompasses a broad spectrum of injuries involving the chest wall, airways, lung parenchyma, pulmonary vasculature, and pleural cavity. A practical clinical classification is based on the mechanism of injury because this strongly influences presentation, imaging findings, management, and prognosis. Pediatric thoracic trauma differs from adult trauma owing to the highly compliant chest wall, which allows significant intrathoracic injury to occur without obvious skeletal injury.

Blunt Thoracic Trauma

Blunt trauma accounts for approximately 85% of pediatric thoracic injuries and is most commonly caused by motor vehicle collisions, pedestrian injuries, falls, sports accidents, and crush injuries. Pulmonary contusion is the predominant injury, followed by pneumothorax, hemothorax, pulmonary laceration, and rib fractures. Associated head and abdominal injuries are common and significantly influence outcomes.

Penetrating Thoracic Trauma

Penetrating injuries result from stab wounds, gunshot wounds, impalement injuries, and other sharp-force mechanisms. Although less common than blunt trauma, penetrating injuries are associated with a higher likelihood of major vascular injury, pulmonary laceration, hemothorax, and cardiac involvement. Management often requires rapid imaging, chest drainage, and, in selected cases, operative intervention.

Ventilator-Associated Pulmonary Trauma

Ventilator-associated injury represents an important cause of secondary pulmonary trauma in neonates and critically ill children. Excessive airway pressures, tidal volumes, and repetitive alveolar collapse may result in barotrauma, volutrauma, atelectrauma, and biotrauma. Clinical manifestations include pneumothorax, pulmonary interstitial emphysema, pneumomediastinum, and ventilator-induced lung injury.

Birth-Related Respiratory Trauma

Birth trauma remains an important cause of pulmonary injury during the neonatal period. Risk factors include prematurity, difficult delivery, shoulder dystocia, breech presentation, instrumental delivery, and neonatal resuscitation. Common injuries include pneumothorax, pulmonary hemorrhage, diaphragmatic injury, and air-leak syndromes. Early recognition is essential because respiratory deterioration may be rapid in neonates.

Child Abuse–Related Thoracic Trauma

Non-accidental injury should be considered in infants and young children presenting with unexplained respiratory symptoms, rib fractures, pulmonary contusions, or recurrent thoracic injuries. Posterior rib fractures are highly suggestive of abusive chest compression. Pulmonary complications may include contusion, hemothorax, aspiration, and traumatic asphyxia.

Blast Injuries

Blast trauma may occur during terrorist attacks, armed conflict, industrial explosions, and accidental detonations. Pulmonary tissue is highly susceptible to blast overpressure because of its extensive air-tissue interfaces. Blast lung injury is characterized by pulmonary hemorrhage, pulmonary contusion, pneumothorax, air embolism, and acute respiratory failure. Children may sustain significant multisystem injuries because of their smaller body size and greater proximity to the blast wave.

Aviation and Air-Crash Injuries

Aviation-related trauma is uncommon but may occur during commercial aviation accidents, helicopter crashes,



military aircraft incidents, or air-ambulance mishaps. The predominant pulmonary injuries include blunt chest trauma, pulmonary contusion, pneumothorax, hemothorax, and inhalational injury associated with post-crash fires. Survivors frequently present with polytrauma requiring coordinated multidisciplinary management.

Iatrogenic Respiratory Trauma

Iatrogenic injuries have become increasingly recognized because of advances in pediatric intensive care, surgery, and interventional procedures. Common causes include: Endotracheal intubation, Mechanical ventilation, Central venous catheter insertion, Chest drain placement, Bronchoscopy, Thoracic surgery, and Extracorporeal membrane oxygenation (ECMO)

Potential complications include pneumothorax, tracheobronchial injury, pulmonary hemorrhage, vascular perforation, and ventilator-induced lung injury. Prevention, early detection, and standardized procedural protocols remain essential components of patient safety.

PULMONARY BAROTRAUMA AND VENTILATOR-INDUCED LUNG INJURY

Pulmonary barotrauma and ventilator-induced lung injury (VILI) are important causes of respiratory morbidity in neonates, infants, and critically ill children requiring mechanical ventilation. Although mechanical ventilation is lifesaving, excessive airway pressures, inappropriate tidal volumes, and prolonged ventilatory support may result in significant pulmonary injury. Children with respiratory distress syndrome, acute respiratory distress syndrome (ARDS), severe pneumonia, sepsis, thoracic trauma, and postoperative respiratory failure are particularly vulnerable. Ventilator-associated lung injury remains a major contributor to prolonged intensive care admission, chronic lung disease, and mortality in critically ill pediatric populations.

Mechanisms of Injury

Ventilator-induced lung injury is a multifactorial process involving mechanical stress, alveolar disruption, and inflammatory activation.

Alveolar Rupture

Excessive alveolar distension may result in rupture of terminal airspaces, allowing air to dissect along perivascular and peribronchial tissues. This process underlies many air-leak syndromes observed in ventilated neonates and children. Alveolar rupture is particularly common in premature infants because of immature lung architecture and reduced elastic tissue support.

Pressure Injury (Barotrauma)

Barotrauma occurs when high airway pressures exceed the mechanical tolerance of alveolar structures. Elevated peak inspiratory and plateau pressures increase the risk of pulmonary air leaks and respiratory deterioration. Clinical severity may range from asymptomatic radiological findings to life-threatening cardiorespiratory collapse.

Ventilator-Induced Inflammation (Biotrauma)

Mechanical stress initiates pulmonary inflammation through cytokine release, neutrophil activation, oxidative injury, and disruption of the alveolar-capillary barrier. This inflammatory response may extend beyond the lungs and contribute to multisystem organ dysfunction. Increasing evidence suggests that biotrauma plays a central role in the progression of severe ventilator-associated lung injury.

Clinical Manifestations

The clinical presentation depends on the degree of pulmonary injury and associated air-leak syndromes.



Pneumothorax

Pneumothorax represents the most common manifestation of pulmonary barotrauma. Symptoms include acute respiratory deterioration, tachypnea, hypoxemia, unilateral reduction in breath sounds, and cardiovascular compromise in cases of tension pneumothorax.

Pneumomediastinum

Air leakage into the mediastinum may occur following alveolar rupture. Clinical manifestations include respiratory distress, retrosternal air collections, and subcutaneous emphysema. Most cases resolve with conservative management.

Pulmonary Interstitial Emphysema

Pulmonary interstitial emphysema occurs when air tracks through the pulmonary interstitial. It is particularly common in premature infants receiving positive-pressure ventilation and may lead to progressive respiratory insufficiency and prolonged ventilator dependence.

Air Embolism

Air embolism is a rare but catastrophic complication resulting from entry of alveolar air into the pulmonary circulation. Clinical manifestations include sudden cardiovascular collapse, neurological injury, and severe hypoxemia. Mortality remains high despite aggressive intervention.

Diagnosis

Diagnosis relies on clinical assessment supported by imaging.

Chest radiography remains the primary diagnostic investigation and may demonstrate pneumothorax, pulmonary interstitial emphysema, pneumomediastinum, and hyperinflation.

Point-of-care ultrasonography provides rapid bedside detection of pneumothorax and pleural complications without radiation exposure.

Computed tomography is rarely required but may help define complex air-leak syndromes and severe pulmonary injury.

Prevention and Management

Prevention remains the most effective strategy for reducing ventilator-associated pulmonary injury.

Lung-Protective Ventilation

Current best practices include: Low tidal volume ventilation, Limitation of plateau and driving pressures, Individualized positive end-expiratory pressure (PEEP), Avoidance of excessive oxygen exposure, and Optimization of patient-ventilator synchrony

These measures reduce alveolar stress and minimize secondary lung injury.

Management of Air-Leak Syndromes

Treatment depends on the severity of the air leak. Small pneumothoraces may be managed conservatively, Symptomatic pneumothoraces require needle decompression or chest drainage, Persistent air leaks may require prolonged drainage or surgical intervention, Severe pulmonary interstitial emphysema may necessitate selective ventilation strategies or high-frequency ventilation.



Advanced Respiratory Support

Children with refractory respiratory failure may require: High-frequency oscillatory ventilation, Prone positioning, Neuromuscular blockade, and Extracorporeal membrane oxygenation (ECMO)

ECMO permits ultra-protective ventilation and may reduce ongoing ventilator-induced injury in selected cases.

NEONATAL AND BIRTH-RELATED RESPIRATORY TRAUMA

Neonatal respiratory trauma represents a distinct subset of pediatric thoracic injury and may occur during delivery, neonatal resuscitation, or early respiratory support. Although uncommon, these injuries can result in significant respiratory compromise because of the limited physiological reserve of newborn infants. Risk factors include macrosomia, instrumental delivery, breech presentation, shoulder dystocia, prematurity, and positive-pressure ventilation during resuscitation.

Pathophysiology

Birth-related thoracic injuries most commonly result from mechanical compression during delivery or from pressure-related injury during neonatal resuscitation. The immature neonatal lung is particularly susceptible to alveolar rupture and air-leak syndromes because of reduced lung compliance and incomplete alveolar development.

Common Injuries

Pneumothorax

Neonatal pneumothorax is one of the most frequent respiratory birth injuries. It may occur spontaneously or following positive-pressure ventilation. Clinical manifestations include: Respiratory distress, Tachypnea, Cyanosis, Reduced breath sounds, and Sudden cardiorespiratory deterioration

Tension pneumothorax constitutes a neonatal emergency requiring immediate decompression.

Pulmonary Hemorrhage

Pulmonary hemorrhage is a severe complication seen particularly in premature infants, neonates with respiratory distress syndrome, and those requiring mechanical ventilation. Presentation includes: Bloody endotracheal secretions, Acute respiratory failure, Hypoxemia, and Hemodynamic instability

Diaphragmatic Injury

Traumatic diaphragmatic injury related to delivery is rare but may occur following difficult extraction or severe birth trauma. Clinical features include respiratory compromise, decreased breath sounds, and bowel sounds within the thorax.

