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COORDINATOR Prof. Katia Varani

Emergency Physician-Performed Fascial Plane Blocks for Multiple Rib Fractures: A Multicentre Prospective Comparison of Analgesic Trajectories and Clinical Outcomes between ESP and SAP Fascial Blocks

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Candidate

Dott. Spampinato Michele Domenico

Supervisor

Prof. De Giorgio Roberto

Co-Supervisor

Prof. Passaro Angelina

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Abstract

Research Subject

Rib fractures are a frequent cause of Emergency Department (ED) visits, associated with high morbidity and mortality, particularly in the elderly, due to pain-induced respiratory impairment. Effective analgesia is pivotal for preventing complications. While fascial plane blocks offer a targeted, opioid-sparing alternative to systemic analgesia, their utilisation remains suboptimal (<3% of trauma patients). Recently, the Erector Spinae Plane (ESP) block has emerged as a promising technique, theoretically providing broader coverage of the dorsal and ventral rami compared to the Serratus Anterior Plane (SAP) block. However, comparative data in the acute setting remain conflicting regarding clinical superiority. Therefore, the primary objective of this study is to compare the analgesic efficacy and safety of ESP and SAP blocks in patients with multiple rib fractures admitted to the ED. Secondary objectives include the assessment of adverse events and primary clinical outcomes (pneumonia, ICU admission, mortality).

Methodologies Used

This is a prospective, multicentre observational study conducted at two academic Emergency Departments in Italy between November 2023 and October 2025. We enrolled adult patients with unilateral blunt chest trauma (≥2 rib fractures) presenting with severe pain (NRS ≥6), hemodynamic stability, and no need for immediate intubation. Patients received either an ESP block or a SAP block (Deep or Superficial approach) based on fracture location and operator proficiency. Pain intensity (Numeric Rating Scale, NRS 0–10) was assessed at baseline, 15, 30, 60 minutes, and 6, 12, 24 hours post-procedure. Clinical outcomes included pneumonia incidence, therapeutic interventions (NIV, respiratory physiotherapy), and in-hospital mortality.

Results Achieved

A total of 145 patients were included (median age 62 years; IQR 52–75), characterised by moderate trauma severity (median ISS 9; TTSS 8) and a median of 3 rib fractures. The

distribution of blocks was: Deep SAP (n=106, 73.1%), ESP (n=31, 21.4%), and Superficial SAP (n=8, 5.5%). Analgesic trajectories revealed a distinct temporal crossover between techniques: Hyper-Acute Phase (0–60 min): The Superficial SAP block demonstrated superior early efficacy, achieving significantly lower static NRS scores at 15, 30, and 60 minutes compared to ESP and Deep SAP ($p < 0.05$). Subacute Phase (6–12 hours): A significant divergence emerged, with the Superficial SAP group exhibiting a marked "rebound" in pain intensity at 6 and 12 hours ($p < 0.05$ vs. ESP), particularly during deep inspiration. Conversely, the ESP block demonstrated the most stable analgesic profile over 24 hours. Therapeutic Burden: Patients in the Superficial SAP group required significantly more respiratory physiotherapy (57.1%) and bronchial hygiene than those in the Deep SAP and ESP groups ($p=0.004$). No significant differences were found between groups regarding the incidence of pneumonia or in-hospital mortality. Pneumonia development was associated with fracture morphology (posterior flail segments) rather than the type of block or analgesic quality. No procedure-related complications were recorded.

Impact and Conclusions

This study confirms that while all fascial blocks are safe and effective for immediate rescue analgesia in the ED, they are not clinically equivalent over time. The ESP and Deep SAP blocks provide sustained coverage suitable for ward admission, whereas the Superficial SAP block is prone to early washout (rebound pain) and correlates with a higher burden of supportive care. Consequently, we propose a paradigm shift towards a lesion-centric protocol: prioritising Deep SAP for lateral injuries and ESP for posterior fractures, while reserving the superficial approach for short-term procedural use.

Keywords: *Rib Fractures; Thoracic Injuries; Emergency Medicine; Nerve Block; Ultrasonography, Interventional; Pain Management; Fascial plane blocks; Pneumonia; Erector Spinae Plane Block; Serratus Anterior Plane Block.*

Chapter 1: Chest Anatomy and Physiology: Implications for Trauma and Regional Anesthesia

The thorax constitutes the superior segment of the trunk, comprising the rib cage, the chest wall musculature, and the internal cavity housing vital cardiopulmonary structures. Understanding the intricate relationship between the skeletal framework, the muscular layers, and the neurovascular distribution is fundamental for both the management of thoracic trauma and the safe execution of ultrasound-guided fascial plane blocks (*Gray's Anatomy*, 2020; K. L. Moore et al., 2017).

1.1. The Thoracic Cage and Skeletal Landmarks

The thoracic skeleton forms an irregular cylinder consisting of twelve thoracic vertebrae, the sternum, and twelve pairs of ribs. This semi-rigid osseous cage provides mechanical protection for visceral organs and serves as the anchor for the negative-pressure mechanics required for respiration. The ribs are the primary osseous landmarks for the Serratus Anterior Plane (SAP) block (Blanco et al., 2013; Mayes et al., 2016). The first seven pairs (true ribs) articulate directly with the sternum; ribs eight through ten (false ribs) attach via the costal cartilage of the seventh rib; and the eleventh and twelfth (floating ribs) end freely in the abdominal musculature. The rib provides a definitive sonographic "backstop" during deep blocks, protecting the underlying pleura from needle perforation. Conversely, the first rib's proximity to the subclavian vessels and brachial plexus makes the superior thoracic aperture a high-risk zone for neurovascular trauma (K. L. Moore et al., 2017). The thoracic vertebrae are characterized by their transverse processes, which articulate with the rib tubercles. The tip of the transverse process serves as the critical sonographic landing point for the Erector Spinae Plane (ESP) block, acting as a safety barrier to prevent neuraxial needle entry (Forero et al., 2016).

1.2. Intercostal Spaces and Neurovascular Anatomy

The intercostal spaces are bridged by three distinct muscular layers, the stratification of which is critical for understanding block depth and safety:

- External Intercostal Muscles: The most superficial layer, involved in inspiration.
- Internal Intercostal Muscles: The intermediate layer.
- Innermost Intercostal Muscles: The deepest layer, separated from the lung by the endothoracic fascia and parietal pleura.

The Neurovascular Bundle (VAN) The intercostal neurovascular bundle runs in the subcostal groove along the inferior margin of the rib, situated specifically in the plane between the internal and innermost intercostal muscles. The structures follow a strict cranio-caudal order (Mnemonic: VAN): Vein (Superior), Artery, and Nerve (Inferior) (*Gray's Anatomy*, 2020; K. L. Moore et al., 2017). Because the intercostal nerve is the most inferior structure, it is the least protected by the costal groove, making it highly vulnerable to traumatic injury.

1.3. Musculature: Targets for Fascial Blocks

The muscles of the chest wall are categorized into intrinsic (acting on the ribs) and extrinsic (connecting the thorax to the limbs or spine). For this thesis, three muscle groups are of paramount importance as they define the injection planes for the studied blocks:

The Lateral Wall (SAP Block Targets)

- Serratus Anterior Muscle (SAM): A broad muscle originating from the first eight ribs and inserting into the scapula. It serves as the primary landmark for the SAP block.
- Latissimus Dorsi Muscle (LDM): A large superficial muscle covering the lower back and lateral thorax, overlying the serratus anterior.

The Posterior Wall (ESP Block Target)

- Erector Spinae Muscles: A complex of muscles running longitudinally along the vertebral column.

While the Superficial SAP block targets the inter-fascial plane between the Latissimus Dorsi and the Serratus Anterior (Blanco et al., 2013), the Deep SAP block targets the plane beneath the Serratus Anterior, directly overlying the rib periosteum (Piracha et al., 2017). The ESP block deposits local anaesthetic deep to the erector spinae muscle, lifting it off the transverse processes and creating a conduit for the anaesthetic to diffuse anteriorly into the paravertebral space, reaching both the dorsal and ventral rami of the spinal nerves (Forero et al., 2016).

1.3.1. Accessory Respiratory Muscles

Other extrinsic muscles, including the pectoralis major/minor, scalenes, and sternocleidomastoid, function as accessory muscles of respiration. In trauma patients, these muscles are recruited during forced breathing to compensate for compromised mechanics, often exacerbating pain from rib fractures.

1.4. Innervation: The Basis of Regional Anaesthesia

The sensory innervation of the chest wall is derived from the thoracic spinal nerves (T1–T12), which divide into two primary branches upon exiting the intervertebral foramen:

- Ventral Rami (Intercostal Nerves): These travel laterally in the intercostal spaces (VAN bundle) to innervate the lateral and anterior chest wall. They give rise to the Lateral Cutaneous Branches (mid-axillary line) and Anterior Cutaneous Branches (parasternal).
- Dorsal Rami: These pass posteriorly to innervate the paraspinal muscles and the skin of the back.

While the SAP block primarily targets the lateral cutaneous branches of the intercostal nerves (Blanco et al., 2013; Mayes et al., 2016), the ESP block is unique in its ability to block the dorsal rami (posterior analgesia) while also allowing diffusion to the ventral rami (anterior/lateral analgesia) via the costotransverse foramina (Forero et al., 2016).

1.5. Physiology of the Thoracic Cavity and Trauma Mechanisms

The thoracic cavity is demarcated inferiorly by the diaphragm, the primary muscle of respiration. In trauma, pain from rib fractures causes reflex inhibition of the diaphragm and splinting of the chest wall muscles, leading to reduced tidal volume (Vt) and inability to clear secretions (ineffective cough) (*ATLS ® Student Course Manual, 10th Edition*, s.d.).

The lungs are enveloped by the visceral and parietal pleura, separated by a potential space. Blunt chest trauma frequently disrupts this integrity, leading to:

- Pneumothorax: Accumulation of air, collapsing the lung.
- haemothorax: Accumulation of blood from ruptured intercostal or pulmonary vessels.
- Mediastinal Injury: While the mediastinum contains vital structures (heart, aorta, trachea), the primary relevance for chest wall blocks is safety; ensuring the needle tip remains superficial to the parietal pleura is the cardinal rule of all chest wall procedures to prevent iatrogenic pneumothorax.

1.6 Vascular Supply and Haemorrhagic Risk

The chest wall is richly vascularized by the internal thoracic (mammary) arteries and the intercostal arteries, which run along the inferior border of the ribs. While this vascularity facilitates the rapid absorption of local anaesthetics (posing a risk for Systemic Toxicity - LAST), it represents a critical hazard in trauma. The laceration of these high-pressure systemic vessels is the leading cause of life-threatening haemorrhage in blunt chest injury. Rupture of an intercostal or internal thoracic artery can result in active bleeding exceeding 200 mL/hour, rapidly leading to massive haemothorax and / or hypovolemic shock (*ATLS ® Student Course Manual, 10th Edition*, s.d.))

Chapter 2 Chest trauma.

2.1. Epidemiology, Biomechanics, and Pathophysiology of Chest Trauma

2.1.1. Epidemiology

Trauma remains a leading cause of global morbidity and mortality, ranking as the primary cause of death for individuals aged 1–44 years in the United States and accounting for approximately 10% of all deaths worldwide (*FastStats*, 2025; *FastStats*, 2025; *Global Status Report on Road Safety 2018*, s.d.; Rhee et al., 2014). Thoracic injuries play a pivotal role in this burden, being directly responsible for 20–25% of trauma fatalities and contributing to mortality in another 25% of polytrauma cases (LoCicero & Mattox, 1989). Rib fractures are the most prevalent thoracic injury, identified in up to 40% of cases, and serve as a critical prognostic marker (Sirmali et al., 2003). This correlation is particularly evident in the elderly population, where mortality rates increase linearly with the number of fractured ribs (Flagel et al., 2005). Despite the high rate of non-operative management (>90%), mortality for chest trauma remains substantial (4–20%), primarily driven by respiratory complications such as pneumonia and ARDS (Battle et al., 2012).

2.1.2. Biomechanics of Trauma

Biomechanics provides the framework for anticipating injury patterns based on the mechanism of energy transfer. By analyzing the vector and magnitude of force, clinicians can predict specific visceral damage with high accuracy. The pathophysiology of blunt chest trauma is governed by two primary Newtonian principles:

- Kinetic Energy Dissipation: Defined by the equation KE = 1/2mv^2. Because velocity (v) is squared, high-speed impacts result in an exponential increase in energy transfer, causing extensive structural destruction beyond the immediate point of impact.
- Inertia and Deceleration: Upon impact, while the thoracic cage abruptly halts, internal organs retain their forward momentum. This disparity generates significant shearing forces at anatomical fixation points (e.g., the ligamentum arteriosum), predisposing patients to catastrophic deceleration injuries such as

traumatic aortic transection or tracheobronchial disruption (*ATLS ® Student Course Manual, 10th Edition*, s.d.).

2.1.2.1 Classification by Mechanism

Thoracic trauma is broadly classified into two categories based on the mechanism of injury: blunt and penetrating.

1) Blunt Thoracic Trauma:

Blunt trauma accounts for the vast majority of chest injuries (approx. 90-95%) in civilian populations, primarily due to motor vehicle collisions and falls (*Rosen's Emergency Medicine*, 2017). The injury mechanisms include:

- Direct Compression: The chest is crushed between two objects. This can cause rib fractures and "paper bag" ruptures of the lungs if the glottis is closed during impact.
- Deceleration/Acceleration: Sudden stops cause organs to collide with the chest wall or tear from their vascular pedicles.
- Blast Injury: A complex mechanism involving a pressure wave that can cause alveolar rupture and air embolism.

2) Penetrating Thoracic Trauma

Penetrating injuries are classified by the energy level of the projectile:

- Low-energy: (e.g., stab wounds). Damage is confined to the direct path of the blade.
- High-energy: (e.g., gunshot wounds). Damage extends beyond the track of the bullet due to the phenomenon of cavitation. The kinetic energy creates a temporary cavity that expands and collapses, damaging surrounding tissues and microvasculature not directly touched by the projectile (Stefanopoulos et al., 2014).

2.1.3 Pathophysiology: The Vicious Cycle of Chest Trauma

The physiological derangement in chest trauma is classically described by the triad of hypoxia, hypercapnia, and acidosis. However, the central driver of this deterioration, particularly in patients with chest wall injuries, is pain (Karmakar & Ho, 2003).

2.1.3.1 . The Role of Pain and Respiratory Mechanics

Pain from rib fractures or soft tissue injury triggers a reflex inhibition of respiratory movement, known as respiratory splinting.This initiates a "vicious cycle":

- Hypoventilation: Pain prevents deep inspiration and effective coughing.
- Retention of Secretions: Inability to clear the bronchial tree leads to mucous plugging.
- Atelectasis: Shallow breathing causes alveolar collapse, reducing functional residual capacity (FRC).
- V/Q Mismatch: Perfusion continues in non-ventilated lung areas (shunt), leading to hypoxemia.
- Infection: Atelectatic and secretion-filled segments are prone to bacterial superinfection, leading to pneumonia (Karmakar & Ho, 2003).

2.1.3.2. Hypoxia

Hypoxia is the most serious early consequence and arises from:

- V/Q Mismatch: Caused by pulmonary contusion (alveolar hemorrhage and edema) and atelectasis.
- Hypovolemia: Massive hemothorax or vascular injury reduces oxygen delivery.
- Altered Intrathoracic Pressure: Tension pneumothorax or open pneumothorax compromises venous return (preload) and ventilatory efficiency.

2.1.3.3. Hypercapnia and Acidosis

Hypercapnia (respiratory acidosis) results from inadequate alveolar ventilation due to pain-induced splinting, flail chest mechanics, or depressed level of consciousness (concomitant Traumatic Brain Injury). Metabolic acidosis is a marker of tissue hypoperfusion (shock).

Initially, patients may compensate through tachypnea (blowing off CO_2). However, as fatigue sets in or if pain is unmanaged, compensation fails. The combination of respiratory and metabolic acidosis leads to a rapid decline in cellular function, coagulopathy, and potentially Multiple Organ Dysfunction Syndrome (MODS) (LoCicero & Mattox, 1989).

2.2 Post-traumatic Chest Injuries: Classification and Pathophysiology

2.2.1 Clinical Classification according to ATLS® Guidelines

According to the 10th edition of the Advanced Trauma Life Support (ATLS®) guidelines, thoracic injuries are categorized based on the immediacy of the threat to life. This classification dictates the diagnostic and therapeutic priority during the trauma assessment (*ATLS ® Student Course Manual, 10th Edition*, s.d.). The first category encompasses immediate life-threatening injuries that must be identified and managed during the Primary Survey (Airway, Breathing, Circulation). The second category includes potentially life-threatening injuries that are typically identified during the Secondary Survey, a detailed head-to-toe evaluation performed once the patient's vital functions have been stabilized.

It is crucial to note that during the chaotic phase of the primary assessment, subtle signs of injury may be masked. Therefore, a high index of suspicion and continuous re-evaluation are mandatory.

The "Deadly Dozen": Thoracic Injuries

1. Immediate Life-Threatening Conditions (Primary Survey)

Airway obstruction (including laryngeal injury)

Tracheobronchial injury

Tension pneumothorax

Open pneumothorax

Massive haemothorax

Cardiac tamponade

Traumatic circulatory arrest (PEA)

2. Potentially Life-Threatening Conditions (Secondary Survey)

Simple pneumothorax

Haemothorax

Pulmonary contusion

Flail chest

Blunt cardiac injury (moderate myocardial contusion)

Traumatic aortic disruption

Traumatic diaphragmatic injury

Blunt esophageal rupture

2.2.2 Post-Traumatic Lung Injury and Pulmonary Contusion

Pulmonary contusion is the most common potentially lethal chest injury and is defined as an injury to the lung parenchyma leading to oedema and blood collection in the alveolar spaces, without a laceration of the lung tissue. In the context of closed chest trauma, the extent of the pulmonary contusion—which can manifest and evolve significantly up to 24–48 hours after the trauma—is a major determinant of outcome. Inadequate pain management in these patients is associated with a significant increase in morbidity and mortality, primarily due to respiratory splinting and ineffective clearance of secretions (Flagel et al., 2005; Sirmali et al., 2003).

Under physiological conditions, respiratory function relies on the synergy between ventilatory mechanics and mucociliary clearance, ensuring effective surfactant turnover. However, in a contused lung, direct injury to the alveolar endothelium leads to a loss of the integrity of the blood-air barrier. This results in increased vascular permeability and the accumulation of interstitial fluid and exudate in the alveolar space (alveolar flooding).

At the molecular level, mechanical tissue injury triggers a potent local inflammatory response. This "sterile inflammation" is mediated by the massive release of pro-inflammatory cytokines, specifically Tumor Necrosis Factor-alpha (TNF-α), Interleukin-1 (IL-1), IL-6, and IL-8 [16,17]. These cytokines promote the chemotaxis and activation of neutrophils in the lung parenchyma. Activated neutrophils release proteolytic enzymes and reactive oxygen species (ROS), which further damage the capillary endothelium and alveolar epithelium. This results in a loss of plasma proteins into the extravascular space, altering the oncotic gradient and drawing in fluids, which worsens the pulmonary oedema. Clinically, this process compromises gas exchange, leading to hypoxaemia, progressive hypercapnia, and reduced pulmonary compliance, ultimately resulting in overt respiratory failure or Acute Respiratory Distress Syndrome (ARDS) (Bastos et al., 2008; Ziegler & Agarwal, 1994).

2.2.3 Rib Fractures: Epidemiology, Diagnosis, and General Management

2.2.3.1 Epidemiology and Impact

Rib fractures are the most common injury in patients with thoracic trauma, occurring in approximately 10% to 15% of all trauma admissions (Ziegler & Agarwal, 1994). The vulnerability of the ribs is due to their superficial anatomical position, with minimal subcutaneous tissue or muscle to protect them from direct impact compared to other skeletal structures. However, the presence of rib fractures is a marker of significant injury severity. Numerous studies have demonstrated a linear correlation between the number of fractured ribs and increased morbidity and mortality (Flagel et al., 2005; Sirmali et al., 2003), and this correlation is particularly stark in the geriatric population: studies indicate that in patients over 65 years of age, each additional rib fracture increases the risk of pneumonia by 27% and mortality by 19% (Bulger et al., 2000). The primary driver of this morbidity is the resulting respiratory failure: this is rarely due to the fracture itself, but rather to a combination of underlying pulmonary contusion and, crucially, severe pain. Pain exacerbated by movement leads to "respiratory splinting"—a reflex limitation of chest wall excursion. This compromises tidal volume, inhibits effective coughing, and prevents the clearance of secretions, creating an ideal environment for the development of atelectasis and subsequent pneumonia (Karmakar & Ho, 2003).

2.2.3.2 Anatomical Patterns and Associated Injuries

The anatomical level of the fracture provides the clinician with vital clues regarding potential associated visceral injuries:

- First to Third Ribs (Upper Zone): These ribs are shielded by the clavicle, scapula, humerus, and heavy musculature. Fractures here imply the transfer of high kinetic energy and raise a high suspicion for severe associated injuries to the aorta, brachial plexus, or tracheobronchial tree. Mortality in these cases can reach 35%, largely due to these concomitant vascular or neurological injuries rather than the fractures themselves (Richardson et al., 1975).
- Fourth to Ninth Ribs (Middle Zone): This is the most susceptible region in blunt trauma. Injuries here are generated by two main mechanisms:

- Anteroposterior compression: Causes the rib to bow outwards, typically resulting in fractures at the mid-axillary line.

- Direct impact: May drive bone fragments inwards, significantly increasing the risk of pneumothorax, haemothorax, or lung laceration.

- Tenth to Twelfth Ribs (Lower Zone): Fractures of the floating ribs are less common but are markers for abdominal solid organ injury. Right-sided fractures are associated with hepatic injury, while left-sided fractures are strongly correlated with splenic rupture (Shweiki et al., 2001).

2.2.3.3 Diagnosis: From Clinical Suspicion to Imaging

The diagnosis is often suspected clinically. The pathognomonic sign is localized pain that worsens with deep inspiration or coughing (pleuritic pain). Physical examination may reveal point tenderness, ecchymosis, bony crepitus, and muscle spasm. Usually, compression of the sternum or the rib cage away from the injury site may elicits pain at the fracture point (indirect tenderness).

Regarding imaging, while the chest X-ray (CXR) remains the primary screening tool in the trauma bay, it has significant limitations, missing up to 50% of rib fractures, particularly those involving the anterior cartilage (costochondral separation) (Livingston et al., 2008). Currently, Computed Tomography (CT) is the gold standard for defining the extent of chest wall injury and excluding intrathoracic complications. However, in the context of modern emergency medicine, thoracic ultrasound has gained prominence: it is more sensitive than CXR for detecting radiolucent fractures and allows for the simultaneous assessment of the pleura (to rule out pneumothorax) and the identification of the optimal fascial plane for nerve blocks (Griffith et al., 1999; Jin et al., 2006).

2.2.3.4 Complications

2.2.3.4.1 Pulmonary Morbidity: The Pathogenesis of Post-Traumatic Pneumonia

Pain is not merely a symptom of rib fractures; it is the fundamental driver of pulmonary morbidity and a decisive predictor of mortality. While the initial trauma causes direct injury to the chest wall and lung parenchyma, the subsequent acute pain initiates a deleterious physiological cascade known as respiratory splinting. This reflex inhibition of chest wall excursion prevents effective alveolar ventilation, reducing the Functional Residual Capacity (FRC) towards the closing capacity of the airways. This mechanical restriction serves as the primary catalyst for the development of atelectasis, which acts as a precursor to secondary respiratory infections and, in severe cases, contributes to the onset of Acute Respiratory Distress Syndrome (ARDS) (Brasel et al., 2006; Karmakar & Ho, 2003; Livingston et al., 2008).

2.2.3.4.2 The Vicious Cycle of Pain and Secretion Retention

Analysing the pathophysiology of rib fracture pain specifically, the severity correlates with the number of fractures, the location of the traumatic insult (anterior vs. posterior), and the type of fracture (e.g., flail segments). Consequently, the patient adopts a protective respiratory pattern characterized by two distinct pathological alterations:

- Reduced Chest Expansion (Hypoventilation): The respiratory pattern becomes rapid and shallow (tachypnea with reduced tidal volume). This prevents the re-expansion of alveoli, promoting absorption atelectasis. This is particularly dangerous in lung zones already compromised by underlying pulmonary contusion, creating large areas of non-ventilated parenchyma.
- Inhibition of the Cough Reflex: Effective coughing requires a deep inspiration followed by a forceful expiration against a closed glottis. Rib fractures make the initial deep inspiration and the subsequent intrathoracic pressure spike excruciatingly painful. The resulting inability to cough leads to the failure of mucociliary clearance and the retention of bronchial secretions. These stagnant secretions, combined with atelectasis, create an ideal culture medium for bacterial proliferation. This leads to pneumonia, which is the single strongest risk factor for late mortality in chest trauma, particularly in elderly patients or those with pre-existing cardiopulmonary comorbidities such as COPD (Brasel et al., 2006; Bulger et al., 2000).

2.2.3.4.3 Epidemiological Correlation and Mortality

The risk of developing a lung infection and experiencing unfavourable outcomes follows a linear dose-response relationship with both the number of fractured ribs and the patient's age (Battle et al., 2012).

- Age Factor: In individuals under 65 years of age, the incidence of pneumonia varies between 6% and 17%. However, in the geriatric population (age > 65), this incidence doubles, reaching up to 34% despite standard care (Bergeron et al., 2003).
- Fracture Burden: As demonstrated by Flagel et al., for each additional rib fracture, the risk of pneumonia increases by 27% and the risk of mortality by 19% (Flagel et al., 2005).

2.2.3.4.4 Ventilation/Perfusion Mismatch and Hypoxia

Beyond the mechanical restriction, the injured lung parenchyma suffers from intrinsic dysfunction. Pulmonary contusion leads to alveolar flooding and oedema, causing a reduction in gas exchange capacity and lung compliance. This results in significant intrapulmonary shunting and Ventilation/Perfusion (V/Q) mismatch. To compensate for this hypoxemia, the patient increases their respiratory drive. However, in the presence of unmanaged pain and stiff lungs, this increased Work of Breathing (WOB) leads to a massive increase in systemic oxygen consumption (VO2). This creates a paradox where the effort to breathe consumes more oxygen than the compromised lungs can supply, worsening the global hypoxic state and precipitating respiratory exhaustion. Pneumonia occurs in approximately 30% of hospitalized patients with significant chest trauma and is the primary driver of respiratory failure (Brasel et al., 2006). The combination of hypoventilation, lobar collapse, and impaired gas exchange frequently necessitates escalation of care to mechanical ventilation, which itself carries risks of ventilator-associated pneumonia (VAP) and barotrauma. Crucially, clinical studies indicate that these respiratory complications typically manifest 48 to 72 hours after the traumatic event (Brasel et al., 2006). This defines a critical "therapeutic window": effective analgesia must be established immediately upon admission to break the cycle of splinting before pneumonia becomes established.

2.2.3.4.5 Acidosis in Chest Trauma: A Marker of Physiological Failure

Acidosis is a key component of the trauma "lethal triad" and is often part of the symptomatic presentation along with hypoxia and hypercapnia. It is defined clinically by a decrease in arterial pH < 7.35. In the specific context of chest trauma, the acidosis is frequently of mixed etiology, requiring careful interpretation to guide appropriate therapy.

- Metabolic Acidosis: This component is primarily linked to systemic hypoperfusion (shock) and hemorrhage. The resulting tissue hypoxia forces cells into anaerobic metabolism, causing the accumulation of serum lactate as a waste metabolite.

- Respiratory Acidosis: In patients with rib fractures, this is the predominant and most concerning feature, resulting from the accumulation of arterial CO_2 due to alveolar hypoventilation and leading to hypercapnia.

While respiratory acidosis can stem from central causes (e.g., concomitant Traumatic Brain Injury affecting the medullary respiratory centres), in the isolated chest trauma patient, it is predominantly a mechanical consequence of pain. The nociceptive input from the fractures forces the patient to limit the respiratory excursion of the rib cage. As alveolar ventilation drops, CO_2 is not effectively eliminated.

Pain therapy plays a life-saving role in correcting respiratory acidosis. Unlike metabolic acidosis, which requires perfusion, respiratory acidosis in these patients is treated by restoring chest wall mechanics. Effective regional anesthesia (such as Fascial Plane Blocks) allows the patient to tolerate deep inspiration, thereby increasing minute ventilation and "blowing off" the excess CO_2. Failure to reverse this acidosis through analgesia is a primary indication for invasive support, such as Non-Invasive Ventilation (NIV) or endotracheal intubation (*Clinical review of non-invasive ventilation | European Respiratory Society*, s.d.; *Official ERS/ATS clinical practice guidelines: noninvasive ventilation for acute respiratory failure | European Respiratory Society*, s.d.). However, intubation in these patients is associated with longer ICU stays and higher morbidity; thus, aggressive early pain control is the preferred strategy to resolve the acidosis and prevent intubation.

2.2.3.4.6 General Principles of Management

The therapeutic management of rib fractures focuses on three pillars: respiratory support, bronchial clearance, and pain management (Bouzat et al., 2017; Coccolini et al., 2025).

- Bronchial Clearance and Physiotherapy: Prophylaxis against the retention of secretions is paramount. This includes aggressive respiratory physiotherapy (incentive spirometry), early mobilization, and the administration of mucolytic agents. In severe cases, fiberoptic bronchoscopy may be required to aspirate mucous plugs and prevent lobar atelectasis.

- Respiratory Support: Supplemental oxygen is standard. In patients with flail chest or severe pulmonary contusion, non-invasive ventilation (NIV) or intubation with mechanical ventilation may be necessary to maintain gas exchange and stabilize the chest wall pneumatically.
- Surgical stabilization of rib fractures (SSRF) is indicated in selected cases of flail chest with failure to wean from ventilation (Hisamune et al., 2024; Pieracci et al., 2017).
- External immobilization (binding/bandaging) is strictly contraindicated as it further restricts lung expansion and increases the rate of pneumonia.
- Analgesia: Effective analgesia is the cornerstone that enables all other therapies (Bouzat et al., 2017; Coccolini et al., 2025; Galvagno et al., 2016; Savoia et al., 2015). Without pain control, deep breathing and coughing are impossible. While systemic multimodal analgesia (NSAIDs, Paracetamol) is the baseline, it is often insufficient for multiple fractures. Historically, Thoracic Epidural Analgesia (TEA) was the gold standard. However, due to its side effects (hypotension) and contraindications (coagulopathy), ultrasound-guided fascial plane blocks are gaining increasingly favor (Gamberini et al., 2025). Specifically, the Serratus Anterior Plane (SAP) block and the Erector Spinae Plane (ESP) block have emerged as safer, opioid-sparing alternatives that target the specific innervation of the chest wall (Galvagno et al., 2016; Thiruvenkatarajan et al., 2018).

2.3 Prognostic and Classification Scales

Accurate risk stratification is fundamental in trauma care. It allows clinicians to predict mortality, estimate the need for intensive care, and facilitate the comparison of outcomes between different treatment groups (e.g., comparing the efficacy of ESP vs. SAP blocks). While numerous scoring systems exist, no single score is universally accepted as the "gold standard" specifically for chest trauma; thus, general trauma scores are often employed alongside thoracic-specific indices.

2.3.1 Abbreviated Injury Scale (AIS) and Injury Severity Score (ISS)

The Injury Severity Score (ISS), introduced by Baker et al. in 1974, remains the most widely used anatomical scoring system in clinical practice and research (Baker et al., 1974). Its calculation relies on the Abbreviated Injury Scale (AIS), a consensus-based lexicon of injury descriptions first introduced in 1971 and periodically updated (most notably in 2005 and 2008) (Gennarelli & Wodzin, 2006).

The AIS assigns a severity score ranging from 1 (minor) to 6 (unsurvivable) to each individual injury.The ISS is then calculated as the sum of the squares of the highest AIS code in each of the three most severely injured ISS body regions ($ISS = A^2 + B^2 + C^2$).The ISS body regions (six) differ slightly from the original AIS anatomical chapters (nine). To ISS calculation, the body is divided into:

- Head or Neck
- Face
- Chest
- Abdominal or Pelvic contents
- Extremities or Pelvic girdle
- External

The resulting score ranges from 0 to 75. An ISS > 15 is the universally accepted definition of "Major Trauma" or polytrauma (*ATLS ® Student Course Manual, 10th Edition*, s.d.).

Despite its widespread use, the ISS has a significant limitation relevant to thoracic research. Because the ISS takes only the single highest AIS score from each body region, it fails to account for multiple severe injuries within the same cavity. For instance, a patient with a severe pulmonary contusion (AIS 4) and multiple rib fractures with flail chest (AIS 4) will only have one score of 4 squared (16) contributed by the chest region. This leads to an underestimation of injury severity in patients with isolated but complex chest trauma compared to those with multisystem injuries (Linn, 1995). This limitation highlights the necessity for chest-specific scoring systems (such as the RibScore or Thoracic Trauma Severity Score) to accurately predict outcomes and guide analgesic interventions.

2.3.2 Thoracic-Specific Scoring Systems

While general trauma scores like ISS provide a holistic view, they lack the granularity required to guide specific thoracic interventions. Consequently, dedicated thoracic scoring systems have been developed to better predict respiratory complications and mortality.

2.3.2.1 AIS Thorax (Abbreviated Injury Scale - Thoracic Module)

The AIS Thorax represents the thoracic-specific component of the AIS system. Originally established in 1971 by the Association for the Advancement of Automotive Medicine (AAAM), it has undergone rigorous validation. A landmark study by Bayer et al. (2017), analyzing data from the TraumaRegister DGU®, confirmed its prognostic utility.The study demonstrated a strong correlation between the AIS Thorax score and critical clinical outcomes:

- The likelihood of intubation and ICU admission.
- The duration of mechanical ventilation and length of ICU stay.
- Mortality rates. Specifically, an AIS Thorax > 4 (representing severe injury) is strongly correlated with increased in-hospital mortality. Interestingly, the study noted that early mortality (within 3 days of ICU discharge) was surprisingly frequent even in patients with lower anatomical severity (AIS Thorax < 3), highlighting the impact of delayed complications like pneumonia in "minor" chest trauma (Bayer et al., 2017).

2.3.2.2 Thoracic Trauma Severity Score (TTSS)

Developed by Pape et al. in 2000, the Thoracic Trauma Severity Score (TTSS) is arguably the most clinically relevant tool for risk stratification in blunt chest trauma. Unlike purely anatomical scores, the TTSS integrates anatomical damage with physiological derangement and patient reserve (age) (Coccolini et al., 2025; Pape et al., 2000).

2.3.2.2.1 Structure of the TTSS

The score ranges from 0 to 25 points, derived from five equally weighted parameters (scored 0-5 each):

- Age: Recognizing that physiological reserve declines with age.
- Rib Fractures: The number of fractures correlates with pain and splinting.
- Pulmonary Contusion: Assessing parenchymal damage.
- Pleural Involvement: Presence of pneumothorax or haemothorax.
- Oxygenation (PaO_2/FiO_2 ratio): The ultimate physiological readout of lung function.

This multidimensional approach addresses a critical gap: radiological data alone often underestimates severity, as contusions may not bloom until 24-48 hours post-injury. By incorporating the P/F ratio and age, the TTSS provides a dynamic assessment of the patient's actual respiratory status. Specifically, Pape et al. demonstrated that while pulmonary contusions are strong predictors of adverse outcomes, the risk associated with rib fractures increases disproportionately with age, becoming the dominant risk factor in patients over 70 years old (Pape et al., 2000).

2.3.2.2.2 Validation and Clinical Utility

Numerous studies have validated the TTSS as a robust predictor of morbidity:

- ARDS Prediction: Aukema et al. (2011) and Daurat et al. (2020) confirmed that a high TTSS on admission is an independent predictor for the development of Acute Respiratory Distress Syndrome (ARDS), allowing for early implementation of lung-protective ventilation and fluid restriction (Aukema et al., 2011; Daurat et al., 2016).
- Need for Mechanical Ventilation: Okabe et al. demonstrated that elevated TTSS scores correlate with prolonged mechanical ventilation in polytrauma patients (Okabe, 2018).

- Failure of Non-Invasive Support: Daurat et al. further highlighted that the TTSS can predict the failure of High-Flow Nasal Cannula (HFNC) therapy, serving as an early warning system for patients likely to require endotracheal intubation (Daurat et al., 2016).