Air-Leak Syndromes

Air-leak syndromes comprise: Pulmonary interstitial emphysema, Pneumomediastinum, Pneumopericardium, Subcutaneous emphysema, and Pneumothorax

These conditions may occur independently or coexist in ventilated neonates.

Diagnosis

Diagnosis relies on prompt clinical assessment supported by imaging.

Chest radiography remains the primary investigation and can identify pneumothorax, pulmonary interstitial



emphysema, pneumomediastinum, and diaphragmatic abnormalities.

Point-of-care ultrasonography is increasingly utilized because it allows rapid bedside diagnosis of pneumothorax and pleural pathology without radiation exposure.

Computed tomography is rarely required but may assist diagnosis when complex thoracic injury is suspected.

Contemporary Management

Management depends on the severity and nature of the injury.

Supportive Management

Supplemental oxygen, Temperature regulation, Hemodynamic support, and Monitoring in a neonatal intensive care setting

Pneumothorax Management

Observation for small asymptomatic pneumothoraces, Needle aspiration for symptomatic lesions, **and** Intercostal drainage for tension pneumothorax or persistent air leak

Pulmonary Hemorrhage Management

Airway stabilization, Mechanical ventilation when required, Correction of coagulation abnormalities, and Management of underlying conditions

Prevention of Ventilation-Related Injury

Current neonatal respiratory care emphasizes: Lung-protective ventilation, Gentle positive-pressure ventilation, Continuous positive airway pressure (CPAP) when appropriate, Avoidance of excessive airway pressure, and Careful oxygen targeting.

These measures have significantly reduced the incidence of severe neonatal air-leak syndromes.

Outcomes

Most neonatal respiratory injuries resolve completely with prompt recognition and treatment. Prognosis is generally excellent for isolated pneumothorax and uncomplicated air-leak syndromes. However, severe pulmonary hemorrhage, extensive ventilator-associated injury, or associated prematurity may contribute to chronic lung disease and prolonged neonatal intensive care admission.

CHILD ABUSE–RELATED THORACIC TRAUMA

Child abuse, or non-accidental injury (NAI), remains an important cause of thoracic trauma in infants and young children and carries significant morbidity and mortality. Thoracic injuries may be occult and are frequently identified during investigation for suspected physical abuse. Recognition of characteristic injury patterns is essential because thoracic trauma may be the first indicator of ongoing abuse and has major safeguarding implications.

Epidemiology

Thoracic injuries account for a smaller proportion of abusive injuries than head or skeletal trauma but are highly specific when present, particularly in infants. Rib fractures resulting from forceful chest compression are among the most important radiological indicators of non-accidental injury. The risk is greatest in children younger than two years, especially non-ambulatory infants.



Clinical Features

Clinical presentation varies according to injury severity and may range from asymptomatic radiographic abnormalities to life-threatening respiratory compromise.

Characteristic findings include: Posterior or posteromedial rib fractures, Multiple rib fractures at different stages of healing, Pulmonary contusions, Pneumothorax or haemothorax, Airway injury, Respiratory distress, Associated skeletal injuries, and Concomitant head or abdominal trauma.

Posterior rib fractures are particularly important because they are strongly associated with non-accidental injury and are uncommon following routine accidental trauma.

Diagnostic Challenges

Diagnosis can be difficult because caregivers may provide a vague, inconsistent, or absent history of trauma. Symptoms may be subtle, and clinical examination may initially appear normal. A high index of suspicion is therefore required in infants presenting with unexplained respiratory symptoms or radiographic abnormalities.

Recommended evaluation includes: Complete physical examination, Skeletal survey, Chest radiography, Computed tomography when clinically indicated, Neuroimaging if associated head injury is suspected, Multidisciplinary assessment involving pediatricians, radiologists, surgeons, and safeguarding teams

The presence of multiple injuries, injuries inconsistent with the developmental stage of the child, or delayed presentation should prompt immediate consideration of abuse.

Surgical and Critical Care Management

Management follows standard trauma principles and depends on injury severity.

Potential interventions include: Respiratory support and oxygen therapy, Analgesia, Chest drainage for pneumothorax or haemothorax, Mechanical ventilation for severe pulmonary contusion, and Surgical intervention for major airway or intrathoracic injuries.

Early involvement of pediatric trauma and intensive care teams is recommended for significant thoracic injury.

Safeguarding Implications

Identification of child abuse-related thoracic trauma is not solely a medical diagnosis but also a safeguarding emergency. Once non-accidental injury is suspected, clinicians have a duty to initiate local child protection procedures to ensure immediate and long-term safety of the child and any siblings.

Management should include: Urgent safeguarding referral, Documentation of all clinical findings, Multidisciplinary case review, Social care involvement, and Long-term psychosocial support

Key Surgical Message

Thoracic trauma in infants without an adequate accidental mechanism should always raise suspicion of non-accidental injury. Posterior rib fractures, unexplained pulmonary contusions, and airway injuries are particularly concerning findings. Early recognition, comprehensive multidisciplinary assessment, and prompt safeguarding intervention are essential to prevent further harm and improve outcomes.

BLUNT PULMONARY TRAUMA

Blunt thoracic trauma accounts for more than 80% of pediatric chest injuries and is most commonly associated with motor vehicle collisions, falls, sports injuries, and crush trauma. Owing to the compliant pediatric chest



wall, significant intrathoracic injury may occur without external signs or rib fractures. Pulmonary contusion is the most frequent injury and remains a major cause of respiratory morbidity following pediatric trauma.

Pulmonary Contusion

Pulmonary contusion results from direct compression of lung parenchyma, causing alveolar hemorrhage, edema, and impaired gas exchange. It is the most common thoracic injury in children and may not be apparent on initial chest radiography, with radiological findings often evolving over 24–48 hours.

Clinical manifestations include: Tachypnea, Hypoxemia, Chest pain, and Hemoptysis Respiratory distress

Computed tomography is more sensitive than chest radiography and accurately demonstrates the extent of parenchymal injury. Most cases are managed conservatively with supplemental oxygen, analgesia, pulmonary toilet, and lung-protective ventilation when required.

Current Controversies in Pulmonary Contusion

Important unresolved issues include: Optimal timing of CT imaging, ICU admission criteria, Role of corticosteroids, Ventilation thresholds, and Predictors of long-term pulmonary dysfunction.

Prospective multicenter studies are required to address these evidence gaps.

Pneumothorax

Traumatic pneumothorax occurs when air enters the pleural cavity following disruption of the lung parenchyma or tracheobronchial tree. It may present with: Sudden respiratory distress, Unilateral reduction in breath sounds, Tachycardia, Hypoxemia.

Tension pneumothorax is a life-threatening emergency characterized by progressive respiratory compromise and cardiovascular instability. Chest radiography and point-of-care ultrasonography are highly effective diagnostic tools. Management depends on size and physiological impact, ranging from observation to needle decompression and tube thoracostomy.

Hemothorax

Hemothorax results from bleeding into the pleural cavity following injury to the chest wall, pulmonary parenchyma, or intrathoracic vessels. Clinical manifestations include: Respiratory distress, Chest pain, Hypovolemia, Reduced breath sounds, Dullness to percussion

Chest radiography and ultrasonography typically demonstrate pleural fluid collections, while CT provides additional anatomical detail. Initial treatment consists of fluid resuscitation and chest tube drainage. Persistent bleeding, retained hemothorax, or hemodynamic instability may necessitate thoracoscopic or open surgical intervention.

Tracheobronchial Disruption

Tracheobronchial injury is rare but potentially fatal. Most injuries occur following severe blunt trauma and are frequently located near the carina or main bronchi. Clinical features include: Massive air leak, Persistent pneumothorax despite chest drainage, Pneumomediastinum, Subcutaneous emphysema, and Respiratory failure.

Flexible bronchoscopy remains the diagnostic gold standard because it allows direct visualization of the airway defect. Early recognition is essential, as delayed diagnosis may result in airway stenosis, recurrent infection, and chronic pulmonary dysfunction.



Current Management

Management of blunt pulmonary trauma follows Advanced Trauma Life Support (ATLS) principles and focuses on maintenance of oxygenation, ventilation, and hemodynamic stability. Contemporary treatment strategies include: Supplemental oxygen and respiratory support, Adequate analgesia, Lung-protective ventilation, Tube thoracostomy for significant pneumothorax or hemothorax, Bronchoscopic assessment of suspected airway injury, Video-assisted thoracoscopic surgery (VATS) for selected complications, Surgical repair of major tracheobronchial disruption.

Most pulmonary contusions and small air-leak syndromes resolve with supportive management. However, severe injuries may require intensive care admission, advanced ventilatory support, or extracorporeal membrane oxygenation (ECMO) in exceptional circumstances. Current outcomes have improved substantially owing to advances in imaging, critical care, and minimally invasive thoracic surgery.

PENETRATING THORACIC TRAUMA

Penetrating thoracic trauma is less common than blunt chest trauma in children but is associated with higher rates of major vascular, pulmonary, and cardiac injury. Injury severity depends on the mechanism, trajectory, kinetic energy transfer, and involvement of mediastinal structures. Although uncommon in most pediatric trauma series, penetrating injuries account for a disproportionate share of thoracic trauma mortality.

Mechanisms

Penetrating injuries arise from disruption of the chest wall and underlying thoracic structures by sharp or high-velocity objects. Common mechanisms include: Gunshot wounds, Stab wounds, Impalement injuries, Projectile-related injuries, Fragment injuries following explosions.

The pattern of injury varies considerably according to projectile velocity. High-energy injuries are more likely to cause extensive pulmonary destruction, vascular injury, and hemothorax, whereas low-energy injuries often result in more localized tissue damage.