In comparative analyses with other scores (e.g., Pulmonary Contusion Score, Wagner Score), the TTSS consistently emerges as the only independent predictor of both mortality and the development of Multiple Organ Dysfunction Syndrome (MODS) (Mommsen et al., 2012).

2.4 Management of Thoracic Trauma: ATLS Principles

The management of chest trauma is dictated by the severity of physiological compromise rather than anatomical injury alone. Following the Advanced Trauma Life Support (ATLS) 10th edition guidelines, the priority is the immediate identification and treatment of life-threatening conditions during the Primary Survey (*ATLS ® Student Course Manual, 10th Edition*, s.d.).

1. Immediate Life-Threatening Injuries (Primary Survey)

These conditions require immediate intervention, often before imaging is completed:

- Airway Obstruction: Requires immediate clearing (suction, foreign body removal) and definitive airway control (intubation).
- Tension Pneumothorax: Clinical diagnosis requiring immediate needle decompression followed by tube thoracostomy (chest drain).
- Massive Haemothorax: Defined as >1500 mL of blood or >200 mL/hr for 2-4 hours. Requires volume resuscitation, large-bore chest drainage, and consideration for emergency thoracotomy.
- Open Pneumothorax: Requires a three-sided occlusive dressing and subsequent chest tube placement.
- Cardiac Tamponade: Requires fluid resuscitation and emergency pericardiocentesis or thoracotomy.

- Traumatic Circulatory Arrest: Requires ACLS protocols with consideration for resuscitative thoracotomy in select penetrating trauma cases.

2. Potentially Life-Threatening Injuries (Secondary Survey)

These injuries are typically addressed after the patient has been stabilized:

- Simple Pneumothorax: Management is size-dependent. Small, asymptomatic pneumothoraces (<35 mm) in stable patients may be managed conservatively with observation, whereas larger or symptomatic ones require tube thoracostomy (Green et al., 2011; F. O. Moore et al., 2011).
- Haemothorax: Requires drainage to prevent fibrothorax and empyema. Surgical intervention (VATS) is indicated for retained clot.
- Rib Fractures and Pulmonary Contusion: The cornerstone of therapy is aggressive multimodal analgesia (including regional blocks) and respiratory support (oxygen therapy, physiotherapy) to prevent pneumonia.
- Blunt Cardiac Injury: Requires continuous ECG monitoring and troponin assessment.
- Traumatic Aortic Disruption: Requires strict blood pressure control (anti-impulse therapy) and endovascular repair (TEVAR)

2.4.1 Respiratory Management: From Oxygen Therapy to Mechanical Ventilation

Prompt optimization of gas exchange is the cornerstone of chest trauma management. Following ATLS principles, the primary goal is to prevent hypoxemia, which drives anaerobic metabolism and contributes to the "lethal triad" (acidosis, hypothermia, coagulopathy) (Battle et al., 2012; MacLeod et al., 2004). However, the therapeutic approach must be dynamic, escalating based on the severity of the pulmonary contusion and the patient's respiratory mechanics.

1. Oxygen Therapy and High-Flow Systems

In mild to moderate trauma, maintaining systemic oxygenation (SpO_2 > 94%) supports cellular metabolism and prevents secondary brain injury in polytrauma patients. While conventional low-flow devices (nasal cannulas, Venturi masks) suffice for minor injuries, patients with significant chest wall trauma often require higher support. High-Flow Nasal Cannula (HFNC) therapy has emerged as a valuable bridge. By delivering heated, humidified oxygen at flow rates up to 60 L/min, HFNC washes out dead space CO_2 and generates a modest level of Positive End-Expiratory Pressure (PEEP), reducing the Work of Breathing (WOB) and improving patient comfort compared to standard masks.

2. Non-Invasive Ventilation (NIV): CPAP and Bi-Level Support

When oxygen therapy alone fails to correct hypoxemia, or when the patient exhibits signs of respiratory fatigue, Non-Invasive Ventilation (NIV) is mandatory.

The rationale for NIV in chest trauma is twofold:

- CPAP (Continuous Positive Airway Pressure): Applies a constant PEEP that recruits collapsed alveoli in contused areas, improves Functional Residual Capacity (FRC), and stabilizes the chest wall ("pneumatic splinting") in cases of flail chest.
- Bi-Level NIV (Pressure Support + PEEP): Adds inspiratory Pressure Support (PS) to unload the respiratory muscles, directly counteracting the fatigue caused by reduced lung compliance (Chiumello et al., 2013; *Clinical review of non-invasive ventilation | European Respiratory Society*, s.d.; *Official ERS/ATS clinical practice guidelines: noninvasive ventilation for acute respiratory failure | European Respiratory Society*, s.d.).

However, the success of NIV is strictly dependent on patient cooperation. A study by Duggal et al. emphasized that NIV is most effective in hemodynamically stable patients who can protect their airway (Duggal et al., 2013).

4. Invasive Mechanical Ventilation (IMV)

Endotracheal intubation is reserved for patients with:

- Refractory hypoxemia despite NIV/HFNC ($PaO2/FiO2 < 200$).

- Respiratory exhaustion (severe respiratory acidosis).
- Hemodynamic instability or altered mental status (GCS < 8).
- Severe chest wall instability requiring internal pneumatic stabilization.

2.4.1.1 The Crucial Link: Analgesia as a Sparing Strategy for Ventilation

There is a direct pathophysiological link between pain control and the need for invasive ventilation. Uncontrolled pain limits chest expansion, making spontaneous breathing inefficient and NIV intolerable. This leads to progressive atelectasis, worsening V/Q mismatch, and eventual respiratory exhaustion requiring intubation. Effective regional anesthesia (such as ESP or SAP blocks) interrupts this cycle. By abolishing the nociceptive drive, these blocks restore tidal volume and allow the patient to tolerate NIV or HFNC interfaces. Consequently, adequate analgesia is independently associated with a reduced rate of nosocomial pneumonia, shorter duration of mechanical ventilation, and a decreased need for intubation (Moon et al., 1999).

2.4.2. Pharmacological Considerations

Current guidelines strongly advise against the routine use of corticosteroids, as they do not improve outcomes in pulmonary contusion. Similarly, antibiotic prophylaxis is contraindicated; it does not prevent pneumonia but selects for multidrug-resistant organisms. Antibiotics should be reserved for treating confirmed infections (Bouzat et al., 2017; Coccolini et al., 2025; Maher & Jayathissa, 2016).

2.4.3 Analgesia in Chest Trauma: Current Standards and Emerging Techniques

2.4.3.1 The Pathophysiology of Pain and Clinical Guidelines

The pain associated with multiple rib fractures is typically severe, with intensity scores ranging between 7 and 10 on the Numeric Rating Scale (NRS). Crucially, this is a dynamic pain, exponentially exacerbated by movement, deep breathing, and coughing. Effective pain management is not merely a matter of symptomatic relief; it is a resuscitative intervention. As noted by Ziegler and Agarwal, rib fractures are associated with a hospital mortality rate ranging from 3% to 13% (Ziegler & Agarwal, 1994). This mortality is largely driven by respiratory failure: acute pain triggers a reflex limitation of chest expansion ("splinting"), which impairs the clearance of bronchial secretions and promotes alveolar collapse. The inhibition of coughing—whether due to spontaneous pain or the sedative side effects of systemic opioids—creates a vicious cycle leading to atelectasis and pneumonia (Wardhan, 2013). The critical importance of aggressive analgesia is enshrined in the guidelines of the Eastern Association for the Surgery of Trauma (EAST), in which adequate pain control is strongly recommend and the limitations of unimodal pharmacological strategies are highlight (Bouzat et al., 2017; Coccolini et al., 2025; Galvagno et al., 2016). Consequently, current protocols advocate for a Multimodal Analgesia approach, combining agents with different mechanisms of action (NSAIDs, Paracetamol, Gabapentinoids) to minimize reliance on opioids and their respiratory-depressant side effects.

2.4.3.1.1 The Limitations of Neuraxial Analgesia

To achieve opioid-sparing analgesia, neuraxial techniques have historically been the gold standard. Thoracic Epidural Analgesia (TEA) involves the continuous infusion of local anesthetics and opioids into the epidural space. While highly effective—and recently confirmed by a Bayesian network meta-analysis by Gamberini et al. (2025) as the superior technique for reducing mechanical ventilation duration (Gamberini et al., 2025)—TEA is increasingly limited in trauma practice. It is often contraindicated due to:

- Hemodynamic Instability: Sympathetic blockade can precipitate hypotension in hypovolemic patients.
- Coagulopathy: Risk of epidural hematoma in patients with traumatic coagulopathy or on antithrombotic therapy.
- Vertebral Trauma: Concomitant spinal fractures often preclude catheter placement. Furthermore, TEA requires advanced technical skills and intensive monitoring, making it less feasible in resource-constrained settings.

2.4.3.1.2 The Shift to Fascial Plane Blocks: SAP and ESP

Given the safety concerns of TEA, Ultrasound-Guided Fascial Plane Blocks have emerged as the preferred alternative. These peripheral techniques allow for targeted analgesia with a superior safety profile, particularly in anticoagulated or hemodynamically labile patients.

1) The Serratus Anterior Plane (SAP) Block

   The SAP block targets the lateral cutaneous branches of the intercostal nerves. Its efficacy is well-supported by recent high-quality evidence. As early as 2019, Southgate et al. demonstrated the success of SAPB in controlling acute traumatic pain (Paul et al., 2020). More recently, the randomized clinical trial SABRE (2024) by Partyka and Asha confirmed that early SAP blocks significantly reduce pain scores and opioid consumption in the first 24 hours compared to standard care (Partyka et al., 2024). Similarly, Serra et al. (2024) highlighted a significant reduction in NRS scores at 3, 6, and 18 hours post-block in an emergency setting (Serra et al., 2024).

2) The Erector Spinae Plane (ESP) Block While the SAP block is effective for lateral pain, the Erector Spinae Plane (ESP) Block has gained attention for its potential to cover posterior fractures and provide visceral analgesia. Most notably, the 2025 network meta-analysis by Gamberini et al. identified the ESP block as the only regional anesthesia technique capable of significantly reducing hospital length of stay (Mean Difference -1.8 days) compared to systemic analgesia, showing an efficacy profile comparable to the epidural standard in this domain (Gamberini et al., 2025).

2.4.3.1.3 Rationale for Comparison

The current literature presents a dichotomy: the SAP block is supported by strong RCT evidence for acute pain relief (SABRE trial), while the ESP block shows promising signals for improving systemic outcomes like length of stay ((Gamberini et al., 2025)). However, direct head-to-head comparisons between these two techniques in chest trauma are scarce. This thesis aims to address this gap by evaluating which block offers the optimal balance of analgesic efficacy and clinical recovery.

Chapter 3: The Pathophysiology and Multidimensional Nature of Acute Pain

3.1 Definition and the Biopsychosocial Model

According to the International Association for the Study of Pain (IASP), pain is defined as "an unpleasant sensory and emotional experience associated with, or resembling that associated with, actual or potential tissue damage" (Raja et al., 2020). In the 2020 revision of this definition, the IASP emphasized distinct explanatory notes that are fundamental for clinical practice:

- Subjectivity: Pain is always a personal experience that is influenced to varying degrees by biological, psychological, and social factors.
- Distinction from Nociception: Pain and nociception are different phenomena. Pain cannot be inferred solely from activity in sensory neurons.
- Learned Experience: Individuals learn the concept of pain through their life experiences (Gibson & Helme, 2001).

This definition underscores the biopsychosocial model of pain. The response to a noxious stimulus is not uniform but modulated by intrinsic and extrinsic variables:

- Age: Geriatric patients often exhibit "stoicism" or a reluctance to report pain due to fear of hospitalization or cognitive decline. Conversely, physiological changes in nociceptive processing in the elderly can alter pain thresholds (Gibson & Helme, 2001).
- Sex and Gender: Biological differences in endogenous pain modulation (e.g., hormonal influence on opioid receptors) and psychosocial gender roles significantly influence pain perception and analgesic response (Mogil, 2020).
- Cultural Determinants: Cultural background shapes the expression of pain ("pain behavior"). In some cultures, stoicism is valued, while in others, the verbalization of distress is a coping mechanism. Recognizing these variations is essential for an accurate assessment in the Emergency Department, avoiding the underestimation of pain in stoic patients (Anderson et al., 2009).

3.2 The Clinician-Patient Interaction

Effective pain management requires a holistic approach that transcends the mere evaluation of objective parameters (intensity, location, onset). The therapeutic alliance—established through active listening and empathy—is clinically relevant. Studies demonstrate that a patient-centered approach reduces anxiety-induced sympathetic activation, thereby lowering the perception of pain and improving therapeutic adherence (Hojat et al., 2010). This aligns with the concept of "humanization of care," ensuring that the trauma pathway remains respectful of the patient's dignity while delivering aggressive medical management.

3.3. The Nociceptive Pathway: Targets for Intervention

Understanding the four phases of nociception is critical, as regional anesthesia specifically targets the transduction and transmission phases to prevent the cortical perception of pain (Basbaum et al., 2009). *3.3.1. Transduction: The Molecular Target*

Transduction is the conversion of a noxious stimulus (mechanical, thermal, or chemical) into an electrical signal. In chest trauma, tissue injury releases an "inflammatory soup" (prostaglandins, cytokines, bradykinin) that sensitizes peripheral nociceptors. This process relies on Voltage-Gated Sodium Channels (Nav), specifically subtypes Nav1.7, Nav1.8, and Nav1.9. Local anesthetics used in fascial blocks (e.g., Ropivacaine) exert their effect here: they bind intracellularly to these channels, locking them in an inactive state and halting the generation of action potentials (Dib-Hajj et al., 2010).

3.3.1. Transmission: The Dual Fiber System

The signal is propagated to the spinal cord via the Dorsal Root Ganglion (DRG) by two distinct types of fibers, creating the biphasic pain experience typical of rib fractures:

- A-delta Fibers (First Pain): Myelinated and fast-conducting (5–30 m/s). They mediate the sharp, well-localized, dynamic pain felt immediately upon coughing or movement.

- C Fibers (Second Pain): Unmyelinated and slow-conducting (< 1 m/s). They mediate the dull, aching, diffuse pain present at rest. Because C-fibers have extensive connections to the limbic system, this pain carries a stronger affective component ("suffering") (Basbaum et al., 2009)

3.3.2. Modulation and Plasticity

The signal is not passively transmitted but modulated in the spinal dorsal horn via several mechanisms:

- Gate Control Theory: Activation of non-nociceptive A-beta fibers (touch) can inhibit nociceptive transmission via interneurons, providing the basis for therapies like TENS (Melzack & Wall, 1965).

- Descending Inhibition: Brainstem centers (Periaqueductal Gray) release serotonin and norepinephrine to suppress pain. This system is the primary target of systemic opioids (Benarroch, 2012)

3.3.3. Perception

The final integration occurs in the cortex: the lateral spinothalamic tract projects to the somatosensory cortex (encoding location/intensity), while the medial tract projects to the limbic system (encoding unpleasantness).

3.4. Clinical Classification: Mechanisms and Chronification

Proper classification guides the choice of analgesic strategy in thoracic trauma (Treede et al., 2015).

3.4.1. Nociceptive vs. Neuropathic Pain

Nociceptive Pain: Arises from damage to non-neural tissue. In chest trauma, it is further divided into somatic (well-localized pain from ribs/muscles) and visceral (poorly localized pain from pleura/mediastinum).

Neuropathic Pain: Arises from a lesion to the somatosensory nervous system. In the context of rib fractures, direct trauma to the intercostal neurovascular bundle can cause Traumatic Intercostal Neuralgia, characterized by burning or electric-shock sensations. This component is often resistant to opioids but highly responsive to nerve blocks (Karmakar & Ho, 2004, 2003).

3.4.2. The Imperative of Early Blockade: Preventing Chronification

Acute pain serves a protective function, but if left untreated, it leads to Central Sensitization (or "wind-up"). Continuous nociceptive bombardment (e.g., from multiple fractures) causes neuroplastic changes in the dorsal horn (NMDA receptor activation), resulting in:

- Hyperalgesia: Exaggerated response to pain.

Allodynia: Pain from non-painful stimuli.

This state is the precursor to Chronic Post-Traumatic Pain, which affects up to 50% of chest trauma patients at 6 months (Gordy et al., 2014). Therefore, fascial plane blocks (ESP/SAP) are not merely symptomatic treatments; by interrupting the afferent barrage early, they act as a preventative measure against the establishment of chronic pain pathways (Andreae & Andreae, 2013; Hachimi-Idrissi et al., 2020; Woolf, 2011).

3.5 Clinical Assessment and Quantification of Pain

3.5.1 Anamnestic Evaluation: The PQRST Model

A structured clinical history is the prerequisite for effective analgesia. In the emergency setting, the PQRST mnemonic provides a standardized framework to characterize pain rapidly:

P (Palliative/Provocative): Identification of modifying factors. In chest trauma, pain is typically exacerbated by deep inspiration, coughing, and truncal movement (provocative), while it may be partially relieved by shallow breathing or splinting the injured side (palliative).

Q (Quality): Description of the sensory nature. Somatic pain from fractures is often "sharp" or "stabbing," while neuropathic pain from intercostal nerve injury may be "burning" or "electric."

R (Radiation): Assessment of referred pain. Posterior rib fractures may radiate anteriorly along the intercostal dermatome.

S (Severity): Quantification using validated scales (see below).

T (Time): Onset and temporal pattern. Acute traumatic pain is typically constant with incident spikes.

3.5.2 Pain Assessment Scales

Standardized quantification is essential for monitoring therapeutic efficacy. The integration of pain scoring into triage protocols has been shown to significantly reduce the time-to-analgesia (Hachimi-Idrissi et al., 2020).

1. Numerical Rating Scale (NRS)

The NRS is the gold standard for cognitively intact adults. The patient assigns a value from 0 ("no pain") to 10 ("worst imaginable pain") and classifies pain as follows: 1-3 Mild pain; 4-6 Moderate pain; 7-10 Severe pain. However, a single static measurement is insufficient and best practice dictates recording two values:

- Static NRS: Pain at rest.
- Dynamic NRS: Pain during deep inspiration or coughing. Dynamic pain is the primary determinant of respiratory complications, and its reduction is the primary endpoint of regional anesthesia studies (Savoia et al., 2010).