Initial Assessment

Management follows Advanced Trauma Life Support (ATLS) principles with emphasis on early identification of life-threatening injuries.

Clinical evaluation should focus on: Airway patency, Respiratory status, Hemodynamic stability, Entry and exit wound identification, Evidence of hemothorax or pneumothorax, Signs of mediastinal injury.

Initial investigations typically include: Chest radiography, Point-of-care ultrasonography (eFAST), Computed tomography (CT), and CT angiography when vascular injury is suspected.

Bronchoscopy and esophagoscopy may be required when tracheobronchial or esophageal injury is suspected. Comprehensive imaging is often necessary because external wounds frequently underestimate underlying injury severity.

Common Thoracic Injuries

Penetrating trauma may result in: Pulmonary laceration, Pneumothorax, Hemothorax, Pulmonary hemorrhage, Tracheobronchial injury, Cardiac injury, Great vessel injury, and Diaphragmatic injury.

Pulmonary laceration and hemopneumothorax are the most frequently encountered pulmonary injuries.

Surgical Indications

Most stable children can initially be managed with chest tube drainage and close observation. Operative inte-



vention is indicated for: Persistent hemodynamic instability, Massive hemothorax, Ongoing intrathoracic bleeding, Major airway disruption, Cardiac injury, Great vessel injury, Retained hemothorax, Persistent air leak, Penetrating diaphragmatic injury.

Video-assisted thoracoscopic surgery (VATS) is increasingly utilized for retained hemothorax, persistent pneumothorax, and selected stable penetrating injuries. However, thoracotomy remains necessary for major vascular injuries and unstable patients.

Outcomes

Outcomes depend primarily on injury severity and associated injuries. Children who survive the initial resuscitation phase generally have favorable long-term outcomes following isolated pulmonary injury. Mortality is highest among children with major vascular injury, cardiac trauma, severe hemorrhage, or associated head injury. Advances in trauma systems, imaging, critical care, and damage-control surgery have contributed to significant improvements in survival over recent decades.

BLAST AND AIR-CRASH INJURIES

Blast and aviation-related thoracic injuries represent uncommon but highly complex forms of pediatric respiratory trauma. These injuries are frequently associated with multisystem trauma, severe pulmonary dysfunction, and high mortality. Children are particularly vulnerable because of their smaller body size, greater body surface area-to-volume ratio, and limited physiological reserve. Blast injuries are traditionally classified into primary, secondary, tertiary, and quaternary injuries according to the mechanism of tissue damage.

Primary Blast Lung Injury

Primary blast injury results directly from the blast overpressure wave and predominantly affects gas-containing organs. The lung is particularly susceptible because abrupt pressure changes across alveolar-capillary membranes cause tissue disruption, alveolar hemorrhage, and edema. Blast lung injury is considered the hallmark thoracic manifestation of explosion-related trauma.

Common pulmonary manifestations include: Pulmonary contusion, Diffuse alveolar hemorrhage, Pneumothorax, Pneumomediastinum, Air embolism, and Acute respiratory distress syndrome (ARDS).

Clinical presentation may include dyspnea, hypoxemia, hemoptysis, chest pain, and respiratory failure. Computed tomography frequently demonstrates bilateral pulmonary infiltrates, ground-glass opacities, and pulmonary hemorrhage. Pediatric series have identified pulmonary contusion as the most frequent imaging finding following blast exposure.

Secondary Blast Injury

Secondary blast injury results from impact by flying debris, fragments, shattered glass, or projectiles generated by the explosion. These injuries resemble penetrating trauma and may involve: Pulmonary laceration, Hemothorax, Pneumothorax, Chest wall injury, and Major vascular injury.

The severity depends on fragment size, velocity, and anatomical trajectory. Multiple penetrating injuries are common in confined-space explosions.

Tertiary Blast Injury

Tertiary blast injury occurs when victims are displaced by blast wind and subsequently collide with surrounding structures. These mechanisms commonly produce: Pulmonary contusion, Rib fractures, Tracheobronchial injury, Flail chest, Polytrauma.

Children may sustain severe injuries because blast displacement forces are proportionally greater relative to



body mass. Traumatic brain injury and abdominal trauma frequently coexist.

Air-Crash Specific Mechanisms

Air-crash injuries share several pathophysiological features with both blunt and blast trauma. Mechanisms include: Rapid deceleration injury, Direct chest compression, Impact trauma, Structural collapse, Post-crash fire exposure, and Inhalational injury.

Pulmonary contusion, hemothorax, pneumothorax, airway burns, and inhalational smoke injury are frequently encountered among survivors. Because aviation accidents commonly produce polytrauma, respiratory injury often occurs in conjunction with head, spinal, abdominal, and orthopedic injuries.

In military and helicopter crashes, additional blast and fuel-related thermal injuries may further complicate respiratory management.

Diagnostic Evaluation

Initial assessment follows Advanced Trauma Life Support (ATLS) principles.

Recommended investigations include: Chest radiography, Point-of-care ultrasonography, Contrast-enhanced CT, CT angiography when vascular injury is suspected, Bronchoscopy for airway injury assessment

Computed tomography remains the most sensitive modality for identifying blast lung injury, pulmonary hemorrhage, and associated thoracic pathology.

Damage-Control Strategies

Management emphasizes rapid stabilization and prevention of secondary lung injury.

Key principles include:

Respiratory Support

High-flow oxygen, Lung-protective mechanical ventilation, Careful positive end-expiratory pressure (PEEP) titration, Avoidance of excessive airway pressure, and Prone positioning when appropriate.

Hemodynamic Stabilization

Damage-control resuscitation, Judicious fluid administration, Blood product replacement when required, and Prevention of hypothermia and coagulopathy.

Management of Associated Thoracic Injuries

Tube thoracostomy for pneumothorax or hemothorax, Bronchoscopy for airway injuries, Surgical intervention for major vascular injury, and Video-assisted thoracoscopic surgery (VATS) for selected complications.

Extracorporeal Support

Extracorporeal membrane oxygenation (ECMO) may be considered in severe blast lung injury with refractory hypoxemia or advanced respiratory failure. Although pediatric experience remains limited, ECMO can provide rescue support while pulmonary recovery occurs.

Outcomes

Outcomes are primarily determined by injury severity, associated multisystem trauma, and the rapidity of definitive intervention. Most isolated pulmonary blast injuries recover with supportive care, whereas mortality



increases significantly when severe brain injury, major vascular trauma, or multisystem injury coexist. Contemporary trauma systems, advanced imaging, and critical care management have substantially improved survival following both blast and aviation-related thoracic trauma.

IATROGENIC RESPIRATORY TRAUMA

Iatrogenic respiratory trauma comprises injuries resulting from diagnostic, therapeutic, and critical care interventions. Although relatively uncommon, these injuries can cause significant morbidity, particularly in neonates and critically ill children with limited respiratory reserve. Increased use of mechanical ventilation, central venous catheterization, bronchoscopy, thoracic drainage procedures, and extracorporeal membrane oxygenation (ECMO) has led to greater recognition of procedure-related thoracic complications. Prevention through meticulous technique, imaging guidance, and standardized protocols remains the most effective strategy.

Mechanical Ventilation

Mechanical ventilation is a major cause of iatrogenic pulmonary injury, particularly in premature neonates and children with severe respiratory failure. Excessive airway pressures and tidal volumes may lead to: Pneumothorax, Pneumomediastinum, Pulmonary interstitial emphysema, Alveolar rupture, and Ventilator-induced lung injury (VILI).

Lung-protective ventilation strategies, including low tidal volume ventilation, limitation of plateau pressures, and individualized positive end-expiratory pressure (PEEP), have significantly reduced the incidence of severe barotrauma and volutrauma.

Central Venous Access

Central venous catheter placement is frequently required in critically ill children but carries recognized thoracic risks. Complications include: Pneumothorax, Hemothorax, Pulmonary hemorrhage, Vascular perforation, and Air embolism.

Subclavian venous catheterization carries the highest risk of pleural injury. Ultrasound-guided vascular access has substantially reduced procedure-related complications and is now considered standard practice in most pediatric centers..

Endoscopy and Bronchoscopy

Flexible and rigid bronchoscopy are essential tools for diagnosing airway disease but may occasionally result in respiratory trauma.

Potential complications include: Airway laceration, Tracheobronchial perforation, Bleeding, Pneumothorax, Hypoxemia, and Airway edema.

Most complications are uncommon and self-limiting; however, major airway disruption may require operative intervention. The risk is increased during therapeutic procedures, foreign-body extraction, and airway dilation.

Thoracic Drainage Procedures

Thoracostomy tube placement remains the standard management for significant pneumothorax and hemothorax but can itself cause injury.

Reported complications include: Pulmonary laceration, Intercostal vessel injury, Diaphragmatic injury, Liver or splenic injury, Malpositioned chest tubes, Infection.

Image-guided placement and adherence to anatomical landmarks significantly improve safety and procedural success.



ECMO-Related Complications

Extracorporeal membrane oxygenation (ECMO) has become an important rescue therapy for severe respiratory failure. Although ECMO may reduce ventilator-associated lung injury by allowing ultra-protective ventilation, the procedure itself carries substantial risks.

Respiratory and thoracic complications include: Pulmonary hemorrhage, Hemothorax, Airway bleeding, Pleural effusions, Thromboembolic complications, and Cannulation-related vascular injury.

Because ECMO is typically reserved for children with severe respiratory failure, distinguishing disease-related complications from ECMO-related injury can be challenging.

Diagnosis

Early recognition of iatrogenic respiratory trauma relies on careful clinical assessment combined with imaging.

Common diagnostic tools include: Chest radiography, Point-of-care ultrasound, Computed tomography and Bronchoscopy

Routine post-procedural imaging may be appropriate following high-risk interventions such as central venous catheter insertion, chest tube placement, and airway procedures.