2. Visual Analogue Scale (VAS)

The VAS consists of a 100-mm continuous line anchored by "no pain" and "worst pain." While mathematically continuous and highly sensitive in research settings, its clinical utility in the Emergency Department is limited by the requirement for fine motor skills and visual acuity, which may be compromised in polytrauma or elderly patients (Bijur et al., 2001). VAS scale classifies pain as follows: 0-4 mm (None); 5-44 mm (Mild); 45-74 mm (Moderate); 75-100 mm (Severe).

3. Verbal Rating Scale (VRS)

A categorical scale using descriptors (None, Mild, Moderate, Severe, Agonizing). It is less sensitive than the NRS/VAS but useful for patients who struggle with abstract numerical concepts (Savoia et al., 2015).

Assessment in special populations:

- Cognitive impairment: PAINAD Scale (Warden et al., 2003)

For patients with dementia or severe cognitive deficits, self-report is often unreliable. The Pain Assessment in Advanced Dementia (PAINAD) scale observes five behaviors: breathing, vocalization, facial expression, body language, and consolability. Each is scored 0-2 (Total 0-10). However, there is significant overlap between pain behaviours and other sources of distress (delirium, hunger, fear). Despite low specificity, it remains the standard of care for this demographic (Zwakhalen et al., 2006).

- Pediatric and Non-Verbal Patients: FLACC Scale (Crellin et al., 2015)

The FLACC scale (Face, Legs, Activity, Cry, Consolability) is a validated observational tool for children aged 2 months to 7 years and non-verbal patients. It provides a reliable objective score (0-10) based on behavioral indicators of distress.

- Pediatric Self-Report: Wong-Baker FACES® (Garra et al., 2010)

Designed for children aged 3-8 years, this scale correlates pain intensity with six facial expressions ranging from smiling (0) to crying (10). While widely used, it risks confounding affect with pain intensity; a child may select the crying face because they are frightened or sad, rather than in severe pain. However, careful explanation by the clinician is required to ensure accuracy.

3.6 The Evolution of Analgesic Strategies: From the WHO Ladder to the "Fourth Step"

3.6.1 The Traditional WHO Analgesic Ladder

Originally proposed by the World Health Organization (WHO) in 1986 for the management of cancer pain, the "Analgesic Ladder" established a sequential framework for pharmacotherapy. While initially designed for progressive oncological pain, its principles have been adapted for acute and chronic non-cancer pain (Ventafridda et al., 1985; World Health Organization, 1986).

The classic model consists of three ascending steps based on pain intensity:

- Step 1 (Mild Pain, NRS 1-3): Non-opioid analgesics (Paracetamol, NSAIDs) with or without adjuvants.
- Step 2 (Moderate Pain, NRS 4-6): Weak opioids (Codeine, Tramadol) combined with non-opioids.
- Step 3 (Severe Pain, NRS 7-10): Strong opioids (Morphine, Oxycodone, Fentanyl) combined with non-opioids.

3.6.2 The "Fourth Step": The Role of Interventional Techniques

In the context of modern pain medicine, and particularly for severe trauma, the three-step model has proven insufficient. This led to the validation of a "Fourth Step" (or bidirectional step), specifically addressing severe, refractory pain or acute crises where systemic opioids are ineffective or contraindicated due to side effects (Vargas-Schaffer, 2010). This fourth level comprises interventional procedures, including:

- Regional Anesthesia: Epidural analgesia and fascial plane blocks (ESP, SAP).
- Neuromodulation: TENS or invasive stimulation.
- Neuroablative procedures: (in chronic settings).

3.6.3 Application in Chest Trauma: The "Reverse Ladder" Concept

While the standard WHO ladder suggests a progressive "step-up" approach, the management of severe blunt chest trauma requires a paradigm shift. Because the risk of respiratory failure is highest in the first 48-72 hours, adhering strictly to a step-up protocol (starting with NSAIDs and waiting for failure) is clinically inappropriate and potentially dangerous. Current trauma guidelines advocate for an "Elevator Model" or "Reverse Ladder" approach: therapy is initiated immediately at the appropriate level of intensity—often at Step 3 (Strong Opioids) or Step 4 (Regional Blocks)—to rapidly control the nociceptive barrage and restore respiratory mechanics. Once the acute phase subsides, therapy is de-escalated (Ventafridda et al., 1985).

The comparison between ESP and SAP blocks in this study represents an investigation into the optimal application of the Fourth Step of the analgesic ladder. By implementing these blocks early (in the Emergency Department), we aim to "spare" the systemic complications associated with Step 2 and Step 3 opioids, thereby improving the safety profile of analgesia in the polytrauma patient.

3.6.4: Pharmacological pain management.

3.6.4.1Paracetamol (Acetaminophen)

Paracetamol represents the first-line analgesic for mild-to-moderate pain and is a cornerstone of multimodal analgesia protocols in trauma. Its favorable safety profile makes it the preferred baseline agent, often serving as an "opioid-sparing" partner.

Mechanism and Pharmacodynamics

Unlike NSAIDs, Paracetamol has negligible peripheral anti-inflammatory activity. Its mechanism is primarily central, involving the inhibition of COX-3 isoforms in the CNS and the modulation of descending serotonergic and endocannabinoid pathways (Graham & Scott, 2005). Crucially, Paracetamol exhibits a "ceiling effect": increasing the dosage beyond the therapeutic threshold does not result in increased analgesia but only increases the risk of toxicity. This pharmacological limitation underscores the necessity of combining it with other modalities (such as fascial plane blocks) for severe chest trauma pain.

Pharmacokinetics and Administration

In the emergency setting, intravenous (IV) administration is preferred. While oral dosing reaches peak concentration in 30-60 minutes, IV infusion achieves significant analgesic onset within 5-10 minutes, facilitating rapid stabilization. The drug undergoes hepatic metabolism. Therefore, while safe at therapeutic doses (maximum 4g/day in adults), caution is mandatory in polytrauma patients with potential liver injury, hypoperfusion ("shock liver"), or chronic alcohol abuse. In these subpopulations, the daily dose should be reduced to avoid the accumulation of the toxic metabolite NAPQI (Dart et al., 2006).

3.6.5 Non-Steroidal Anti-Inflammatory Drugs (NSAIDs)

3.6.5.1 Mechanism of Action and Clinical Rationale

NSAIDs represent a critical component of Step 1 of the WHO analgesic ladder and are essential in multimodal trauma protocols for their opioid-sparing effects. Their primary mechanism is the inhibition of Cyclooxygenase (COX) enzymes, preventing the conversion of arachidonic acid into prostaglandins and thromboxanes.

- COX-1 (Constitutive): Generally responsible for physiological "housekeeping" functions, such as gastric mucosal protection, renal blood flow maintenance, and platelet aggregation (Thromboxane A2).
- COX-2 (Inducible): Up-regulated at sites of tissue injury, driving the inflammatory response (pain, fever, swelling) via prostaglandins PGE2 and PGI2.

3.6.5.2 Limitations and Risks in the Trauma Patient

In the context of chest trauma, NSAIDs are theoretically ideal as they directly target the intense inflammatory cascade generated by rib fractures and muscular contusion, significantly reducing "dynamic" pain upon coughing (Vane & Botting, 1998). Despite their analgesic efficacy, the systemic administration of NSAIDs in polytrauma patients is severely limited by their side effect profile. This limitation serves as a primary indication for alternative regional techniques (ESP/SAP blocks).

1. Coagulation and Bleeding Risk

NSAIDs reversibly inhibit COX-1, reducing the synthesis of Thromboxane A2, a potent platelet aggregator. This leads to platelet dysfunction and prolonged bleeding time.

Clinical Implication: In patients with concomitant solid organ injuries (liver/spleen lacerations) or traumatic coagulopathy, NSAIDs are relatively contraindicated.

Aspirin Interaction: As demonstrated by Catella-Lawson et al., concomitant use of competitive NSAIDs (like Ibuprofen) can antagonize the irreversible cardioprotective effect of Aspirin, a crucial consideration in elderly trauma patients with cardiovascular comorbidities (Catella-Lawson et al., 2001).

<u>2. Renal Toxicity (Acute Kidney Injury)</u>

Prostaglandins (PGE2, PGI2) play a critical role in maintaining renal perfusion by dilating the afferent arteriole, particularly during states of hypovolemia or hypotension.

Clinical Implication: Trauma patients are frequently hypovolemic or exposed to nephrotoxic contrast media (CT scans). In this setting, NSAID administration removes this protective vasodilation, precipitating prerenal failure and Acute Kidney Injury (AKI) (Harirforoosh & Jamali, 2009).

<u>3. Gastrointestinal Toxicity</u>

Inhibition of COX-1 compromises the gastric mucosal barrier, increasing the risk of stress ulcers and gastrointestinal bleeding. This risk is compounded in trauma patients receiving high-dose corticosteroids or anticoagulants.

<u>4. The "Bone Healing" Controversy</u>

There is a longstanding theoretical concern that NSAIDs may inhibit osteoblast activity and delay fracture healing (non-union). While recent systematic reviews suggest this risk may be overstated for short-term courses, many trauma surgeons remain cautious, limiting their use in patients with severe multiple fractures (Marquez-Lara et al., 2016).

3.6.5.3 Conclusion and Contraindications

Due to these systemic risks, NSAIDs are often withheld or under-dosed in the acute phase of severe chest trauma. Absolute and Relative Contraindications include:

- Active hemorrhage or coagulopathy.
- Renal insufficiency (acute or chronic).
- Hypovolemia/Shock.
- History of peptic ulcer disease.
- Pregnancy (risk of premature closure of the ductus arteriosus).
- Known hypersensitivity/Asthma (Samter's triad).

Consequently, the inability to safely utilize NSAIDs in many polytrauma patients leaves a therapeutic gap that is best filled by regional anesthesia.

3.6.7 Weak Opioids

3.6.7.1 Clinical Indication and Pharmacodynamics

"Weak" opioids, such as Tramadol and Codeine, represent Step 2 of the WHO ladder. They are indicated for moderate pain (NRS 4-6) or as "step-down" analgesics during the weaning phase from strong opioids. Although they share the same receptor targets as strong opioids, their clinical utility is limited by lower intrinsic activity and dose-limiting toxicities, creating an effective "ceiling effect" beyond which side effects outweigh analgesic benefits.

3.6.7.2 Mechanism of Action

Opioids exert their effect by binding to G-protein coupled receptors (mu, delta, kappa) in the central and peripheral nervous system. Contrary to some simplified descriptions, the binding of the opioid agonist triggers a cascade that inhibits (does not activate) the enzyme adenylate cyclase. This results in:

- Reduction of intracellular cyclic adenosine monophosphate (cAMP).
- Activation of potassium channels (K+ efflux), causing neuronal hyperpolarization.

- Inhibition of voltage-gated calcium channels (Ca2+ influx), preventing the presynaptic release of nociceptive neurotransmitters (Glutamate, Substance P) (Lambert, 2023).

Specific Agents and Trauma-Related Limitations

1. Tramadol

Tramadol is a unique, centrally acting analgesic with a dual mechanism of action:Weak affinity for the μ-opioid receptor (approx. 1/6000th of morphine). Inhibition of the reuptake of Serotonin and Norepinephrine (SNRI-like effect), enhancing descending inhibitory pathways. While Tramadol causes less respiratory depression than morphine, it lowers the seizure threshold. This makes it potentially hazardous in polytrauma patients with concomitant Traumatic Brain Injury (TBI) or those receiving other pro-convulsant medications. Furthermore, its serotonergic activity carries a risk of Serotonin Syndrome if combined with antidepressants (SSRIs/TCAs) often used for neuropathic pain (Schug, 2007).

2. Codeine

Codeine is a prodrug with very low affinity for opioid receptors. Its analgesic effect depends entirely on its hepatic conversion into morphine via the CYP2D6 isoenzyme. However, approximately 10% of the Caucasian population lacks a functional CYP2D6 enzyme ("Poor Metabolizers"). In these patients, Codeine provides no analgesia. Conversely, "Ultra-Rapid Metabolizers" can convert Codeine into dangerous levels of morphine rapidly, leading to unexpected respiratory depression. Due to this unpredictable variability, its use in acute high-stakes trauma management is increasingly discouraged (Dean & Kane, 2012).

In conclusion, due to the genetic unpredictability of Codeine and the neuro-excitatory risks of Tramadol, "weak" opioids play a marginal role in the acute phase of severe chest trauma. They are insufficient for multiple rib fractures and are best reserved for the de-escalation phase. This therapeutic gap further reinforces the need for regional anesthesia techniques (ESP/SAP blocks) to bridge the transition from strong opioids to non-opioid analgesia.

3.6.8 Strong Opioids

3.6.8.1 Classification and Clinical Pharmacology

For severe pain (NRS > 7) refractory to multimodal strategies, strong opioids remain the systemic rescue therapy. Unlike weak opioids, pure agonists have no "ceiling effect" for analgesia; the limiting factor is solely the onset of adverse events (respiratory depression and sedation).

<u>1. Classification by Receptor Interaction</u>

Opioids are categorized based on their intrinsic activity at the receptor site:

- Full Agonists (e.g., Morphine, Fentanyl, Oxycodone): They bind to mu, delta, and kappa receptors with high affinity and intrinsic activity, producing a maximal response thus being the gold standard for severe trauma pain.
- Partial Agonists (e.g., Buprenorphine): These have high affinity for the mu-receptor but lower intrinsic activity. Consequently, they exhibit a ceiling effect for both analgesia and respiratory depression. Their high affinity can displace full agonists, potentially precipitating withdrawal or reducing the efficacy of rescue morphine (Khanna & Pillarisetti, 2015).
- Antagonists (e.g., Naloxone, Naltrexone): These agents have high affinity but zero intrinsic activity. They competitively displace agonists from the receptor and are essential for reversing opioid-induced respiratory depression (toxicity) or diagnosing overdose.

<u>2. Classification by Chemical Structure</u>

Understanding the structural class is clinically relevant for managing opioid rotation in patients with allergies or intolerable side effects (nausea/hallucinations, often linked to the 6-hydroxyl group in phenanthrenes)

- Phenanthrenes: Morphine, Codeine, Oxycodone, Hydromorphone, Buprenorphine.

- Phenylpiperidines: Fentanyl, Sufentanil, Remifentanil. (Synthetic opioids characterized by high potency and lipid solubility).
- Diphenylheptanes: Methadone. Benzomorphans: Pentazocine (rarely used in modern trauma protocols).

3.6.8.2 Modulation of the Affective Component

Beyond somatic analgesia, strong opioids act centrally on the limbic system (via mu-receptors on GABAergic interneurons in the VTA and nucleus accumbens). By disinhibiting dopaminergic and serotonergic pathways, they induce a state of "emotional detachment" from the pain (Zubieta et al., 2003). In the context of chest trauma, this anxiolytic effect is beneficial for reducing the distress of air hunger (dyspnea), provided it does not compromise the respiratory drive.

3.6.8.4 Systemic Adverse Effects of Opioids: The Clinical Limiting Factor

While opioids provide potent analgesia via central mechanisms, their lack of receptor selectivity leads to a myriad of systemic adverse effects. In the context of chest trauma, these complications can compromise physiological reserves, creating a narrow therapeutic index.

<u>1. Respiratory Depression: The Primary Threat</u>

The most lethal adverse effect is Opioid-Induced Respiratory Depression (OIRD). Opioids activate mu-receptors in the pre-Bötzinger complex of the brainstem, reducing the sensitivity of respiratory centers to hypercapnia (CO_2). This results in a decrease in respiratory rate and tidal volume. In a patient already suffering from V/Q mismatch due to pulmonary contusion and restrictive mechanics due to rib fractures, OIRD can precipitate acute respiratory failure. This risk is dose-dependent and exacerbated by the concurrent use of sedatives (e.g., benzodiazepines) (Dahan et al., 2010).

<u>2. Gastrointestinal Effects: Opioid-Induced Bowel Dysfunction (OIBD)</u>

mu-receptors are densely expressed in the enteric nervous system (Auerbach's and Meissner's plexuses). Opioid binding inhibits acetylcholine release, leading to:

- Reduced Peristalsis: Delayed gastric emptying and constipation (affecting 40-95% of patients).
- Sphincter Hypertonicity: Specifically of the Sphincter of Oddi, causing biliary colic or functional obstruction (dilation of the common bile duct), which can mimic abdominal trauma injuries (Brock et al., 2012).
- Nausea and Vomiting (PONV): Triggered by direct stimulation of the Chemoreceptor Trigger Zone (CTZ) and vestibular apparatus.

In trauma patients, OIBD and constipation increase intra-abdominal pressure, elevating the diaphragm and further reducing functional residual capacity (FRC) potentially complicating the course of a polytrauma patient (e.g., increasing intra-abdominal pressure). To counteract this without losing analgesia, fixed-dose combinations of Prolonged-Release Oxycodone and Naloxone (e.g., ratio 2:1) have been developed. Naloxone has very low oral bioavailability due to extensive first-pass hepatic metabolism. When taken orally, it blocks local mu-receptors in the gut (preventing constipation) but is metabolized before it can antagonize the central analgesic effect of Oxycodone in the brain (Simpson et al., 2008).

Moreover, PAMORAs (Peripherally Acting Mu-Opioid Receptor Antagonists) like Methylnaltrexone or fixed-dose Oxycodone/Naloxone can mitigate these effects, they add pharmacological complexity and cost (Brock et al., 2012).

3. Cardiovascular and Urinary Effects

Hemodynamic Instability: Morphine induces histamine release, causing vasodilation and hypotension. This is particularly deleterious in hypovolemic trauma patients. Methadone carries a specific risk of QT-interval prolongation and Torsades de Pointes (Rouby et al., 1981).

Urinary Retention: Opioids increase the tone of the vesical sphincter and decrease the detrusor reflex, often necessitating urinary catheterization, which introduces a risk of Catheter-Associated Urinary Tract Infections (CAUTI). This is notably common with neuraxial (epidural) administration (Verhamme et al., 2008).

4. Long-term Sequelae: Tolerance and Hyperalgesia

Even in acute settings, the phenomena of neuroadaptation can complicate management:

- Tolerance: A physiological desensitization requiring escalating doses to maintain analgesia.
- Opioid-Induced Hyperalgesia (OIH): A paradoxical state where opioid exposure lowers the pain threshold, causing diffuse pain sensitivity, probably mediated by NMDA receptor activation and neuroinflammation. Clinically, this can be mistaken for worsening trauma pain, leading to a dangerous cycle of dose escalation (Lee et al., 2011).

3.6.9 Ketamine: The NMDA Antagonist and Dissociative Anesthetic

3.6.9.1 Mechanism of Action and Classification

Ketamine is a phencyclidine derivative introduced in clinical practice in 1970. Ketamine acts primarily as a non-competitive antagonist at the N-methyl-D-aspartate (NMDA) receptor located in the dorsal horn of the spinal cord and the brain. By blocking the NMDA channel, Ketamine interrupts the transmission of excitatory signals (mediated by Glutamate) and prevents the influx of calcium. While opioids treat pain that is already perceived, Ketamine prevents the amplification of the pain signal, making it particularly effective against the neuropathic component of rib fracture pain (Peltoniemi et al., 2016; Riccardi et al., 2023). Moreover, this mechanism is of primary importance in the setting of Central sensitization, being able to reduce the "Wind-Up" phenomena.

Secondary mechanisms include (Riccardi et al., 2023):

- Weak binding to mu-opioid receptors (synergistic effect).

- Inhibition of monoamine reuptake (Serotonin, Norepinephrine, Dopamine), contributing to descending inhibitory modulation and antidepressant effects.
- Anti-inflammatory activity via inhibition of cytokine production

Ketamine is highly lipid-soluble, ensuring rapid onset. It undergoes extensive hepatic metabolism (CYP3A4) into Norketamine, an active metabolite with approximately 30% of the analgesic potency of the parent compound. Its plasma half-life is short (2-3 hours), but the accumulation of Norketamine can prolong analgesia. Unlike opioids, Ketamine is a sympathomimetic: it increases heart rate and blood pressure, making it the induction agent of choice in hypotensive trauma patients (Davis et al., 2019; Green et al., 2011; Kurdi et al., 2014, 2014; Peltoniemi et al., 2016; Riccardi et al., 2023).

3.6.9.2 Dose-Dependent Clinical Effects (The "Ketamine Curve")

The clinical effects of ketamine are strictly dose-dependent, creating a continuum from analgesia to general anesthesia.

- Analgesic Dose ("Low-Dose" or "Sub-dissociative"):Dose: 0.1 – 0.3 mg/kg IV.Effect: Potent analgesia without loss of consciousness. The patient remains cooperative but with a significantly higher pain threshold. This is the ideal range for multimodal analgesia in chest trauma.
- Psychomimetic Dose:Dose: 0.35 – 0.5 mg/kg IV.Effect: This is the "therapeutic window" to avoid. Patients may experience dysphoria, hallucinations, and agitation (resembling acute psychosis/schizophrenia).
- Dissociative Anesthetic Dose: Dose: 1 – 2 mg/kg IV (Induction). The patient enters a catalepsy-like state characterized by a functional dissociation between the thalamocortical system (consciousness) and the limbic system (emotions). The patient may appear awake with eyes open ("The lights are on, but nobody's home"), yet they are profoundly unresponsive to sensory input. Crucially, pharyngeal and laryngeal reflexes remain intact, and spontaneous respiration is maintained, offering a significant safety advantage over opioids in patients with compromised airways (Green et al., 2011).

3.6.9.3 Role in Chest Trauma Management

Ketamine represents an essential "Step 3/4" adjuvant. Its ability to maintain respiratory drive and bronchodilation (via smooth muscle relaxation) makes it superior to opioids for patients with severe pulmonary contusion or asthma. However, its side effect profile (emergence delirium, hypersalivation, tachycardia) limits its use as a monotherapy.

3.6.10 Adjuvant Medications in Multimodal Trauma Protocols

Adjuvant analgesics are defined as drugs whose primary indication is not pain management but which possess analgesic properties in specific clinical contexts. In chest trauma, they are indispensable components of Multimodal Analgesia, specifically targeting the neuropathic and muscular components of rib fracture pain that often resist standard opioid therapy.

1) Anticonvulsants (Gabapentinoids)

Gabapentin and Pregabalin are the first-line adjuvants for managing the neuropathic component of chest trauma (e.g., traumatic intercostal neuralgia).

Mechanism: They bind to the alpha 2-\delta subunit of voltage-gated calcium channels in the CNS, reducing the release of excitatory neurotransmitters (glutamate, substance P).

Clinical Role: Several studies suggest that early initiation of gabapentinoids in rib fracture patients reduces neuropathic pain intensity and total opioid consumption.Limitations: Dose-dependent dizziness and sedation can interfere with early mobilization and respiratory physiotherapy, particularly in the elderly (Gordh et al., 2008).

2) Intravenous Lidocaine

Systemic lignocaine (Lidocaine) infusions have emerged as a valuable alternative when regional anesthesia is contraindicated or technically not feasible.

Mechanism: It creates a "pharmacological block" by blocking sodium channels and exerting potent anti-inflammatory effects on the traumatized lung and chest wall.

Efficacy: Meta-analyses indicate it significantly reduces pain scores and opioid requirements in patients with multiple rib fractures (Patton et al., 2022).

3) Muscle Relaxants

Reflex muscle spasm of the intercostal, latissimus dorsi, and pectoral muscles contributes significantly to the "dynamic" pain of rib fractures.

Agents: Cyclobenzaprine, Baclofen, or Methocarbamol.

Clinical Role: While useful for breaking the spasm-pain cycle, their use is limited by their sedative potential. They should be used cautiously to avoid compounding opioid-induced sedation (Bresgen et al., 2025).

4) Antidepressants (TCAs and SNRIs)

Tricyclic Antidepressants (TCAs) (e.g., Amitriptyline) and Serotonin-Norepinephrine Reuptake Inhibitors (SNRIs) (e.g., Duloxetine) are effective for subacute or chronic neuropathic pain (Bates et al., 2019; Finnerup et al., 2015; Moisset et al., 2021).

Mechanism: They inhibit the reuptake of serotonin and norepinephrine, enhancing the descending inhibitory pain pathways.

Trauma Context: Their slow onset of action makes them less useful in the hyper-acute phase (Emergency Department), but they are crucial for preventing the transition to chronic post-traumatic pain. Note: SSRIs are generally considered less effective than TCAs/SNRIs for pain.

5) Management of Side Effects

Prokinetics and Laxatives: Given the near-certainty of opioid-induced constipation, prophylactic regimens (e.g., Macrogol, Senna) are mandatory for all patients on opioids.

Benzodiazepines (A Warning): While useful for anxiety, benzodiazepines act synergistically with opioids to depress respiratory drive. In patients with compromised respiratory mechanics due to chest trauma, they should be avoided or used with extreme caution to prevent respiratory failure (Jones et al., 2012).

Relevance to the Thesis

The complexity and side effect burden of these adjuvant cocktails (sedation from gabapentinoids, hypotension from lidocaine, respiratory depression from benzodiazepines) further validate the search for a definitive regional solution. Fascial Plane Blocks (ESP/SAP) offer the unique advantage of treating the neuropathic and somatic components directly at the source, potentially rendering this complex polypharmacy unnecessary.

3.6.11 Non-Pharmacological Adjuvants in Chest Trauma

In the context of Multimodal Analgesia, non-pharmacological interventions represent a complementary strategy aimed not at blocking nociception directly, but at modulating the affective-motivational component of pain. By reducing anxiety and muscle tension, these techniques can lower the perception of pain via the Gate Control mechanism and descending inhibitory pathways (Melzack & Wall, 1965).

1) Physical Modalities

Unlike psychological interventions, physical modalities interact directly with peripheral tissues and spinal processing.

- Transcutaneous Electrical Nerve Stimulation (TENS)

TENS is the most relevant non-pharmacological modality for rib fractures. It involves the application of electrical current via skin electrodes to stimulate large-diameter A-1beta fibers.

Mechanism: Activation of A-3beta fibers inhibits nociceptive transmission from C-fibers at the dorsal horn (Gate Control Theory).

Evidence: Several studies, including a meta-analysis by Sbruzzi et al., indicate that TENS, when added to pharmacological therapy, significantly reduces pain intensity and improves vital capacity in patients with rib fractures (Johnson et al., s.d.; Oncel et al., 2002).

- Cryotherapy (Cold Therapy)

The application of ice packs is a simple, cost-effective measure.

Mechanism: Vasoconstriction reduces local edema and inflammation, while cooling decreases the conduction velocity of peripheral nerves.

Clinical Role: Useful for superficial contusions and anterior rib fractures (Bleakley et al., 2004).

2) Cognitive-Behavioral and Mind-Body Therapies

Anxiety is a potent amplifier of pain. In chest trauma, the fear of "air hunger" (dyspnea) creates a feedback loop of panic and tachypnea.

- Relaxation Techniques and Hypnosis

Techniques involving diaphragmatic breathing (where feasible), progressive muscle relaxation, and guided imagery aim to reduce sympathetic outflow. Hypnosis has shown efficacy in procedural pain and acute trauma settings. By inducing a state of focused attention, it allows the patient to dissociate from the painful stimulus. Studies suggest that hypnosis can stabilize hemodynamic parameters and reduce anxiety during invasive procedures (e.g., chest tube insertion) (Patterson & Jensen, 2003).

- Music Medicine

Music serves as a powerful auditory distractor and anxiolytic.

Mechanism: Listening to music stimulates the limbic system (nucleus accumbens), promoting dopamine release and reducing cortisol levels.

Application: Distinguishing between Music Therapy (active intervention by a specialist) and Music Medicine (passive listening to recorded music) is important. In the acute trauma setting, passive listening is more feasible. A meta-analysis by Chai et al. confirmed that music reduces self-reported pain and anxiety in acute settings, acting as a valuable opioid-sparing adjunct (Angkoontassaneeyarat et al., 2025).

Limitations and Conclusion

While beneficial for reducing anxiety and the subjective experience of suffering, non-pharmacological therapies have a limited ceiling of efficacy. They are insufficient as monotherapy for the severe, dynamic nociceptive barrage of multiple rib fractures. Their role is strictly adjuvant: they facilitate patient compliance and comfort, but they cannot replace the definitive interruption of nociceptive transmission provided by Regional Anesthesia (ESP/SAP blocks).

Chapter 4: The Clinical Reality: Oligoanalgesia and Barriers to Care

4.1 Definition and Epidemiology

Despite pain being the primary complaint in 70-80% of Emergency Department (ED) visits, a significant gap remains between the prevalence of pain and the quality of its management. This phenomenon is termed "Oligoanalgesia" (from Greek oligos, little/scant), defined as the inadequate, delayed, or absent administration of analgesia despite clinical indications. First described by Wilson and Pendleton in 1989, who noted that 56% of patients with acute pain received no treatment, the problem persists decades later (Wilson & Pendleton, 1989). Recent prospective data confirm this trend globally:

- A study in a Norwegian university hospital found that only 14% of patients with moderate-to-severe pain received analgesics (*Assessment of pain in a Norwegian Emergency Department | Scandinavian Journal of Trauma, Resuscitation and Emergency Medicine*, s.d.).
- In Italy, Mura et al. (2017) reported that among 2,838 ED patients, only 32% received pharmacological treatment, despite 76% reporting severe pain (Mura et al., 2017).

4.2 Root Causes and Barriers

The persistence of oligoanalgesia is multifactorial, stemming from both structural and cultural barriers(Mitchell et al., 2009):

- Opioid Phobia: Reluctance among clinicians to prescribe opioids due to fear of respiratory depression (particularly in the elderly/trauma patients) or addiction potential.
- Lack of Training: Insufficient education in regional anesthesia techniques among emergency physicians and surgeons.
- Overcrowding: ED saturation leads to delayed assessment and administration.

- Diagnostic Bias: The misconception that analgesia might "mask" physical signs (e.g., in abdominal trauma), a dogma long refuted by evidence (Abbuhl & Reed, 2003).

4.3 The Biological Cost of Undertreatment

Oligoanalgesia is not merely a humanitarian failure; it is a clinical hazard.

- Acute Stress Response: Severe untreated pain triggers a massive sympathetic surge (catecholamines, cortisol), increasing myocardial oxygen demand and immunosuppression. In a polytrauma patient, this can precipitate organ failure.
- Chronification: As highlighted by Cohen et al., unrelieved acute pain drives neuroplastic changes (central sensitization). The transition to chronic pain occurs in a significant percentage of trauma patients (up to 50-60% post-thoracotomy/trauma), directly correlating with the intensity of acute pain (Cohen et al., 2004).

4.4 Ethical and Legal Imperatives

Recognizing pain relief as a fundamental human right, international bodies (IASP, WHO, EFIC) promulgated the Declaration of Montreal (2010) (International Pain Summit Of The International Association For The Study Of Pain, 2011). In the Italian context, this ethical duty was codified into law with Legge 38/2010 ("Disposizioni per garantire l'accesso alle cure palliative e alla terapia del dolore"). This landmark legislation mandates the recording of pain intensity in the medical record as a vital sign and simplifies the prescribing of opioids, making the failure to treat pain not only unethical but potentially legally actionable (*Gazzetta Ufficiale*, s.d.).

4.5 Conclusion: The Case for Protocolized Regional Anesthesia

The prevalence of oligoanalgesia, driven largely by the fear of systemic opioid side effects ("Opioid Phobia"), creates a critical need for alternative strategies. Ultrasound-Guided Fascial Plane Blocks (ESP and SAP) directly address these barriers:

- They provide potent analgesia without systemic respiratory depression (bypassing the fear of opioids)
- They are technically feasible in the ED setting.
- They offer a "definitive" solution that prevents the central sensitization driving chronic pain.

This thesis aims to demonstrate that implementing these blocks is the most effective strategy to bridge the gap between the ethical mandate to treat pain and the clinical reality of trauma care.

Chapter 5. Ultrasound-Guided Fascial Plane Blocks: Comparative Efficacy and Clinical Implementation

5.1. The Paradigm Shift: From Neuraxial Exclusion to Fascial Standard of Care

The analgesic management of blunt chest trauma has historically been anchored to the "gold standard" of Thoracic Epidural Analgesia (TEA). While TEA provides potent, segment-specific analgesia, its application in the acute trauma setting is frequently hindered by a narrow therapeutic index and stringent contraindications. As highlighted by Jensen et al., the polytrauma patient often presents with coagulopathy (traumatic or pharmacologically induced), hemodynamic instability, or vertebral fractures, rendering neuraxial techniques unsafe or technically unfeasible in a significant proportion of cases (Jensen et al., 2018). In response to these limitations, a decisive paradigm shift has occurred with the advent and widespread adoption of Ultrasound-Guided Fascial Plane Blocks ("Wall Blocks"). Defined by the injection of large volumes of local anesthetic into potential intermuscular spaces, these techniques rely on passive, volume-dependent hydrodissection to bathe the peripheral nerves traversing the fascial layers (Chin & El-Boghdadly, 2021; Edwards et al., 2021; Gamberini et al., 2025; Kot et al., 2019; Marhofer et al., 2020; Thiruvenkatarajan et al., 2018). This mechanism offers a superior safety profile: by avoiding the neuraxis, fascial blocks minimize the risk of spinal hematoma and sympathetic blockade-induced hypotension, making them viable even in anticoagulated or hemodynamically labile patients.

This transition is not merely technical but represents a strategic evolution in trauma care governance, supported by major international guidelines. The Eastern Association for the Surgery of Trauma (EAST) guidelines explicitly emphasize the necessity of multimodal analgesia (MMA) to prevent pulmonary morbidity, advocating for regional techniques that spare systemic opioids (Galvagno et al., 2016). Crucially, the ownership of these procedures has expanded beyond the domain of Anesthesiology. As articulated in the landmark Policy Statement by the American College of Emergency Physicians (ACEP), ultrasound-guided nerve blocks (UGNBs) are now recognized as "core competencies" for

Emergency Physicians (EPs). The policy asserts that EPs should possess the training and credentialing to perform these procedures as part of routine multimodal pain management in the Emergency Department (ED) (*Ultrasound-Guided Nerve Blocks | ACEP*, s.d.). This stance is reinforced by Gottlieb (2025), who argues that integrating UGNBs into standard emergency care is an ethical imperative to combat oligoanalgesia and the opioid epidemic (Gottlieb, 2024). Empirical evidence of this adoption is provided by the recent scoping review by Gawel et al. (2025). In their comprehensive analysis of the literature, the authors document an exponential trajectory in EP-performed blocks over the last decade. Specifically, the Serratus Anterior Plane (SAP) and Erector Spinae Plane (ESP) blocks have emerged as the vanguard techniques, identified as the most rapidly adopted and extensively studied interventions for thoracic trauma in the emergency setting due to their favorable learning curve and high safety margin (Gawel et al., 2025).

5.2. Serratus Anterior Plane (SAP) Block

5.2.1. Historical Evolution and Nomenclature

First described by Blanco et al. in 2013, the SAP block was originally conceived to target the lateral cutaneous branches of the intercostal nerves (T2-T9) for breast surgery analgesia. It has since become a cornerstone of trauma analgesia due to its simplicity and efficacy for anterolateral rib fractures (Blanco et al., 2013). The nomenclature has been standardized by the ASRA-ESRA Delphi Consensus (2021) into two distinct approaches based on the injection plane relative to the Serratus Anterior Muscle (SAM): Superficial and Deep (El-Boghdadly et al., 2021).

5.2.2. Comparative Anatomy: Superficial vs. Deep Approach

The injection is performed in the mid-axillary line, where the SAM overlies the ribs. The choice of plane dictates the physiological mechanism and safety profile.

1. Superficial SAP Block (The Inter-muscular Plane)

Target: The potential space between the Latissimus Dorsi Muscle (LDM) and the Serratus Anterior Muscle (SAM).

Physiological Mechanism: This plane contains the cutaneous sensory branches and the Long Thoracic Nerve (LTN). While nerve injury is a theoretical risk in blind techniques, under ultrasound guidance, bathing the LTN with local anesthetic is a strategic opportunity. Temporary paresis of the serratus anterior muscle reduces the reflex muscle spasm associated with rib fractures. As noted by Mayes et al., this "spasmolysis" acts synergistically with sensory blockade to control dynamic pain during coughing and deep inspiration (Mayes et al., 2016).

Pharmacokinetics: Some authors, such as Piracha et al., suggest that the superficial plane, being less vascularized than the deep muscular interface, may promote slower absorption of local anesthetic, potentially extending the duration of analgesia (Piracha et al., 2017).