Management

Management depends on the type and severity of injury.

General principles include: Immediate recognition of complications, Stabilization of airway and respiration, Correction of procedure-related abnormalities, Treatment of pneumothorax or hemorrhage, and Minimization of additional respiratory injury.

Most minor injuries respond to conservative management, whereas major airway disruption, vascular injury, or persistent air leak may require surgical intervention.

Outcomes

The majority of iatrogenic respiratory injuries are successfully managed without long-term sequelae when identified promptly. However, delayed recognition may result in prolonged hospitalization, respiratory failure, chronic pulmonary dysfunction, and increased mortality. Ongoing emphasis on simulation-based training, ultrasound guidance, procedural standardization, and quality improvement programs continues to improve patient safety.

STATE-OF-THE-ART IMAGING

Accurate imaging is fundamental to the diagnosis and management of pediatric pulmonary and respiratory trauma. Contemporary imaging strategies aim to rapidly identify life-threatening thoracic injuries while minimizing radiation exposure. Advances in ultrasonography, multidetector computed tomography (CT), low-dose imaging protocols, and artificial intelligence (AI)-assisted image analysis have significantly improved diagnostic accuracy and treatment planning.

Chest Radiography

Chest radiography remains the first-line imaging modality in most children presenting with thoracic trauma. It is rapid, widely available, and useful for detecting: Pneumothorax, Hemothorax, Pulmonary contusion, Rib fractures, Mediastinal widening, Diaphragmatic abnormalities.



However, radiographs may underestimate the severity of pulmonary contusions and airway injuries, particularly during the first 24 hours following trauma. Serial radiographs are therefore often required.

Point-of-Care Ultrasound

Point-of-care ultrasound (POCUS) has become an integral component of modern pediatric trauma assessment. Extended focused assessment with sonography for trauma (eFAST) enables rapid bedside evaluation without ionizing radiation.

Major applications include: Detection of pneumothorax, Identification of hemothorax, Detection of pleural effusions, Assessment of diaphragmatic motion, and Guidance for pleural interventions.

POCUS may be more sensitive than chest radiography for detecting occult pneumothorax and can be repeated serially in critically ill children.

Computed Tomography

Multidetector CT remains the diagnostic gold standard for significant thoracic trauma. CT provides excellent visualization of: Pulmonary contusions, Pulmonary lacerations, Tracheobronchial injuries, Pleural injuries, Mediastinal pathology, and Diaphragmatic disruption

CT is particularly valuable when clinical findings and chest radiographs are discordant. Modern pediatric protocols utilize low-dose techniques to minimize radiation exposure while maintaining diagnostic quality.

CT Angiography

CT angiography (CTA) is indicated when vascular injury is suspected and has largely replaced conventional angiography as the primary diagnostic modality.

Major indications include: Traumatic aortic injury, Major vascular disruption, Penetrating mediastinal trauma, Massive hemothorax, and Suspected pulmonary vascular injury.

CTA accurately defines vascular anatomy and facilitates operative or endovascular planning.

Magnetic Resonance Imaging

Magnetic resonance imaging (MRI) plays a limited role in acute trauma because of longer acquisition times and reduced availability in emergency settings. Nevertheless, MRI can be valuable in: Follow-up of complex thoracic injuries, Assessment of diaphragmatic injuries, Evaluation of mediastinal pathology, and Long-term pulmonary imaging without radiation exposure.

MRI may be particularly useful in children requiring repeated imaging during recovery.

AI-Assisted Trauma Imaging

Artificial intelligence currently serves as a promising adjunct rather than a standard component of pediatric trauma care. Emerging applications include automated pneumothorax detection, pulmonary contusion quantification, image segmentation, and outcome prediction models. Although early studies demonstrate encouraging diagnostic performance, pediatric-specific validation studies remain limited and further prospective evaluation is required before widespread implementation.

CONTEMPORARY MANAGEMENT OF PEDIATRIC THORACIC TRAUMA

The management of thoracic trauma in children has evolved considerably over the past two decades with improvements in trauma systems, advanced imaging, critical care, minimally invasive surgery, extracorporeal support, and interventional radiology. Despite these advances, the majority of pediatric thoracic injuries can



still be managed non-operatively. Contemporary management emphasizes early recognition of life-threatening injuries, physiological stabilization, organ preservation, and multidisciplinary care.

Advanced Trauma Life Support (ATLS) Principles

Initial assessment and management should follow Advanced Trauma Life Support (ATLS) principles, prioritizing airway, breathing, circulation, disability, and exposure. Particular attention should be directed toward immediately life-threatening thoracic injuries, including: Tension pneumothorax, Massive hemothorax, Open pneumothorax, Cardiac tamponade, and Tracheobronchial disruption.

Children possess remarkable physiological reserve and may maintain normal vital signs until significant decompensation occurs. Consequently, early recognition of respiratory compromise and occult injury remains essential.

Pediatric Trauma Algorithms

Pediatric trauma management differs from adult trauma because of important anatomical and physiological differences: Greater chest wall compliance, Increased elasticity of ribs, Smaller circulating blood volume, and Higher metabolic oxygen demand.

As a result, significant intrathoracic injury may occur without external signs of trauma or rib fractures. Pediatric trauma algorithms emphasize: Early respiratory stabilization., Judicious use of imaging., Non-operative management whenever feasible., Frequent reassessment., Multidisciplinary decision-making.

Trauma scoring systems, including the Pediatric Trauma Score and Injury Severity Score, may assist in risk stratification and outcome prediction.

Damage-Control Resuscitation

Damage-control resuscitation has increasingly been adopted in severely injured children with major thoracic trauma and hemorrhagic shock.

Key principles include: Early hemorrhage control, Balanced blood-product resuscitation, Prevention of hypothermia, Correction of coagulopathy, Restrictive crystalloid administration, and Maintenance of tissue perfusion.

Massive transfusion protocols tailored to pediatric physiology have improved outcomes in major thoracic and polytrauma patients. Definitive surgical repair is often delayed until physiological stabilization has been achieved.

Thoracoscopy

Video-assisted thoracoscopic surgery (VATS) has transformed the management of thoracic trauma in children.

Current indications include: Retained hemothorax, Persistent pneumothorax, Ongoing air leak, Diaphragmatic injuries, Foreign body retrieval, and Diagnostic evaluation of selected penetrating injuries.

Advantages of thoracoscopy include: Reduced postoperative pain, Better cosmetic outcomes, Improved visualization, Shorter hospital stay, and Lower morbidity compared with thoracotomy.

Open thoracotomy remains necessary for unstable patients with major hemorrhage, complex airway injuries, or significant intrathoracic vascular trauma.

Extracorporeal Membrane Oxygenation (ECMO)

ECMO has emerged as a valuable rescue therapy for selected children with severe thoracic injuries and refrac-



ctory respiratory failure.

Potential indications include: Severe pulmonary contusion with hypoxemia, Acute respiratory distress syndrome (ARDS), Major airway trauma, and Combined pulmonary and cardiac injury.

ECMO allows lung-protective ventilation while definitive treatment and pulmonary recovery occur. Although resource-intensive, survival rates continue to improve in expert centers.

Interventional Radiology

Interventional radiology has become an increasingly important component of pediatric trauma care and frequently reduces the need for operative intervention.

Applications include: Embolization of bleeding intercostal vessels, Management of pulmonary arteriovenous fistulae, Treatment of vascular complications, Image-guided drainage procedures, Percutaneous management of thoracic collections.

Advances in catheter technology and embolization techniques have expanded the role of minimally invasive therapy in pediatric thoracic trauma.

Multidisciplinary Care

Optimal outcomes require collaboration between: Pediatric surgeons, Trauma surgeons, Pediatric intensivists, Anesthetists, Respiratory physicians, Interventional radiologists, Cardiothoracic surgeons, and Rehabilitation specialists.

Early multidisciplinary involvement facilitates coordinated management, minimizes complications, and improves long-term outcomes.

Key Surgical Message

Contemporary pediatric thoracic trauma management prioritizes physiological stabilization, non-operative treatment where appropriate, minimally invasive intervention, and multidisciplinary decision-making. Thoracoscopy, damage-control resuscitation, ECMO, and interventional radiology have expanded the therapeutic options available for complex thoracic injuries while reducing morbidity and improving survival.

LONG-TERM OUTCOMES

Advances in trauma systems, pediatric intensive care, extracorporeal support, and thoracic surgery have improved survival following severe pulmonary and respiratory trauma. Nevertheless, survivors may experience persistent respiratory, neurodevelopmental, psychological, and functional sequelae that extend well beyond the acute recovery period. Long-term follow-up is therefore an important component of comprehensive pediatric trauma care. Thoracic trauma remains associated with significant morbidity despite improvements in mortality.

Pulmonary Function

The long-term impact of pulmonary trauma depends on the extent of the initial injury, associated respiratory complications, duration of mechanical ventilation, and underlying pulmonary health.

Most children with isolated pulmonary contusions or uncomplicated pneumothoraces recover normal lung function within weeks to months. However, severe injuries may result in: , Persistent restrictive ventilatory defects, Reduced exercise tolerance, Chronic respiratory symptoms, Airway hyperreactivity, Impaired diffusion capacity, and Ventilator-associated chronic lung disease.



Children who develop severe blast lung injury, extensive pulmonary contusions, prolonged mechanical ventilation, acute respiratory distress syndrome (ARDS), or ventilator-induced lung injury are at greatest risk of long-term pulmonary impairment. Formal pulmonary function testing should be considered during follow-up, particularly in children with severe injuries or prolonged intensive care admissions.

Neurodevelopment

Neurodevelopmental outcomes are influenced not only by thoracic injury itself but also by associated hypoxemia, hypotension, traumatic brain injury, prolonged critical illness, and intensive care exposure.