2. Deep SAP Block (The Retro-Serratus Plane)

Target: The plane between the SAM and the external intercostal muscles/ribs.

Safety Profile: This approach uses the rib as a definitive osseous "backstop". This anatomical barrier minimizes the risk of pleural puncture and pneumothorax, making the deep approach technically safer and more reproducible for operators with varying levels of ultrasound experience in the acute setting (Serra et al., 2024).

5.2.3. The Debate on Superiority: Clinical Evidence

The comparative efficacy of the superficial versus deep SAP block remains a subject of ongoing debate in regional anesthesia literature, with consensus often diverging based on the clinical indication. Qiu et al. (2021) and Tan et al. (2022) argue for the superiority of the superficial approach in thoracic and breast surgery, positing that the inter-muscular plane between the latissimus dorsi and serratus anterior facilitates optimal diffusion to the lateral cutaneous branches of the intercostal nerves, thereby better controlling incisional pain (Qiu et al., 2021; Tan et al., 2022). Conversely, in the setting of rib fractures, the deep approach is increasingly favored. Piracha et al. (2017) and Edwards et al. (2021) suggest that the deep plane creates a "depot effect" beneath the heavy musculature, maximizing contact with the periosteum and pleura to treat deep somatic and visceral pain (Edwards et al., 2021; Piracha et al., 2017).Moreover, a recent trial by Mostafa et al. (2024) in rib fracture patients demonstrated that the deep SAP block provided superior analgesic duration and improved deep breathing compared to the superficial variant (Mostafa et al., 2025).

5.3. Erector Spinae Plane (ESP) Block

5.3.1. Historical Evolution and Rapid Adoption

Since its first description by Forero et al. in 2016 for the management of thoracic neuropathic pain, the ESP block has experienced a meteoric rise in clinical application (Forero et al., 2016). Originally conceptualized as a simple alternative to paravertebral blockade for chronic pain, its indication quickly expanded to acute trauma and surgery. As noted in the scoping review by Gawel et al. (2025), the ESP block is currently one of the fastest-growing techniques in Emergency Medicine literature, accounting for a significant proportion of novel publication trends. Its popularity stems from its safety profile: unlike the paravertebral block, the ESP target is distant from the pleura, separated by the transverse process, which acts as an anatomical safety barrier (Gawel et al., 2025).

5.3.2. Mechanism of Action: "Paravertebral by Proxy"

The ESP block is defined as a paraspinal fascial plane block. The injection is performed deep to the erector spinae muscle complex (spinalis, longissimus, iliocostalis) at the tip of the transverse process. The mechanism of analgesia is the subject of extensive anatomical investigation. The prevailing hypothesis, supported by cadaveric and MRI studies cited by Kot et al., posits that the local anesthetic diffuses anteriorly through the costotransverse foramen (the "anatomical window") into the paravertebral space (Kot et al., 2019). This diffusion pathway allows the ESP block to function as a "paravertebral block by proxy," theoretically targeting:

- Dorsal Rami: Providing analgesia to the posterior chest wall and spinal muscles (critical for posterior rib fractures).
- Ventral Rami (Intercostal Nerves): Providing analgesia to the lateral and anterior chest wall.

- Rami Communicantes: Reaching the sympathetic chain, thereby modulating visceral pain—a distinct advantage over the SAP block, which is strictly somatic [130].

5.3.3. Standardized Technique (USRA & NYSORA Protocol)

To ensure reproducibility and safety, adherence to standardized guidelines (USRA, NYSORA) is mandatory (El-Boghdadly et al., 2021; Sotome et al., 2021).

- Patient Position: The patient is typically placed in a sitting, lateral decubitus, or prone position. Note: This requirement represents a significant logistical limitation in the polytrauma patient with unstable spinal or pelvic injuries, compared to the supine-friendly SAP block.
- Probe Selection: High-frequency Linear (for thin patients/upper thoracic) or Convex (for obese/muscular patients).
- Scanning Technique: Place the probe in a paramedian sagittal orientation, approximately 2–3 cm lateral to the spinous processes.
- Landmark Identification: Crucial differentiation between the Transverse Processes (TPs) and the Ribs. TPs appear as "squared-off" acoustic shadows, while ribs appear as rounded, hyper-echoic contours with the pleura visible immediately deep to them.
- Identify the three muscular layers: Trapezius (superficial), Rhomboids (middle), and Erector Spinae (deep).
- Needle Approach: In-plane, cranio-caudal orientation. The needle tip must traverse the erector spinae muscle and contact the tip of the TP.
- Injection: Hydrodissection of the fascial plane between the muscle and the bone.
- Volume: Large volumes (20–30 mL of Ropivacaine 0.5%) are necessary to generate sufficient pressure for anterior diffusion into the paravertebral space [131].

5.3.4. Efficacy and Systemic Outcomes

The ESP block is unique among peripheral techniques for its demonstrated impact on systemic recovery parameters.

- Respiratory Mechanics (Spirometry): El Malla et al. (2022) provided pivotal physiological evidence, demonstrating that the ESP block significantly increases inspiratory capacity in patients with rib fractures increasing diaphragmatic excursion in multiple rib fractures. By mitigating the sharp pain of chest expansion, the block reverses the "splinting" phenotype, directly targeting the pathophysiology of post-traumatic pneumonia (El Malla et al., 2022).
- Hospital Length of Stay (LOS): The 2025 network meta-analysis by Gamberini et al. identified the ESP block as the only peripheral technique capable of significantly reducing hospital LOS (Mean Difference −1.8 days; 95% CrI: −3.1 to −0.4) compared to systemic analgesia. In this domain, the ESP block performed comparably to the gold-standard Thoracic Epidural, likely due to its broader dermatomal and visceral coverage (Gamberini et al., 2025).
- Opioid Sparing: Multiple randomized trials confirm its potency. Abdelhamid et al., Elsabeeny et al. and several trials and systemic reviews reported significant reductions in 24-hour opioid consumption compared to systemic therapy. Furthermore, in comparative studies involving thoracic surgery (VATS), the ESP block has shown superiority over the SAP block in reducing fentanyl consumption, attributed to its ability to block the posterior and visceral nociceptive inputs that the SAP block spares (El Malla et al., 2022; Elsabeeny et al., 2021; Finnerty et al., 2020; Gaballah et al., 2019, 2019; Gamberini et al., 2025; Taketa et al., 2019).

5.3.5. Limitations and Weaknesses

Despite its efficacy, the ESP block is not without limitations:

- Positioning: The need for posterior access is a major barrier in the undifferentiated trauma patient who is strictly immobilized supine.

- Variable Spread: The diffusion into the paravertebral space is variable and volume-dependent. In some cases, the block may remain confined to the dorsal compartment, resulting in excellent back analgesia but patchy anterior coverage (an outcome less consistent than the targeted SAP block for lateral fractures).
- Technical Complexity: While safer than a paravertebral block, distinguishing TPs from ribs requires a higher level of sonographic skill than identifying the serratus anterior muscle, presenting a steeper learning curve for non-specialists.

5.4. Discussion: Comparative Analysis and Clinical Outcomes

The integration of ultrasound-guided fascial plane blocks into trauma protocols necessitates a rigorous comparison of efficacy. The current literature presents a complex dichotomy: while the Erector Spinae Plane (ESP) block demonstrates superior theoretical coverage and systemic outcomes in aggregate analyses, the Serratus Anterior Plane (SAP) block exhibits robust non-inferiority in real-world trauma settings, often with a more favorable safety-feasibility profile.

5.4.1. Analgesic Efficacy: Intensity and Duration

The primary endpoint of most comparative trials is the reduction in Visual Analog Scale (VAS) or Numeric Rating Scale (NRS) scores.

Gaballah et al. (2019) and Elsabeeny et al. (2021) compared the two techniques in patients undergoing video-assisted thoracoscopic surgery (VATS) and thoracotomy. Both studies concluded that the ESP block resulted in significantly lower postoperative pain scores and reduced total fentanyl consumption compared to the SAP block (Elsabeeny et al., 2021; Gaballah et al., 2019). However, El Malla & El Fawy (2022), while finding a statistical difference favoring ESP in trauma patients, noted that the absolute difference in pain scores was often less than 1.5 points on the NRS. This raises the question of clinical relevance: does a marginal improvement in pain score justify the increased technical complexity and repositioning required for an ESP block? (El Malla et al., 2022).

The Bayesian network meta-analysis by Gamberini et al. provides a high-level synthesis comparing various regional techniques against a control group receiving only intravenous (IV) analgesian(Gamberini et al., 2025).

- ESP Block: Demonstrated a robust and statistically significant reduction in pain intensity scores at 24 hours (SMD −0.79).
- SAP Block: In the aggregate analysis, the SAP block did not reach statistical significance over IV analgesia.

5.4.2. Opioid Sparing and Rescue Analgesia

Reducing the "opioid load" is critical to preventing respiratory depression.

ESP Efficacy: Gamberini et al. report that the ESP block is superior to IV analgesia in reducing the cumulative rescue analgesic doses at 24 hours, with an SMD of −1.2 (95% CrI: −2.1, −0.37). In this specific metric, it performed numerically better than the Thoracic Epidural (SMD −0.95)(Gamberini et al., 2025).

SAP Efficacy: Despite the comparative data favoring ESP, the absolute opioid-sparing effect of the SAP block remains clinically profound. Serra et al. (2025) documented a statistically significant reduction in Morphine Milligram Equivalents (MME) in SAP-treated trauma patients versus standard care, confirming its utility as a primary opioid-sparing strategy in the ED (Serra et al., 2025).

5.4.3. Systemic Impact: Hospital Length of Stay (LOS) and Pulmonary Morbidity

The most compelling argument for the ESP block comes from "hard outcomes."

- Length of Stay: According to Gamberini et al., the ESP block is the only peripheral technique associated with a significant reduction in Hospital LOS (Mean Difference −1.8 days; 95% CrI: −3.1, −0.4). The SAP block showed no significant impact on LOS in this meta-analysis (Gamberini et al., 2025).
- Pulmonary Function: Adhikary et al. (2019) utilized incentive spirometry to prove that ESP blockade significantly increases inspiratory volume, directly reversing

the "splinting" physiology (Adhikary et al., 2019). While SAP also improves mechanics, the visceral coverage of the ESP (sympathetic chain) may provide superior relief from the deep, vague visceral pain of pulmonary contusion, facilitating earlier discharge.

5.4.4. Non-Inferiority to the "Gold Standard"

A crucial finding for Emergency Medicine is that fascial blocks are often non-inferior to invasive neuraxial techniques, validating their use as a safer alternative.

SAP vs. Epidural: The multicenter study by Beard et al. (2020) compared SAP, Paravertebral Block (TPVB), and Epidural (TEA) in rib fractures. Strikingly, they found no significant difference in pain scores or functional outcomes at 24 hours, suggesting that the simpler SAP block is clinically equivalent to the gold standard for many patients (Beard et al., 2020).

ESP vs. Paravertebral (TPVB): The Safety-Efficiency Advantage

While the Thoracic Paravertebral Block (TPVB) has historically been considered the "gold standard" for unilateral chest wall analgesia, recent evidence challenges its primacy based on safety and efficiency profiles. Taketa et al. (2019), in a randomized controlled non-inferiority trial, demonstrated that the ESP block provides analgesic efficacy comparable to TPVB (non-inferior NRS scores at 24 hours) but with distinct procedural advantages (Taketa et al., 2019). Specifically, the ESP block is associated with a significantly shorter procedure time and a lower risk of complications such as pneumothorax and hypotension. This safety benefit stems from the anatomical target: unlike the TPVB, which requires needle advancement close to the pleura and sympathetic chain, the ESP block targets the transverse process, which acts as a bony backstop, minimizing the risk of pleural puncture and distinct hemodynamic instability associated with sympathetic blockade (Fenta et al., 2023; Taketa et al., 2019).

Cost-Effectiveness: Jensen et al. (2018) highlighted that while TEA reduces costs compared to systemic opioids, the labor-intensive nature of epidural management (ICU monitoring) is a burden. Fascial blocks, being "single-shot" or catheter-compatible on general wards, offer a more streamlined cost-benefit profile (Jensen et al., 2018).

5.4.5. Synthesis: The "Feasibility vs. Efficacy" Trade-off

The choice between ESP and SAP involves a trade-off between maximum theoretical efficacy and technical feasibility.

The ESP Block appears to be the "systemic champion," offering visceral coverage, LOS reduction, and superior opioid sparing in head-to-head trials. It is the technique of choice for posterior fractures or high-risk patients where preventing pneumonia is paramount.

The SAP Block, however, remains the "pragmatic champion" of the ED. Supported by Beard et al. and Serra et al., it proves non-inferior to invasive standards for pain control while being performable in the supine position—a critical advantage for the unstable polytrauma patient with potential spinal injuries

Chapter 6: Materials and Methods

6.1. Rationale and Study Objectives

6.1.1 Rationale

Chest trauma represents a critical challenge in the polytrauma patient, particularly in the elderly and those with comorbidities, where even minor injuries can precipitate severe respiratory failure. As extensively discussed in previous chapters, the pathophysiology of adverse outcomes is driven by pain-induced hypoventilation, ineffective cough, and subsequent atelectasis. While Thoracic Epidural Analgesia (TEA) has historically been the gold standard, its application in the emergency setting is often limited by contraindications (coagulopathy, spinal trauma) and logistical barriers. Consequently, Ultrasound-Guided Fascial Plane Blocks (specifically SAP and ESP blocks) have emerged as promising, safer alternatives. However, despite their theoretical advantages, data regarding their real-world efficacy when performed by Emergency Physicians (EPs) in the acute phase—and their impact on systemic outcomes such as opioid consumption and respiratory complications—require further validation.

6.1.2 Primary Objective

The primary objective of this study is to evaluate the analgesic efficacy and safety of ultrasound-guided fascial plane blocks (Deep SAPB, Superficial SAPB, and ESPB) administered in the Emergency Department setting for patients with multiple rib fractures.

Specifically, the study aims to:

- Quantify the reduction in pain intensity (measured via NRS) at fixed time intervals (0, 3, 6, 12, 24 hours) following the procedure.
- Compare the analgesic trajectory of patients receiving fascial blocks versus those receiving standard systemic analgesia alone.
- Assess the safety profile of these procedures in the hands of Emergency Physicians, monitoring for immediate complications (e.g., pneumothorax, vascular puncture, LAST).

6.1.3 Secondary Objectives

Secondary objectives focus on the systemic impact of the analgesic intervention:

- Opioid Sparing: To determine if the implementation of fascial blocks significantly reduces the total consumption of opioids (expressed as Morphine Milligram Equivalents - MME) in the first 24 hours.
- Respiratory Function: To evaluate changes in respiratory mechanics, assessed via the SpO_2/FiO_2 ratio or spirometric parameters where available.
- Clinical Outcomes: To analyze the association between early regional analgesia and "hard outcomes," specifically:
- - Incidence of hospital-acquired pneumonia.
- - Need for admission to the Intensive Care Unit (ICU).
- - Need for mechanical ventilation (invasive or non-invasive).
- In-hospital mortality

<u>6.2. Study Design and Setting</u>

This investigation was designed as an observational, prospective, multicentre study. The research was conducted across two high-volume trauma centres in the Emilia-Romagna region of Italy:

- Arcispedale "Sant'Anna" (Ferrara), a Hub University Hospital.
- "M. Bufalini" Hospital (Cesena), a Hub Trauma Center.

Study Period: Data collection spanned from November 2023 to October 2025, enrolling consecutive patients presenting with blunt chest trauma

<u>6.3. Study Population: Inclusion and Exclusion Criteria</u>

The study enrolled adult patients (age > 18 years) presenting to the Emergency Departments of the participating centres with a diagnosis of blunt chest trauma characterized by multiple rib fractures (≥2), confirmed by standard imaging (Chest X-Ray or CT scan). To be eligible, patients were required to report moderate-to-severe pain (Numeric

Rating Scale [NRS] > 4) despite initial systemic analgesia and to have received an ultrasound-guided fascial plane block (Deep/Superficial SAP or ESP) for analgesic purposes within 24 hours of admission. Enrollment was strictly limited to patients managed within the Emergency Department, Short Stay Observation Unit, or Emergency Medicine Ward to ensure consistent monitoring.

Conversely, patients were excluded if they met any of the following criteria:

- Refusal of informed consent.
- Local contraindications to regional anesthesia, such as compromised tissue integrity or active infection at the injection site.
- Known hypersensitivity or allergy to local anesthetics (active ingredients).
- Severe hemodynamic instability requiring immediate massive transfusion or urgent surgical intervention, precluding safe block execution.
- Severe cognitive impairment preventing reliable self-assessment of pain (NRS).
- Direct transfer from the ED to external departments (e.g., Intensive Care Unit, Operating Theatre for non-thoracic surgery) which prevented standardized observational follow-up

6.4. Operator Standardization and Training

To minimize inter-operator variability—a known confounder in ultrasound-guided procedures—a rigorous training protocol was implemented prior to study initiation.

- Curriculum: All participating physicians underwent a standardized theoretical-practical course led by nationally certified instructors in clinical ultrasound and regional anesthesia.
- Credentialing: Following the course, operators entered a period of bedside supervision. Procedures were performed under the direct guidance of an expert mentor until complete technical autonomy was verified.

- Trainee Supervision: Resident physicians followed the same educational pathway but performed all procedures (preparation, execution, and monitoring) under the direct supervision of a credentialed tutor.

6.5. Procedural Protocol and Standardization

To ensure homogeneity across centres, a unified operational protocol was established.

Standardized Equipment Kit: A pre-assembled procedure kit was available in all treatment areas to streamline execution and maintain sterility:

Sterile Field: Chlorhexidine disinfectant, sterile drapes, sterile gauze, gowns, and gloves.

Ultrasound Equipment: Portable ultrasound systems equipped with a high-frequency linear probe (6-13 MHz) were utilized to ensure optimal resolution of superficial fascial planes. Sterile probe covers were mandatory.

Needles and Delivery System: A 20G or 22G Quincke spinal needle connected via silicone extension tubing to a three-way stopcock. This setup allowed for immobile needle placement while a second operator managed the injection (two 20 mL syringes).

6.5.1 Procedural Technique and Sonographic Guidance

All procedures were performed strictly under ultrasound guidance, utilizing a standardized two-operator technique to ensure sterility and precision.