Potential consequences include: Cognitive impairment, Learning difficulties, Attention deficits, Delayed developmental milestones, Executive dysfunction, and Academic challenges

Infants and young children are particularly vulnerable because critical stages of neurological development coincide with periods of severe illness and hospitalization. Children requiring prolonged mechanical ventilation, ECMO, or extended intensive care support warrant formal developmental surveillance.

Psychological Effects

Psychological sequelae following major pediatric trauma are increasingly recognized. Traumatic injury may affect both the child and family members.

Common psychological outcomes include: Anxiety disorders, Post-traumatic stress symptoms, Sleep disturbance, Depression, Social withdrawal, Fear of future injury.

Blast injuries, aviation accidents, child abuse, major intensive care admissions, and near-fatal respiratory events are particularly associated with adverse psychological outcomes. Early psychological assessment and multidisciplinary support may improve long-term recovery.

Quality of Life

Quality of life has emerged as a critical outcome measure in pediatric trauma survivorship. Although most children achieve good functional recovery, residual symptoms may affect multiple domains.

Factors influencing quality of life include: Persistent respiratory symptoms, Physical limitations, Neurodevelopmental impairment, Psychological health, School performance, and Social integration.

Children with isolated thoracic injuries generally demonstrate favorable long-term health-related quality-of-life outcomes. However, those with severe multisystem trauma, prolonged intensive care stays, or chronic pulmonary sequelae may experience ongoing functional limitations requiring multidisciplinary follow-up.

Long-Term Follow-Up Recommendations

Follow-up should be individualized according to injury severity and clinical course.

Recommended assessments may include: Clinical respiratory review, Pulmonary function testing, Exercise tolerance assessment, Developmental screening, Psychological evaluation, School performance assessment, and Quality-of-life measurement.

A multidisciplinary approach involving pediatric pulmonologists, trauma specialists, rehabilitation teams, psychologists, and primary care providers is often beneficial for children recovering from severe respiratory trauma.

FUTURE DIRECTIONS

Rapid advances in imaging, critical care, computational medicine, and translational research are expected to



transform the management of pediatric pulmonary and respiratory trauma. Future developments will likely focus on earlier diagnosis, individualized treatment strategies, prevention of secondary lung injury, and improvement of long-term functional outcomes. Despite substantial progress in trauma systems and critical care, important evidence gaps remain regarding optimal ventilatory management, long-term pulmonary sequelae, and recovery trajectories following severe thoracic injury.,

AI-Assisted Diagnosis

Artificial intelligence (AI) is increasingly being integrated into trauma imaging and critical care workflows. Potential applications include: Automated pneumothorax detection, Pulmonary contusion quantification, Rib fracture detection, CT image segmentation, Trauma severity prediction, and Early identification of occult injuries.

Machine-learning algorithms may facilitate rapid triage, improve diagnostic accuracy, and reduce observer variability, particularly in high-volume emergency departments. AI-assisted interpretation of chest radiographs and CT scans may also accelerate decision-making in critically injured children. Although current pediatric-specific evidence remains limited, AI is expected to become an important adjunct to trauma imaging in the near future.

Precision Trauma Care

Traditional trauma management is largely protocol driven. Future pediatric trauma care is likely to adopt a precision medicine approach that incorporates: Patient-specific physiological variables, Advanced ventilatory monitoring, Biomarker profiling, Genomic susceptibility factors, Individual injury patterns, and Predictive outcome modeling.

Such strategies may permit individualized ventilatory settings, targeted anti-inflammatory therapies, and personalized rehabilitation programs aimed at minimizing long-term pulmonary dysfunction.

Pediatric Trauma Registries

Because severe pediatric respiratory trauma is relatively uncommon, many clinical decisions continue to rely on retrospective series and institutional experience. International pediatric trauma registries have the potential to generate robust multicenter data regarding: Injury epidemiology, Imaging strategies, Ventilator-related complications, Surgical outcomes, Long-term pulmonary function and Quality-of-life measures.

Collaborative databases will likely play an increasingly important role in developing evidence-based guidelines and benchmarking outcomes across institutions.

Advanced Ventilatory Strategies

Ongoing developments in respiratory support aim to reduce ventilator-induced lung injury while optimizing gas exchange.

Emerging approaches include: Individualized lung-protective ventilation, Mechanical power-guided ventilation, Advanced modes of neutrally adjusted ventilatory assist, Closed-loop ventilatory control systems, High-frequency ventilation refinements, and ECMO-supported ultra-protective ventilation.

Future ventilatory platforms may incorporate artificial intelligence and real-time physiological feedback to continuously optimize respiratory support and reduce the incidence of barotrauma, volutrauma, and biotrauma.

Regenerative Therapies

Regenerative medicine represents a promising frontier in the treatment of severe pulmonary injury. Experimental investigations are evaluating: Mesenchymal stem-cell therapies, Exosome-based therapies, Bioengineered lung tissue, Anti-fibrotic interventions, and Alveolar regeneration strategies.



Although these therapies remain largely investigational, they may eventually facilitate recovery following severe pulmonary contusion, acute respiratory distress syndrome, and ventilator-induced lung injury. Translation into pediatric clinical practice will require further experimental and clinical validation.

Limitations of Current Evidence

The evidence base for pediatric pulmonary and respiratory trauma remains constrained by several factors. Randomized controlled trials are uncommon, and most available evidence is derived from retrospective studies, registry analyses, institutional experiences, and expert consensus. Significant heterogeneity exists in injury classification systems, imaging pathways, treatment thresholds, and outcome reporting, limiting direct comparison between studies. Furthermore, rare injury mechanisms such as blast injury, major airway disruption, and aviation-related trauma remain primarily represented by case reports and small case series. Long-term pulmonary, developmental, and quality-of-life outcomes remain incompletely characterized.

Key Future Priorities

- Integration of artificial intelligence into trauma imaging and clinical decision support.
- Development of personalized ventilatory and critical care strategies.
- Expansion of multicenter pediatric trauma registries.
- Improvement of long-term outcome surveillance and quality-of-life assessment.
- Translation of regenerative therapies from experimental studies into clinical practice.
- Establishment of evidence-based international guidelines for pediatric pulmonary trauma management.

CONCLUSION

Pulmonary and respiratory trauma in infants and children encompasses a diverse spectrum of injuries ranging from neonatal air-leak syndromes and ventilator-induced lung injury to blunt, penetrating, blast-related, and iatrogenic trauma. Unique pediatric anatomical and physiological characteristics frequently permit severe intrathoracic injury in the absence of obvious external signs, making early diagnosis challenging.

Advances in trauma imaging, bronchoscopy, lung-protective ventilation, minimally invasive thoracic surgery, interventional radiology, and extracorporeal support have substantially improved outcomes. Nevertheless, significant evidence gaps remain regarding optimal ventilatory management, rare airway injuries, blast trauma, and long-term respiratory outcomes.

Future progress will depend upon multicenter collaboration, international trauma registries, artificial intelligence-assisted diagnostics, precision trauma care, and longitudinal outcome research. These developments have the potential to improve survival, pulmonary function, neurodevelopment, and quality of life among children affected by respiratory trauma.

Key Messages

- Pulmonary contusion remains the most common pediatric thoracic injury.
- Ventilator-induced lung injury and neonatal air-leak syndromes are important causes of morbidity in critically ill children.
- Point-of-care ultrasound and low-dose CT have transformed diagnostic evaluation.
- Most injuries can be managed successfully with lung-protective, multidisciplinary care.

- Artificial intelligence, advanced ventilation strategies, and international trauma registries are likely to shape future pediatric respiratory trauma care.

Figures

Figure Legends

Figure 1. Classification of pediatric pulmonary and respiratory trauma. Structural schema categorizing thoracic insults based on their primary anatomical and biomechanical targets. Pathologies are divided into direct parenchymal/pulmonary conditions and structural airway/dynamic volume conditions. This distinction is dictated by the highly compliant pediatric chest wall, which permits massive internal mechanical disruption frequently in the absence of overlapping rib fractures.

Figure 1. Classification of pediatric pulmonary and respiratory trauma

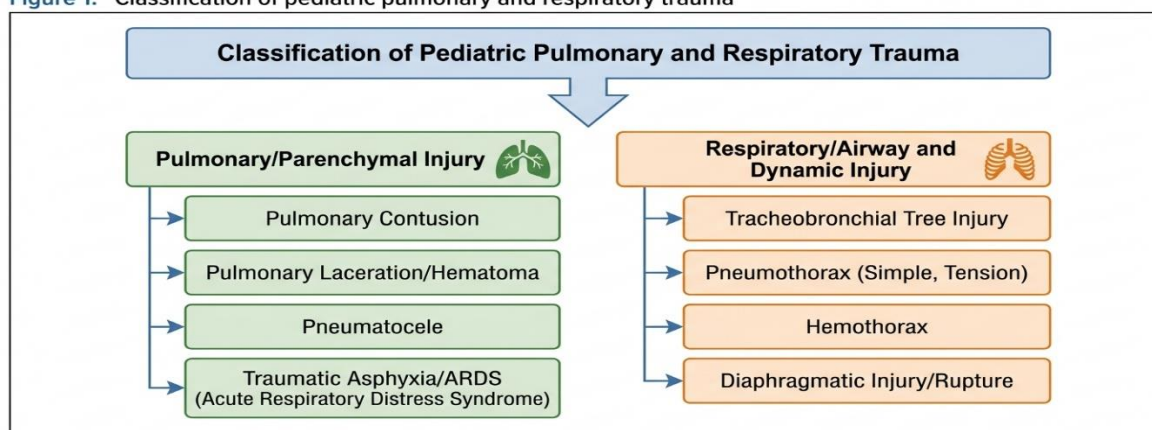


Figure 1. Classification of pediatric pulmonary and respiratory trauma

Figure 2. Molecular and physical pathophysiology of ventilator-induced lung injury (VILI). Biomechanical flowchart demonstrating how mechanical mechanical ventilation stresses can precipitate secondary parenchymal damage. Volutrauma (alveolar overdistension), barotrauma (high pressure), and atelectrauma (cyclic collapse and opening) converge to cause physical microvascular and alveolar-capillary membrane rupture. This induces an inflammatory signaling cascade (biotrauma) mediated by pro-inflammatory cytokines ($\text{IL-1}\beta$, IL-6 , $\text{TNF-}\alpha$) and macrophage recruitment, culminating in pulmonary edema, reduced compliance, structural progression to ARDS, and potential multi-organ failure. Key: Blue arrows indicate mechanical stress vectors; green arrows represent inflammatory signaling pathways; red arrows track downstream injury progression.