- Operator 1 (Sterile): Responsible for ultrasound scanning, needle insertion, and maintenance of the target view.
- Operator 2 (Assistant): Responsible for managing the injection system (silicone extension tubing, three-way stopcock, and syringes), allowing for controlled aspiration and administration of the anesthetic without disturbing the needle position.

6.5.1.1. Erector Spinae Plane (ESP) Block Technique

- Patient Positioning: The patient is positioned in a sitting posture (where hemodynamically feasible) or lateral decubitus. The arms are crossed anteriorly or rested on a support to abduct the scapulae and maximize exposure of the paravertebral area.

- Sonographic Scanning: A high-frequency linear probe is orientated longitudinally (cranio-caudal axis) approximately 2-3 cm lateral to the spinous processes.

- Identification of Landmarks: The scan begins by identifying the ribs at the mid-scapular level. The probe is then moved medially to capture the transition from the rounded acoustic shadow of the rib to the squared-off, flatter acoustic shadow of the transverse process (TP) of the T5 vertebra.

- Muscular Layers: Superficial to the TP, the Trapezius, Rhomboid Major, and Erector Spinae Muscle (ESM) are visualized in sequence.

- Needle Insertion and Injection: Using an in-plane approach (cranio-caudal or caudo-cranial), the needle is advanced through the ESM until the tip contacts the bony surface of the transverse process.

- Hydrodissection: Correct placement is confirmed by injecting a small bolus (3-5 mL) of normal saline. Visualization of the ESM lifting off the TP (creating a fusiform anechoic pocket) confirms the integrity of the fascial plane.

- Administration: Following negative aspiration, the full volume of local anesthetic is injected. The spread should be visualized extending cranially and caudally along the paravertebral gutter.

6.5.1.2 Serratus Anterior Plane (SAP) Block Technique

- Patient Positioning: The patient is positioned supine with the ipsilateral arm abducted and flexed at 90 degrees (or hand behind the head), exposing the lateral hemithorax and axilla.

- Sonographic Scanning: The linear probe is placed in a transverse or oblique orientation along the mid-axillary line at the level of the 4th or 5th rib (approximately at the nipple line in males).

- Anatomical Landmarks: From superficial to deep, the following structures are identified:

 - Subcutaneous tissue.

 - Latissimus Dorsi Muscle (LDM).

 - Serratus Anterior Muscle (SAM).

 - Ribs (hyperechoic cortex with acoustic shadowing) and the Pleura (hyperechoic line with sliding sign).

- Needle Insertion and Injection: The needle is introduced in-plane (typically antero-posterior direction) to target one of two planes depending on the specific indication and operator judgment:

- Superficial SAP Block: The target is the fascial plane between the Latissimus Dorsi and Serratus Anterior muscles. This plane contains the thoracodorsal artery (a key landmark) and the long thoracic nerve.

- Deep SAP Block: The target is the plane deep to the Serratus Anterior muscle, immediately superficial to the rib. The needle tip is advanced until it contacts the rib, using the bone as a safety backstop.

- Administration: Hydrodissection with saline confirms the opening of the potential space. The local anesthetic is then injected, appearing as a hypoechoic lens spreading between the muscular layers or between the muscle and the rib cage.

6.5.2 Pharmacological Regimen:

Local Anesthetic: Long-acting agents (Ropivacaine 0.5% or Levobupivacaine 0.5%) were used. Dosages were calculated based on patient weight, respecting the maximum safety threshold to prevent Local Anesthetic Systemic Toxicity (LAST).

Safety Measures: Multiparameter monitoring (ECG, SpO2, NIBP) was continuous during the procedure. A rescue kit containing 20% Lipid Emulsion (Intralipid) was readily accessible in all locations as the specific antidote for LAST

6.6. Data Collection and Follow-up

Data were recorded in real-time using a structured electronic case report form (eCRF) at the patient's bedside. Follow-up Schedule: Pain scores (NRS at rest and during deep inspiration/cough) and vital signs were recorded at fixed intervals to construct a precise analgesic trajectory.

Early phase to assess onset and quality of block:

- T0: Baseline (immediately pre-block).
- T15 min,
- T30 min,
- T45 min,
- T60 min:

Late phase to evaluate duration and opioid-sparing effect: T6h, T12h, T24h:

6.6.1 Data Collection and Study Variables

6.6.1.1 Baseline Assessment (T0)

Upon enrolment, a comprehensive baseline assessment was performed to establish clinical status prior to the intervention. The following parameters were systematically recorded:

- Demographic and Anthropometric Data: Age, sex, weight, and height.
- Hemodynamic Parameters: Non-invasive blood pressure (NIBP), heart rate (HR).
- Respiratory Parameters: Respiratory rate (RR), peripheral oxygen saturation (SpO_2), and gas exchange indices derived from arterial blood gas analysis, specifically the PaO_2/FiO_2 ratio (P/F) and the Alveolar-arterial oxygen gradient ($A\text{-}aDO_2$).
- Neurological Status: Level of sedation or agitation assessed via the Richmond Agitation-Sedation Scale (RASS)

- Pain Assessment Methodology: Pain characterization included anatomical localization and intensity quantification under two distinct conditions:

- Static Pain: Measured at rest.

- Dynamic Pain: Measured during deep inspiration or mobilization (coughing).

- Standardized scales were employed based on the patient's cognitive status:

Numeric Rating Scale (NRS): Adopted for communicative, cognitively intact patients (scale 0–10).

Pain Assessment in Advanced Dementia (PAINAD): Utilized for patients with cognitive impairment or inability to verbalize.

6.6.1.2 Severity Scores and Comorbidities

To stratify the study population based on injury severity and baseline health status, validated scoring systems were calculated:

- Injury Severity Score (ISS): To assess global anatomical injury burden.
- Thoracic Trauma Severity Score (TTSS): To specifically quantify chest trauma severity, incorporating age, number of fractures, and pulmonary contusions.
- Charlson Comorbidity Index (CCI): To categorize the burden of pre-existing comorbidities and predict 10-year mortality risk.

6.6.1.3. Longitudinal Monitoring and Follow-up

Following the procedure, a strict monitoring protocol was implemented to evaluate the temporal evolution of analgesia, vital signs, cumulative administration of rescue analgesics and complications were recorded.

Clinical Endpoints and Complications:

The follow-up focused on the occurrence of major adverse events and hard outcomes, defined as:

- Development of symptoms related to or establishing the diagnosis of Local Anaesthetics Toxicity Syndrome (LAST), including (Neal et al., 2018):

1) Central Nervous System signs:

i) *Prodromal Symptoms* (Metallic taste or Dysgeusia; Circumoral paraesthesia or Numbness around the mouth/lips; Tinnitus or auditory changes.; Light-headedness or dizziness; Visual disturbances.

ii) *Excitatory Phase* (Agitation, confusion, or anxiety; Muscle twitching or tremors; Generalized tonic-clonic seizures.

iii) *Depressive Phase* (Drowsiness or obtundation; Coma.; Respiratory depression leading to apnoea;

2. Cardiovascular System (CVS) Signs

i) Initial (Hyperdynamic) Phase (Hypertension; Tachycardia)

ii) Progressive (Depressive) Phase: (Hypotension; Bradycardia; Conduction defects; Ventricular arrhythmias; Asystole.

- Development of hospital-acquired pneumonia.

- Need for escalation of care (admission to the Intensive Care Unit - ICU).

- In-hospital mortality.

6.7. Statistical Analysis

Statistical analyses were performed using IBM SPSS version 25 (IBM Corp., Armonk, NY, USA), MedCalc version 17.6 (MedCalc Software, Ostend, Belgium), and JAMOVI version 2.6.24 (The jamovi project, 2024).

6.7.1 Descriptive Statistics:

Continuous variables were evaluated for distribution normality. Given the non-normal distribution of the dataset, continuous data are expressed as median and interquartile range (IQR).

Categorical variables are reported as absolute numbers (n) and percentages (%).

6.7.2 Inferential Statistics:

- Continuous Variables: Differences between two independent groups were compared using the Mann–Whitney U test. For the comparison of paired data (intra-group longitudinal analysis, e.g., T0 vs T1h), the Wilcoxon signed-rank test was utilized.

- Categorical Variables: Differences between two independent groups were assessed using the Pearson Chi-square test (chi^2). Comparisons between paired categorical groups were performed using the McNemar test.

The level of statistical significance was set at $p < 0.05$ (two-tailed) for all analyses.

Chapter 7: results

7.1. Demographic and Baseline Characteristics

The study population comprised 145 patients who received fascial nerve blocks, consisting of 44 women (30%) and 101 men (70%). The analgesic techniques performed were distributed as follows: 31 Erector Spinae Plane (ESP) blocks, 114 Serratus Anterior Plane (SAP) blocks (106 deep SAP block (92%) and 8 superficial SAP block (8%)).

The median age of the cohort was 62 years (IQR 52-74). The median Body Mass Index (BMI) was 26.1 (IQR 23.4-28.4), while the burden of comorbidities, assessed via the Charlson Comorbidity Index (CCI), showed a median score of 2 (IQR 1–3). The prevalence of Chronic Obstructive Pulmonary Disease (COPD) within the sample was 9.70%.

Vital signs and blood gas analysis parameters recorded upon admission showed no significant deviations, except for HR, which was significantly lower in the ESP group, as detailed in Table 1.

Table 1. general characteristics of patients included.

Characteristic	**N = 145**	**SAP block, N = 11 (79%)**	**ESP block N = 31 (21%)**	**p-value**
Sex, male	101 (70%)	74 (65%)	27 (87%)	0.017
Age, years	62 (52, 74)	62 (52, 76)	64 (56, 70)	0.92
BMI	26.1 (23.4, 28.4)	26.6 (23.5, 29.1)	25.8 (22.9, 26.7)	0.086
Myocardial infarction	8 (11%)	5 (8.8%)	3 (20%)	0.35
CHF	3 (4.2%)	2 (3.5%)	1 (6.7%)	0.51
Peripheral vascular	1 (1.4%)	0 (0%)	1 (6.7%)	0.21
CVA or TIA	8 (11%)	5 (8.8%)	3 (20%)	0.35
Dementia	5 (6.9%)	5 (8.8%)	0 (0%)	0.58
Chronic pulmonary	7 (9.7%)	5 (8.8%)	2 (13%)	0.63
Connective tissue disease	2 (2.8%)	2 (3.5%)	0 (0%)	>0.99
Peptic ulcer disease	2 (2.8%)	2 (3.5%)	0 (0%)	>0.99
Liver disease	5 (7.0%)	4 (7.1%)	1 (6.7%)	>0.99
Diabetes mellitus	8 (11%)	7 (12%)	1 (6.7%)	>0.99
Moderate to severe CKD	2 (2.8%)	0 (0%)	2 (13%)	0.041

Solid tumor	4 (5.6%)	4 (7.0%)	0 (0%)	0.57
Metastatic Solid tumor	2 (2.8%)	2 (3.5%)	0 (0%)	>0.99
Leukemia				
Lymphoma	2 (2.8%)	2 (3.5%)	0 (0%)	>0.99
AIDS				
Charlson Comorbidity	2.00 (1.00, 3.00)	2.00 (1.00, 3.75)	2.00 (1.00, 3.00)	0.79
exclusively chest trauma	40 (51%)	30 (48%)	10 (62%)	0.29
multiple pain sites	17 (12%)	15 (13%)	2 (6.5%)	0.53
RASS				0.34
-1,00	7 (4.9%)	7 (6.2%)	0 (0%)	
0,00	121 (84%)	92 (81%)	29 (94%)	
1,00	12 (8.3%)	11 (9.7%)	1 (3.2%)	
2,00	4 (2.8%)	3 (2.7%)	1 (3.2%)	
RR, apm	18.0 (16.0, 20.0)	18.0 (16.0, 20.0)	18.0 (15.0, 18.0)	0.17
Spo2, %	96.00 (94.00, 97.00)	96.00 (94.00, 97.00)	97.00 (95.50,	0.085
fiO2, %				0.78
21,00	38 (26%)	29 (25%)	9 (29%)	
32,00	2 (1.4%)	2 (1.8%)	0 (0%)	
36,00	4 (2.8%)	3 (2.6%)	1 (3.2%)	
50,00	5 (3.4%)	5 (4.4%)	0 (0%)	
HR, ppm	80 (70, 90)	80 (70, 90)	70 (65, 79)	0.002
SBP, mmHg	140 (124, 150)	140 (130, 150)	130 (120, 150)	0.18
DBP, mmHg	80 (70, 90)	80 (70, 90)	80 (70, 85)	0.062

Note: All data are expressed in median (25, 75 percentile) or number (%). AIDS: Acquired Immunodeficiency Syndrome; CHF: Chronic heart failure; CKD: chronic kidney disease; CVA: Cerebrovascular Accident; DBP: Diastolic blood pressure; FiO2: fraction of inspired oxygen; HR: heart rate; RASS: Richmond agitation sedation scale; RR: respiratory rate, SBP: systolic blood pressure; TIA: transient ischemic attack

7.2. Injury Characteristics and Severity Scores

Consistent with the inclusion criteria, the cohort consisted exclusively of blunt trauma patients; no cases of penetrating injury were recorded. From an anatomical perspective, isolated chest trauma (without significant extra-thoracic injuries) accounted for 51% of the sample. However, regarding symptomatology, 128 patients (88%) reported pain localized solely to the thoracic region, indicating that in the remaining polytrauma subset, chest pain was the dominant or most distressing symptom.

Severity Assessment:

The clinical burden of injury was moderate-to-severe.

iii) The median Thoracic Trauma Severity Score (TTSS) was 8 (IQR 7–9.8).

iv) The median Injury Severity Score (ISS) was similarly 9 (IQR 4–13).

As illustrated in Table 2, the study groups (i.e. patients who underwent SAP or ESP block) were homogeneous with respect to the mechanism of injury, trauma severity—assessed via Abbreviated Injury Scale (AIS) and Injury Severity Score (ISS), except for the abdomen AIS score, which was higher in the SAP block group, and the number and location of fractured ribs.

However, most importantly, patients who underwent ESP blocks compared to those who underwent SAP blocks had more frequent and higher numbers of total lateral rib fractures and bifocal lateral rib fractures ($p < 0.05$) (see Table 2).

Table 2. Severity of the trauma sustained as a function of the type of trauma, AIS and ISS, and number and location of rib fractures

Characteristic	**N = 145**	**SAP block, N = 114 (79%)**	**ESP block N = 31 (21%)**	**p-value**
Trauma Team	26 (36%)	23 (40%)	3 (20%)	0.14
Penetrating	0 (0)	0 (0)	0 (0)	
Exclusive	40 (51%)	30 (48%)	10 (62%)	0.29
Multiple pain	17 (12%)	15 (13%)	2 (6.5%)	0.53
Head/neck AIS				0.54
0	63 (80%)	51 (81%)	12 (75%)	
1	4 (5.1%)	2 (3.2%)	2 (12%)	
2	9 (11%)	7 (11%)	2 (12%)	
3	1 (1.3%)	1 (1.6%)	0 (0%)	
4	2 (2.5%)	2 (3.2%)	0 (0%)	

Face AIS score				>0.99
0	72 (92%)	56 (90%)	16 (100%)	
1	3 (3.8%)	3 (4.8%)	0 (0%)	
2	2 (2.6%)	2 (3.2%)	0 (0%)	
3	1 (1.3%)	1 (1.6%)	0 (0%)	
Thorax AIS				0.020
1	1 (1.3%)	0 (0%)	1 (6.2%)	
2	41 (53%)	35 (56%)	6 (38%)	
3	26 (33%)	22 (35%)	4 (25%)	
4	9 (12%)	4 (6.5%)	5 (31%)	
5	1 (1.3%)	1 (1.6%)	0 (0%)	
Abdomen AIS				0.020
0	65 (83%)	52 (84%)	13 (81%)	
1	1 (1.3%)	1 (1.6%)	0 (0%)	
2	6 (7.7%)	6 (9.7%)	0 (0%)	
3	3 (3.8%)	3 (4.8%)	0 (0%)	
4	3 (3.8%)	0 (0%)	3 (19%)	
Extremities AIS				>0.99
0	70 (90%)	55 (89%)	15 (94%)	
1	3 (3.8%)	3 (4.8%)	0 (0%)	
2	5 (6.4%)	4 (6.5%)	1 (6.2%)	
External AIS				0.76
0	72 (92%)	57 (92%)	15 (94%)	
1	3 (3.8%)	2 (3.2%)	1 (6.2%)	
2	1 (1.3%)	1 (1.6%)	0 (0%)	
3	2 (2.6%)	2 (3.2%)	0 (0%)	
ISS	9.0 (4.0, 13.0)	9.0 (4.0, 12.0)	13.0 (7.0, 16.5)	0.095

7.3. Baseline Pain Perception

Regarding baseline pain perception (T0), the recorded values indicated severe uncontrolled pain despite pre-hospital or triage analgesia:

v) Static NRS (at rest): 8 (IQR 7-9).

vi) Dynamic NRS (on coughing/movement): 8 (8-10).

Pain intensity was homogeneously distributed across treatment groups ($p > 0.05$). Specifically, prior to the execution of the fascial block, the median static pain score (at rest) was 8 (IQR 7-9] both in the ESP and SAP cohorts.

7.4. Clinical Management and Major Outcomes

7.4.1 Analgesic Management

During the first 24 hours after enrollment, there were no differences between groups in term of paracetamol or NSAIDs administered. Opioids were administered in form of I.V. morphine, I.V. fentanyl, I-V. Tramadol or transcutaneous Fenanyl in 69 patients (47.6%), 50% of cases in SAP block and in 38.7% of cases in ESP block, without significative differences ($p = 0.264$). Considering only patients who reveived opioids, in the first 24 hours patients received a median of 45 MME (IQR 16.5-45), without differences between groups (45 MME (IQR 16.5-52.5) in SAP group vs. 41.25 MME (IQR 14.55-45) in ESP group, $p > 0.05$). Additionally, no difference was found between superficial SAP group, deep SAP group and ESP group ($p = 0.426$) in terms of opioid administration.