Figure 2. Pathophysiology of ventilator-induced lung injury (VILI)

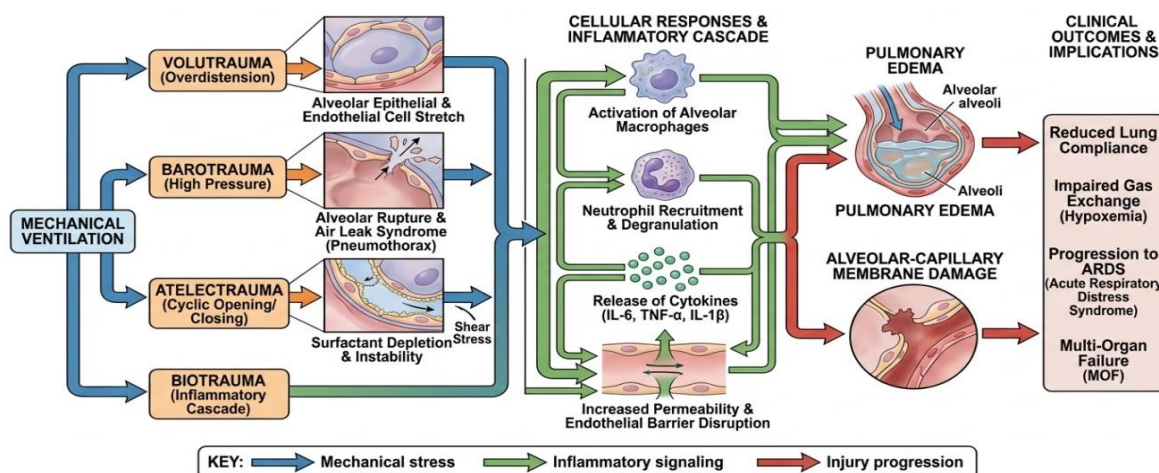


Figure 3. Algorithm for initial evaluation and triage of pediatric thoracic trauma. Clinical decision-making tree for emergency department and trauma bay presentation. The protocol prioritizes the primary

survey via standard Advanced Trauma Life Support (ATLS) and Pediatric Advanced Life Support (PALS) protocols to isolate immediate life-threats from hemodynamically stable cohorts. Unstable patients move rapidly to point-of-care ultrasound (POCUS/eFAST) and decompression maneuvers, while stable, high-risk, or radiographically abnormal patients bypass to high-resolution multidetector contrast-enhanced computed tomography (MDCT). Key: Orange boxes denote urgent actions or stabilization pathways; blue elements show diagnostic workup steps; green boxes represent management disposition nodes.

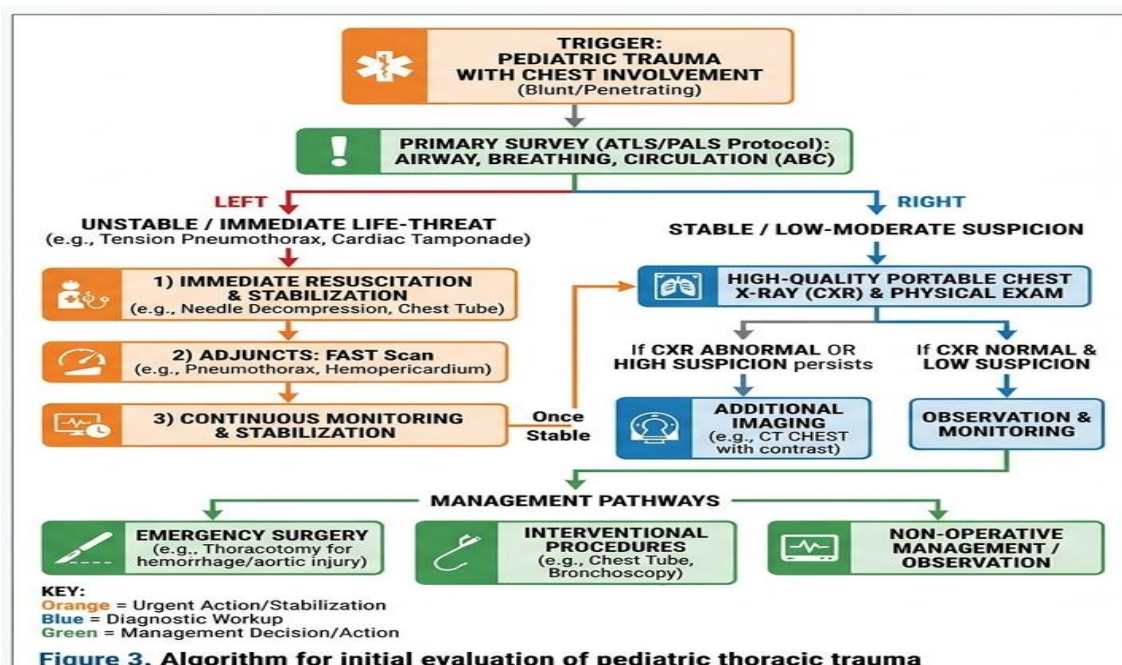


Figure 4. Imaging pathway for respiratory trauma. Comparative timeline tracking diagnostic pathways across stable and unstable configurations. Unstable trajectories prioritize rapid, bedside portable chest radiographs (CXR) to immediately confirm life-threatening conditions like a massive hemothorax or tension pneumothorax. Stable configurations leverage structural examination combined with physical indicators to guide the selective use of multidetector computed tomography (MDCT), mitigating radiation exposure risks while tracking deep parenchymal lesions such as pulmonary contusions and aortic disruptions.

Figure 4. Imaging pathway for respiratory trauma

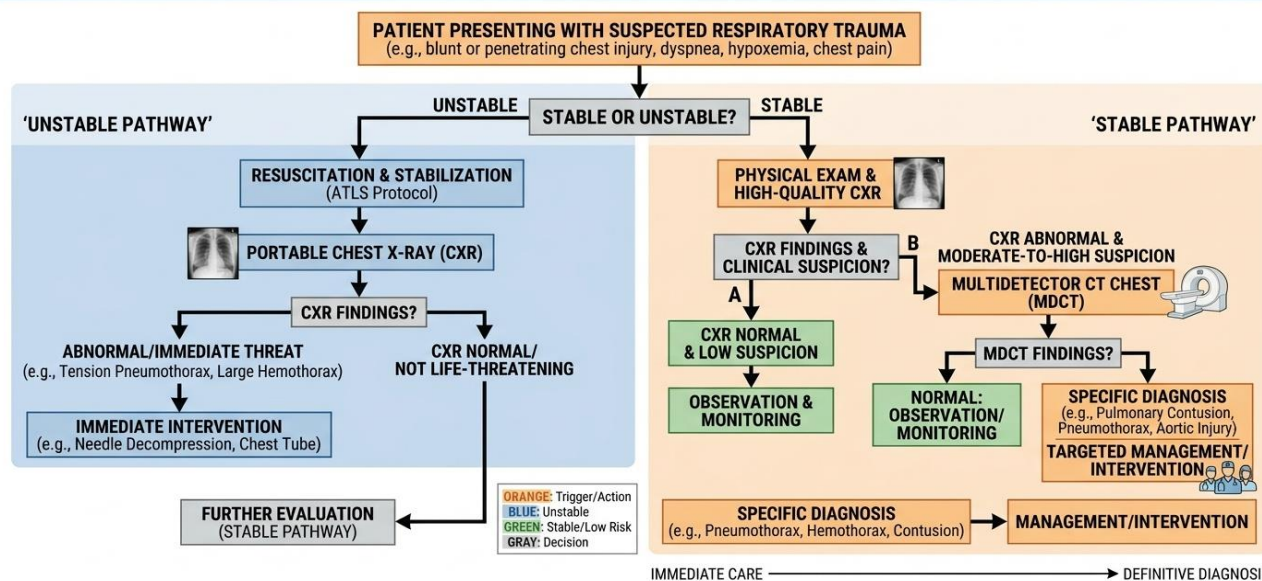


Figure 5. Management strategy for pulmonary contusion and air-leak syndromes. Clinical roadmap outlining conservative non-operative protocols for parenchymal trauma. For pulmonary contusions,

management scales from non-sedating multi-modal analgesia and chest physiotherapy in mild cases to lung-protective mechanical support in severe hypoxemia. For air-leak syndromes (pneumothorax/pneumomediastinum), the pathway differentiates asymptomatic observation facilitated by an oxygen flush from invasive intercostal tube thoracostomy triggered by progressive volumetric extension or cardiorespiratory compromise.

Figure 5. Management strategy for pulmonary contusion and air-leak syndromes

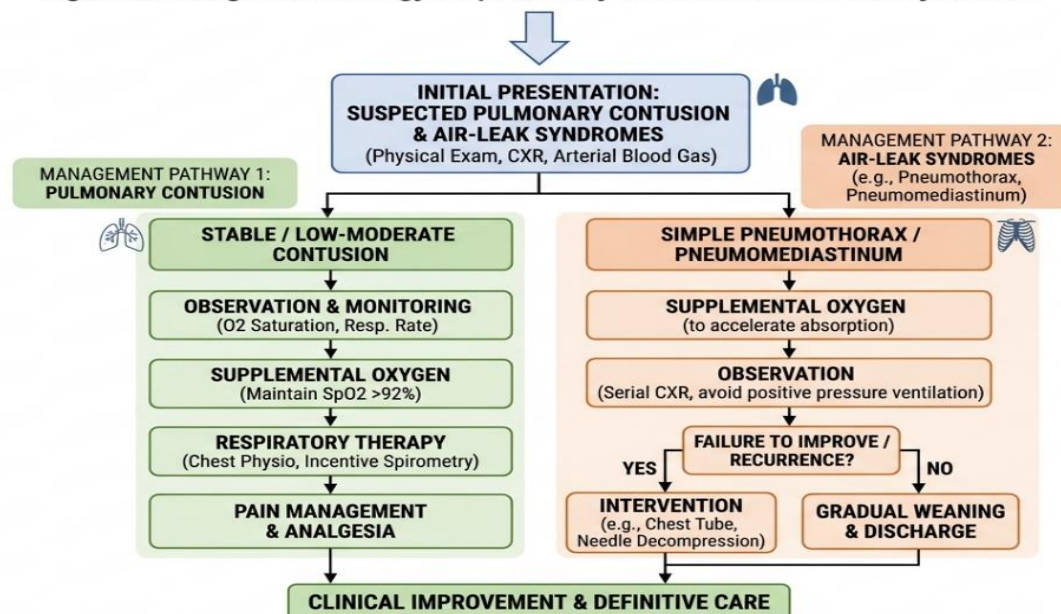


Figure 6. Physical mechanisms and blast overpressure mechanics causing blast lung injury. Pathophysiological cascade detailing the thoracic impact of high-velocity explosion shock waves. The image isolates the classic primary blast injury (BLI) physical triad: the spalling effect (wave reflections at dense tissue borders), inertial differentials (differential acceleration rates between dense fluids and gas channels), and the implosion effect (violent compression and expansion of micro-gas pockets). These vectors cause diffuse alveolar hemorrhage, widespread membrane tearing, localized vascular surge, and systemic gas emboli. Key: Blue arrows map primary mechanical kinetic forces; green arrows show secondary cellular inflammatory loops; red arrows trace macro-vascular events.

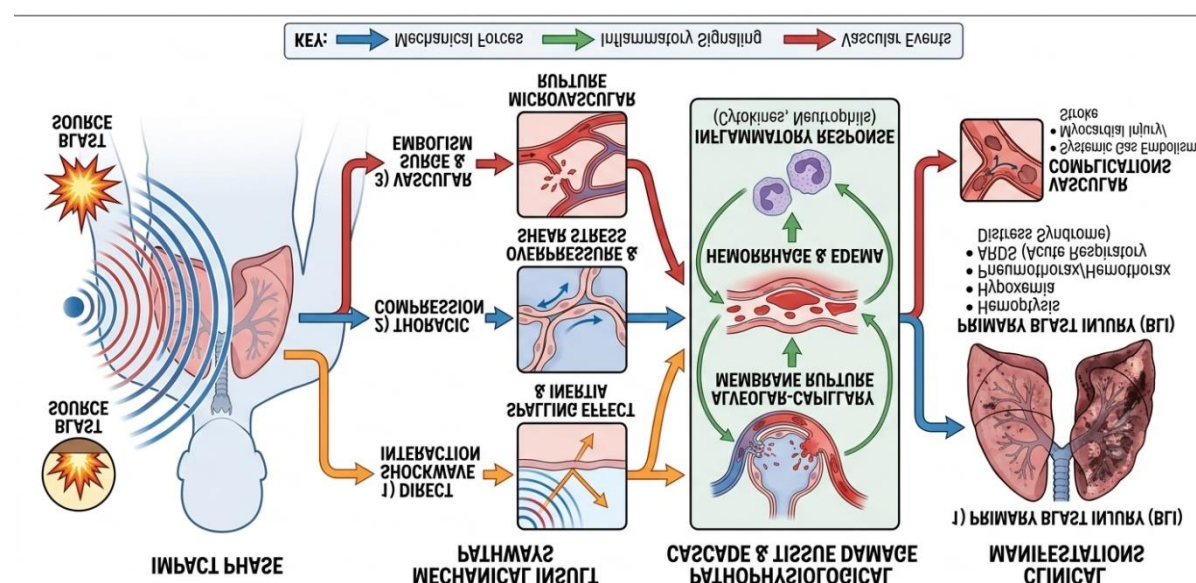


Figure 6. Blast lung injury mechanisms

Figure 7. Long-term integrated outcome framework for pediatric trauma survivors. Multidisciplinary tracking template mapping chronic, multi-system sequelae over a 5-year longitudinal horizon. Post-traumatic

recovery is divided into three distinct chronological segments (Acute, Intermediate, and Long-Term) across four core domains: Pulmonary (restrictive defects and chronic lung disease), Neurodevelopmental (hypoxemic cognitive delays and motor milestone tracking), Psychological/Psychosocial (pediatric medical traumatic stress and family anxiety), and Functional/Physical (exercise limitation, structural skeletal deformities, and chronic pain). *Key: Solid lines denote direct structural impacts; dashed lines outline inter-domain influences; color gradients track temporal disease progression.*

Figure 7. Long-term outcome framework

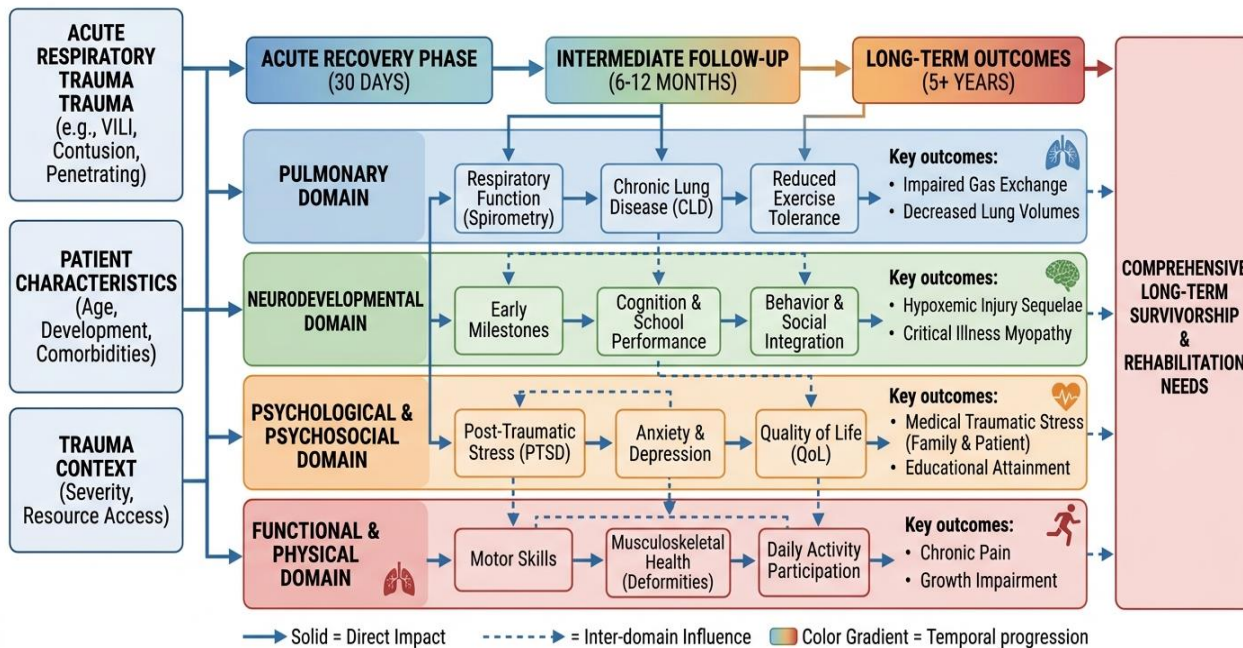


Figure 7. Long-term outcome framework

Tables

Table 1. Classification of Pediatric Pulmonary and Respiratory Trauma

Table Legend: Classification of pediatric pulmonary and respiratory trauma according to mechanism and predominant injury pattern.

Category	Common Mechanisms	Typical Injuries
Blunt trauma	Motor vehicle collisions, falls, sports injuries	Pulmonary contusion, pneumothorax, hemothorax
Penetrating trauma	Gunshot wounds, stab wounds, impalement	Lung laceration, vascular injury
Ventilator-associated trauma	Mechanical ventilation	Barotrauma, volutrauma, air-leak syndromes
Birth trauma	Difficult or instrumental delivery	Pneumothorax, pulmonary hemorrhage
Child abuse-related trauma	Chest compression, shaking, suffocation	Rib fractures, contusion, traumatic asphyxia
Blast trauma	Explosions, terrorist attacks, warfare	Blast lung injury, air embolism
Air-crash trauma	Aviation accidents	Polytrauma, pulmonary contusion
Iatrogenic trauma	Intubation, central lines, bronchoscopy	Pneumothorax, airway injury

Table 2. Common Pulmonary Injuries According to Mechanism

Mechanism	Common Injuries
Blunt trauma	Pulmonary contusion, pneumothorax, hemothorax
Penetrating trauma	Lung laceration, vascular injury
Mechanical ventilation	Pulmonary interstitial emphysema, pneumothorax
Blast injury	Diffuse alveolar hemorrhage, contusion
Child abuse	Rib fractures, pulmonary contusions
Iatrogenic trauma	Tracheal injury, tension pneumothorax

Table 3. Imaging Modalities in Pediatric Respiratory Trauma

Modality	Advantages	Limitations
Chest radiograph	Rapid, accessible	Low sensitivity
Ultrasound	No radiation	Operator dependent
CT	Highest diagnostic accuracy	Radiation exposure
CT angiography	Vascular assessment	Contrast requirement
MRI	No radiation	Limited emergency use
Bronchoscopy	Direct airway visualization	Invasive

Table 4. Developmental Factors Influencing Pediatric Pulmonary Trauma

Anatomical Characteristic	Clinical Consequence
Compliant rib cage	Severe intrathoracic injury without rib fractures
Narrow airways	Rapid airway obstruction
Small functional residual capacity	Early hypoxemia
High oxygen consumption	Rapid respiratory decompensation
Thin mediastinal tissues	Greater susceptibility to pressure effects
Developing lungs	Potential long-term growth impairment

Table 5. Mechanisms of Pediatric Lung Injury

Mechanism	Pathology	Typical Findings
Compression	Pulmonary contusion	Hypoxia, infiltrates
Deceleration	Pulmonary laceration	Air leak, hemoptysis
Positive-pressure ventilation	VILI	Pneumothorax, interstitial emphysema
Blast overpressure	Blast lung injury	Diffuse hemorrhage
Penetrating trauma	Parenchymal disruption	Hemothorax, air leak
Child abuse	Compression injury	Rib fractures, contusion

Table 6. Contemporary Management of Common Pulmonary Trauma

Injury	First Line Management	Intervention
Pulmonary contusion	Oxygen, analgesia	Rarely surgery
Pneumothorax	Observation or drain	Thoracostomy
Hemothorax	Drainage	VATS/thoracotomy
Tracheobronchial injury	Airway stabilization	Surgical repair
VILI	Lung-protective ventilation	ECMO if severe
Blast lung injury	Supportive care	ECMO in selected cases

Table 7. Forms of Ventilator-Induced Lung Injury

Mechanism	Pathophysiology	Common Clinical Manifestations
Barotrauma	Excessive airway pressure	Pneumothorax, pneumomediastinum
Volutrauma	Alveolar overdistension	Reduced compliance, hypoxemia
Atelectrauma	Repetitive alveolar collapse	Progressive respiratory failure
Biotrauma	Cytokine-mediated inflammation	Systemic inflammatory response
Oxygen toxicity	Reactive oxygen species injury	Diffuse lung damage

Table Legend: Major mechanisms responsible for ventilator-induced lung injury in neonates and children requiring respiratory support.

Table 8. Major Neonatal and Birth-Related Respiratory Injuries

Injury	Risk Factors	Clinical Features	Management
Pneumothorax	Positive-pressure ventilation, prematurity, difficult delivery	Respiratory distress, cyanosis	Observation, aspiration, chest drain
Pulmonary hemorrhage	Prematurity, respiratory distress syndrome	Bloody secretions, hypoxemia	Ventilatory support, stabilization
Pulmonary interstitial emphysema	Mechanical ventilation	Persistent oxygen requirement	Lung-protective ventilation
Pneumomediastinum	Birth trauma, resuscitation	Respiratory distress, mediastinal air	Usually conservative
Pneumopericardium	Severe barotrauma	Cardiovascular compromise	Pericardial drainage if tamponade occurs
Diaphragmatic injury	Difficult extraction, severe birth trauma	Respiratory compromise	Surgical repair when indicated

Table Legend: Common neonatal and birth-related pulmonary injuries, associated risk factors, presentation, and current management strategies.

Table 9. Major Blunt Pulmonary Injuries in Children

Table Legend: Common forms of blunt pulmonary trauma in children, including pathophysiology, clinical presentation, and contemporary management strategies.

Injury	Pathophysiology	Clinical Features	Primary Management
Pulmonary Contusion	Alveolar hemorrhage, interstitial edema, and ventilation–perfusion mismatch following blunt chest trauma	Hypoxemia, tachypnea, respiratory distress, chest pain, increasing oxygen requirement	Supportive care, analgesia, supplemental oxygen, respiratory physiotherapy, non-invasive or mechanical ventilation when required
Pneumothorax	Accumulation of air within the pleural cavity due to pulmonary or airway injury	Reduced breath sounds, chest pain, respiratory distress, hypoxia, tachycardia	Observation for small stable pneumothoraces; tube thoracostomy for symptomatic or enlarging lesions
Hemothorax	Accumulation of blood within the pleural space secondary to intercostal, pulmonary, or vascular injury	Respiratory distress, diminished breath sounds, hypovolemia, tachycardia, shock in severe cases	Tube thoracostomy, fluid resuscitation, blood transfusion, surgical exploration when bleeding persists
Pulmonary Laceration	Disruption of lung parenchyma resulting in formation of air- or blood-filled cavities	Hemoptysis, persistent pneumothorax, air leak, respiratory distress	Observation and supportive care in most cases; operative intervention for ongoing bleeding or major parenchymal disruption
Tracheobronchial Disruption	Partial or complete injury to the trachea or major bronchi following severe blunt trauma	Persistent air leak, pneumomediastinum, surgical emphysema, respiratory compromise, failure of lung re-expansion	Early bronchoscopic assessment, airway stabilization, and definitive surgical repair
Pneumomediastinum	Leakage of air into the mediastinum caused by alveolar rupture or airway injury	Chest pain, neck swelling, subcutaneous emphysema, Hamman sign	Observation, oxygen therapy, investigation for associated airway or oesophageal injury
Flail Chest (<i>rare in children</i>)	Multiple consecutive rib fractures causing paradoxical chest wall movement	Respiratory distress, paradoxical respiration, significant pain	Analgesia, respiratory support, aggressive pulmonary care, occasional surgical stabilization
Pulmonary Herniation	Protrusion of lung tissue through a defect in the thoracic wall following severe trauma	Localized chest wall bulge, pain, respiratory symptoms	Observation in minor cases; surgical repair when symptomatic or enlarging

Key Point: Pulmonary contusion is the most common clinically significant blunt thoracic injury in children. Most blunt pulmonary injuries can be managed non-operatively with meticulous respiratory support, while major airway injuries and persistent haemorrhage typically require surgical intervention.

Table 10. Common Penetrating Thoracic Injuries and Management

Injury	Clinical Features	Initial Management	Definitive Treatment
Pneumothorax	Dyspnea, reduced breath sounds	Oxygen, chest drainage	Observation or surgery
Hemothorax	Respiratory compromise, hypovolemia	Tube thoracostomy	VATS or thoracotomy
Pulmonary laceration	Hemoptysis, air leak	Stabilization	Selective surgical repair
Tracheobronchial injury	Persistent air leak, pneumomediastinum	Airway stabilization	Surgical reconstruction
Cardiac injury	Shock, tamponade	Emergency resuscitation	Surgical repair
Great vessel injury	Massive hemorrhage	Damage-control resuscitation	Emergency surgery

Table Legend: Major penetrating thoracic injuries in children and their contemporary management.

Table 11. Classification of Blast-Related Thoracic Injuries

Blast Injury Type	Mechanism	Common Thoracic Manifestations
Primary	Blast overpressure wave	Pulmonary contusion, alveolar hemorrhage, pneumothorax, air embolism
Secondary	Projectiles and debris	Pulmonary laceration, hemothorax, penetrating injury
Tertiary	Body displacement by blast wind	Pulmonary contusion, rib fractures, airway injury
Quaternary	Burns, inhalation injury, toxic exposure	Airway burns, smoke inhalation, respiratory failure

Table Legend: Classification of thoracic injuries following explosive events according to the predominant mechanism of injury.

Table 12. Imaging Modalities in Pediatric Pulmonary Trauma

Imaging Modality	Major Advantages	Limitations	Typical Indications
Chest radiography	Rapid, inexpensive, readily available	May underestimate injury severity	Initial assessment
Point-of-care ultrasound	No radiation, bedside application	Operator dependent	Pneumothorax, hemothorax
CT	Highest diagnostic accuracy	Radiation exposure	Significant thoracic trauma
CT angiography	Excellent vascular assessment	Requires contrast	Suspected vascular injury
MRI	No ionizing radiation	Longer acquisition times	Follow-up imaging
Bronchoscopy*	Direct airway visualization	Invasive	Airway injury assessment

*Bronchoscopy is included as an imaging adjunct because of its critical role in tracheobronchial injury evaluation.

Table Legend: Contemporary imaging modalities used in pediatric pulmonary and respiratory trauma and their principal clinical applications. turn224search37

Table 13. Major Causes of Iatrogenic Respiratory Trauma

Procedure	Common Complications	Management
Mechanical ventilation	Pneumothorax, VILI, pulmonary interstitial emphysema	Lung-protective ventilation, chest drainage
Central venous catheterization	Pneumothorax, hemothorax, vascular injury	Observation, drainage, vascular repair
Bronchoscopy	Airway perforation, bleeding, hypoxemia	Supportive care, airway management
Thoracostomy tube insertion	Pulmonary laceration, organ injury, malposition	Repositioning or surgical correction
ECMO cannulation	Hemorrhage, pleural complications, vascular injury	Multidisciplinary critical care management

Table Legend: Common causes of iatrogenic respiratory trauma in infants and children, associated complications, and contemporary management approaches.

Table 14. Long-Term Sequelae of Pediatric Pulmonary and Respiratory Trauma

Domain	Potential Long-Term Effects	Recommended Follow-Up
Pulmonary	Reduced lung function, exercise limitation, chronic respiratory symptoms	Pulmonary function testing, respiratory review
Neurodevelopmental	Cognitive delay, learning difficulties, developmental impairment	Developmental assessment
Psychological	Anxiety, PTSD, depression, behavioral changes	Psychological evaluation
Functional	Reduced activity levels, exercise intolerance	Rehabilitation assessment
Quality of Life	School and social participation difficulties	Longitudinal follow-up

Table Legend: Major long-term outcomes following pediatric pulmonary and respiratory trauma and suggested surveillance strategies.

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