7.4.2 Adjunctive therapeutic management

- Emergency Department (ED) Phase

Upon presentation to the ED, respiratory support was required for a significant portion of the cohort: 39% of patients received standard oxygen therapy, 7.6% required High-Flow Nasal Cannula (HFNC), and 2.5% necessitated Non-Invasive Ventilation (NIV). Consistent with the study's inclusion criteria, no patient underwent Orotracheal Intubation (OTI) in the acute phase.

vii) In-Hospital Phase

During the subsequent hospitalization, the demand for respiratory support evolved. Standard oxygen therapy was required by 52% of patients, while the use of HFNC increased to 22%, and NIV was utilized in 3.9% of cases. No patient required escalation to invasive mechanical ventilation (OTI) during the entire hospital stay.

Regarding pharmacological and rehabilitative adjuvants, antibiotic therapy was initiated in 21% of the total population, and respiratory physiotherapy was prescribed for 15 patients (19%). In the aggregate analysis, no statistically significant differences were observed across the three treatment groups (Table 3).

7.4.2.1 Subgroup Analysis: The Impact of Block Type on Care Burden

However, a stratified analysis revealed a notable disparity in the requirement for active respiratory interventions. Patients treated with the Superficial SAP block exhibited a disproportionately higher need for adjunctive care compared to the Deep SAP and ESP groups:

viii) Bronchial Hygiene: Required in 16.7% of the Superficial SAP group, compared to 0% in the Deep SAP and 13.3% in the ESP groups.

ix) Respiratory Physiotherapy: Prescribed for 57.1% of the Superficial SAP group, a rate significantly higher than that observed in the Deep SAP (14.5%) and ESP (18.8%) groups ($p < 0.05$ for all comparisons).

Interpretation of Significance:

While these differences reached statistical significance ($p < 0.05$), highlighting a potential clinical trend where superficial blockade correlates with higher care needs, these findings must be interpreted with caution. Given the limited sample size of the Superficial SAP cohort, these high percentages correspond to a small absolute number of patients. Therefore, while the signal is indicative of a higher therapeutic burden, it requires validation in larger cohorts to confirm generalizability.

Table 3. Adjunctive therapeuty intervention, including osygen therapy, HFNC, CPAP, non invasive and invasive ventilation, and chest drainage in the ED and during in-hospital stay.

Characteristic	N = 145	SAP block, N = 114 (79%)	ESP block N = 31 (21%)	p-value
ED_o2tp	31 (39%)	26 (41%)	5 (31%)	0.46
ED_HFNC	6 (7.6%)	5 (7.9%)	1 (6.2%)	>0.99
ED_CPAP	0 (0%)	0 (0%)	0 (0%)	-
ED_NIV	2 (2.5%)	1 (1.6%)	1 (6.2%)	0.37
ED_OTI	0 (0%)	0 (0%)	0 (0%)	-
ED_Unilateral	8 (10%)	6 (9.5%)	2 (12%)	0.66
ED_Bilateral chest	0 (0%)	0 (0%)	0 (0%)	-
IHS_O2Tp	40 (52%)	34 (55%)	6 (40%)	0.30
IHS_HFNC	17 (22%)	13 (21%)	4 (27%)	0.73
IHS_CPAP	0 (0%)	0 (0%)	0 (0%)	-
IHS_NIV	3 (3.9%)	1 (1.6%)	2 (13%)	0.10
OHS_OTI	0 (0%)	0 (0%)	0 (0%)	-
IHS_Unilaterale	11 (14%)	8 (13%)	3 (20%)	0.44
IHS_Bilateral chest	0 (0%)	0 (0%)	0 (0%)	-
IHS_Bronchial	3 (3.9%)	1 (1.6%)	2 (13%)	0.10
Antibiotic therapy	16 (21%)	12 (19%)	4 (25%)	0.73
Respiratory	15 (19%)	12 (19%)	3 (19%)	>0.99

Note: CPAP: continuous positive airway pressure; ED: emergency department; HFNC: high flow nasal cannula; IHS:in-hospital stay; NIV: non invasive ventilation; O2Tp: oxygen therapy; OTI: oro-tracheal intubation;

7.5. Analysis of Injury Patterns and TTSS Components

The breakdown of Thoracic Trauma Severity Score (TTSS) components demonstrated a generally homogeneous distribution across groups, with specific notable variations in respiratory mechanics and anatomical injury patterns. Speficically, no differences were note at admission in terms of Respiratory Function (PaO_2/FiO_2), Pulmonary Contusion, Pleural Involvement or Fracture Burden (see Table 4).

Table 4: Complete description of the Thoracic Trauma severity score (TTSS) in patients included.

	N = 145	SAP block, N = 114 (79%)	ESP block N = 31 (21%)	p-value
TTSS	8.0 (7.0, 9.8)	8,0 (7.0, 9.0)	8.0 (6.8, 10.5)	0.81
TTSS_PF	309 (246, 361)	309 (271, 358)	295 (192, 383)	0.65
TTSS lung contusion	42 (54%)	36 (58%)	6 (38%)	0.14
TTSS unilateral	15 (19%)	13 (21%)	2 (12%)	0.72
TTSS Bilateral single-	6 (7.7%)	5 (8.1%)	1 (6.2%)	>0.99
TTSS unilateral	12 (15%)	10 (16%)	2 (12%)	>0.99
TTSS	4 (5.1%)	4 (6.5%)	0 (0%)	0.58
TTSS contusion of at	6 (7.7%)	5 (8.1%)	1 (6.2%)	>0.99
TTSS pleural	47 (60%)	39 (63%)	8 (50%)	0.35
TTSS PNX	31 (40%)	24 (39%)	7 (44%)	0.71
TTSS haemothorax or	17 (22%)	14 (23%)	3 (19%)	>0.99
TTSS haemothorax or	2 (2.6%)	1 (1.6%)	1 (6.2%)	0.37
TTSS tension	4 (5.1%)	3 (4.8%)	1 (6.2%)	>0.99
TTSS ribs fractures				0.62
1	38 (49%)	32 (52%)	6 (38%)	
3	1 (1.3%)	1 (1.6%)	0 (0%)	
5	1 (1.3%)	1 (1.6%)	0 (0%)	
TTSS, 1 to 3 ribs	12 (15%)	11 (18%)	1 (6.2%)	0.44
TTSS 4 to 6 rib fractures	56 (72%)	44 (71%)	12 (75%)	>0.99
TTSS > 3bilaterale ribs	13 (17%)	10 (16%)	3 (19%)	0.72
TTSS costal flail	4 (5.1%)	2 (3.2%)	2 (12%)	0.18

Note: PF: Ratio between partial pressure of O_2 (measured with blood gas analysis) / FiO_2 (fraction of inspired oxygen); PNX: pneumothorax; TTSS: Thoracic trauma severity score;

Interpretation: Although global severity scores did not differ significantly, descriptive analysis suggests a clinical trend wherein the Deep SAP block was preferentially utilized (or randomly allocated) to patients with a more complex anatomical injury pattern (higher rates of contusion and pneumothorax).

7.6. Fracture Anatomy and Procedural Selection

Comparative analysis regarding the anatomical distribution, total burden, and complexity of rib fractures revealed no overall statistically significant differences across the treatment groups ($p > 0.05$) (see Table 5).

Table 5: Rib fractures localization and type of fascial block performed.

	N = 145	**SAP block, N = 114 (79%)**	**ESP block N = 31 (21%)**	**p-value**
Ribs fractures	3.0 (0.0, 6.0)	3.0 (0.0, 5.0)	3.0 (0.0, 6.5)	0.73
Number of anterior	3.0 (0.0, 5.0)	3.0 (0.0, 5.0)	1.0 (0.0, 7.0)	0.95
Anterior chest,				0.20
0	61 (42%)	50 (44%)	11 (35%)	
1	5 (3.4%)	3 (2.6%)	2 (6.5%)	
2	2 (1.4%)	2 (1.8%)	0 (0%)	
3	3 (2.1%)	3 (2.6%)	0 (0%)	
4	3 (2.1%)	1 (0.9%)	2 (6.5%)	
5	1 (0.7%)	1 (0.9%)	0 (0%)	
6	1 (0.7%)	1 (0.9%)	0 (0%)	
7	1 (0.7%)	1 (0.9%)	0 (0%)	
10	1 (0.7%)	0 (0%)	1 (3.2%)	
Anterior chest,				0.33
0	49 (34%)	36 (32%)	13 (42%)	
1	9 (6.2%)	7 (6.1%)	2 (6.5%)	
2	4 (2.8%)	4 (3.5%)	0 (0%)	
3	8 (5.5%)	8 (7.0%)	0 (0%)	
4	3 (2.1%)	3 (2.6%)	0 (0%)	
5	3 (2.1%)	3 (2.6%)	0 (0%)	
6	1 (0.7%)	0 (0%)	1 (3.2%)	
7	1 (0.7%)	1 (0.9%)	0 (0%)	
Lateral chest,				0.035
1	2 (1.4%)	2 (1.8%)	0 (0%)	
2	8 (5.5%)	6 (5.3%)	2 (6.5%)	
3	12 (8.3%)	7 (6.1%)	5 (16%)	
4	5 (3.4%)	5 (4.4%)	0 (0%)	

6	1 (0.7%)	1 (0.9%)	0 (0%)	
7	2 (1.4%)	1 (0.9%)	1 (3.2%)	
8	1 (0.7%)	0 (0%)	1 (3.2%)	
10	1 (0.7%)	0 (0%)	1 (3.2%)	
Lateral chest,				0.019
1	4 (2.8%)	2 (1.8%)	2 (6.5%)	
2	3 (2.1%)	2 (1.8%)	1 (3.2%)	
3	3 (2.1%)	2 (1.8%)	1 (3.2%)	
4	2 (1.4%)	2 (1.8%)	0 (0%)	
5	1 (0.7%)	0 (0%)	1 (3.2%)	
6	1 (0.7%)	1 (0.9%)	0 (0%)	
7	1 (0.7%)	0 (0%)	1 (3.2%)	
10	1 (0.7%)	0 (0%)	1 (3.2%)	
Lateral chest,				0.053
1	5 (3.4%)	5 (4.4%)	0 (0%)	
2	5 (3.4%)	2 (1.8%)	3 (9.7%)	
3	4 (2.8%)	3 (2.6%)	1 (3.2%)	
4	1 (0.7%)	1 (0.9%)	0 (0%)	
5	1 (0.7%)	0 (0%)	1 (3.2%)	
Posterior chest,	0.00 (0.00, 3.00)	0.00 (0.00, 3.00)	0.50 (0.00, 3.00)	0.53
Posterior chest,				0.35
1	4 (2.8%)	3 (2.6%)	1 (3.2%)	
2	3 (2.1%)	3 (2.6%)	0 (0%)	
3	4 (2.8%)	3 (2.6%)	1 (3.2%)	
4	1 (0.7%)	0 (0%)	1 (3.2%)	
5	1 (0.7%)	1 (0.9%)	0 (0%)	
7	2 (1.4%)	1 (0.9%)	1 (3.2%)	
Posterior chest,				0.42
1	3 (2.1%)	2 (1.8%)	1 (3.2%)	
2	2 (1.4%)	1 (0.9%)	1 (3.2%)	
3	4 (2.8%)	2 (1.8%)	2 (6.5%)	
4	2 (1.4%)	2 (1.8%)	0 (0%)	
5	3 (2.1%)	3 (2.6%)	0 (0%)	
8	1 (0.7%)	1 (0.9%)	0 (0%)	

However, a notable exception was observed regarding the total number of lateral rib fractures and the number of lateral, bifocal rib fractures, significantly higher in the ESP blockgroup ($p < 0.05$).

Regarding fracture localization, no differences were noted between the two groups in terms of localization, including posterior ribs fractures.

7.7. Procedural Characteristics

The technical parameters related to the execution of the ultrasound-guided blocks (e.g., procedure time, depth of target, and number of attempts) were analyzed and are detailed in Table [X].

7.7.1. Pharmacological Profile

Local Anesthetic and Volume:

The choice of local anesthetic was homogeneous across the study groups ($p > 0.05$), with Ropivacaine being the predominant agent (85.3%), followed by Levobupivacaine (13.2%) and Bupivacaine (1.4%). Similarly, the absolute dosage of the active ingredient showed no statistically significant variation: the median dosage was 78 mg (IQR 70–100) for ESP, 100 mg (IQR 80–100) for Deep SAP, and 75 mg (IQR 75–75) for Superficial SAP.

However, a statistically significant difference was observed regarding the total volume of injectate administered ($p = 0.016$). The ESP block utilized a lower median volume (20 mL, IQR 20–30) compared to both the Deep SAP (30 mL, IQR 30–30) and Superficial SAP (35 mL, IQR 30–40) blocks, reflecting the different anatomical compliance of the target fascial compartments.

Adjuvants:

The co-administration of adjuvants was a standard practice, occurring in 86.2% of the total cohort. Dexamethasone (8 mg) was the most frequently utilized regimen, administered in 73.6% of the entire population (specifically: 100% of ESP and Superficial SAP cases, and 82.1% of Deep SAP cases). Alternative dosages (4 mg or 6 mg) were rare, and a single use of Methylprednisolone (80 mg) was recorded in the Superficial SAP group. The rate of adjuvant non-administration was comparable across groups (ESP 21.4%, Deep SAP 11.5%, Superficial SAP 16.7%), with no statistically significant differences found ($p = 0.645$).

7.7.2. Sonographic Quality and Hydrodissection

The quality of the ultrasound window and the confirmation of correct execution were assessed by visualizing the fascial separation (hydrodissection) caused by the spread of the local anesthetic.

Complete visualization of fascial detachment was achieved in 94% of the overall sample. Despite no overall differences were noted in percentage of correct fascial detachment obtained using SAP or ESP block (94% vs 97%, respectively, $p>0.99$), a comparative analysis revealed a statistically significant difference between techniques ($p = 0.01$):

x) High Visibility: Optimal visualization was recorded in 96% of Deep SAP blocks and in 97% of ESP blocks.

xi) Low Visibility: In contrast, the Superficial SAP block was associated with a significantly lower success rate in visualizing complete spread, achievable in only 62% of cases with a partial spread obtained in 38% of cases. .

This finding suggests a greater technical reproducibility and sonographic clarity for the Deep SAP and ESP approaches in the emergency setting compared to the superficial technique.

7.8. Dynamic Evolution of Pain Intensity

Analgesic efficacy was evaluated through longitudinal monitoring of NRS pain scores from the immediate post-procedural phase up to 24 hours.

Overall Trend:

As detailed in Table 6, the analysis of pain intensity in the immediate post-procedural phase (15, 30, and 60 minutes) revealed no statistically significant differences among the treatment groups ($p > 0.05$). All three techniques demonstrated a comparable magnitude of pain reduction, confirming their uniform effectiveness as rescue analgesic interventions in the acute setting.

However, a marked divergence in efficacy emerged in the subacute phase. A statistically significant difference regarding both static and dynamic pain was observed between treatment arms at 6 and 12 hours post-procedure ($p < 0.05$). This finding indicates that while the onset of analgesia is uniform, the duration and stability of relief are dependent on the specific fascial plane targeted.

Table 6: Differences in static pain and dynamic pain between SAP and ESP block groups.

	N = 145	**SAP block, N = 114 (79%)**	**ESP block N = 31 (21%)**	**p-value**
		Static Pain, NRS		
admission	8 (7.0, 9.0)	8.0 (7.0, 9.0)	8.0 (7.0, 9.0)	0.773
15 min	6 (5.0, 7.0)	6.0 (5.0, 8.0)	6.0 (4.0, 6.0)	0.331
30 min	5 (3.0, 6.0)	5 (3.0, 6.0)	4 (3.0, 5.0)	0.066
60 min	3 (2.0, 4.0)	3.0 (2.0, 4.0)	3.0 (1.0, 4.0)	0.202
6 h	3 (2.0, 4.0)	3.0 (3.0, 4.0)	2 (1.0, 3.0)	0.006
12 h	3 (2.0, 4.0)	3 (2.0, 4.0)	2 (0.0, 3.0)	0.026
24 h	3 (1.0, 3.0)	3 (2, 3)	2 (1.0, 4.0)	0.555
		Dynamic Pain, NRS		
admission	8 (8.0, 10.0)	8 (8.0, 10.0)	8 (7.0, 9.0)	0.539
15 min	6 (5.0, 8.0)	6 (5.0, 8.0)	6 (5.0, 7.0)	0.264
30 min	5 (4.0, 6.0)	5 (4.0, 6.0)	4 (4.0, 5.0)	0.062
60 min	3 (2.0, 5.0)	3 (3.0, 5.0)	3 (2.0, 4.0)	0.290
6 h	4 (3.0, 5.0)	4 (3.0, 6.0)	2 (1.0, 4.0)	0.005
12 h	4 (2.0, 5.0)	4 (3.0, 5.0)	2 (2.0, 4.0)	0.101
24 h	3 (2.0, 4.0)	3 (2.0, 5.0)	3 (2.0, 4.0)	0.271

<u>Subgroup Analysis:</u>

A stratified analysis comparing the specific SAP variants (Superficial vs. Deep) against the ESP block highlighted distinct temporal patterns (see Table 7).

Specifically, the Superficial SAP block was associated with rapid onset in the early phase but exhibited a significant loss of efficacy at 6 and 12 hours. Conversely, the ESP block demonstrated superior stability, resulting in significantly lower pain scores both at rest and during deep inspiration at these later time points ($p < 0.05$).

Based on these data, the analgesic profile can be categorized into three distinct phases:

7.8.1. Early Phase (0–60 minutes)

In the immediate post-procedural window, the Superficial SAP block demonstrated the most rapid analgesic onset. Median NRS scores recorded for this group were consistently low: 3.0 (IQR 1.0–5.0) at 15 and 30 minutes, further decreasing to 1.0 (IQR: 0.0–3.0] at 60 minutes.

Regarding safety, no adverse events were recorded in the first hour following the administration of any block.

7.8.2. Mid-to-Late Phase (6–24 hours)

Longitudinal analysis at 6, 12, and 24 hours revealed a significant divergence in analgesic efficacy, characterizing a "rebound" phenomenon in the superficial group and superior stability in the ESP group.

xii) Static Pain (Rest):

At 6 hours, a statistically significant difference emerged ($p = 0.016$). The Deep SAP group reported slightly higher median pain scores (3.0, IQR 3–4) compared to the ESP group (2.0, IQR 1–3), while the Superficial SAP group showed intermediate values (3.0, IQR 2–3).

However, at 12 hours, the efficacy of the Superficial SAP block significantly degraded, showing a median NRS of 4.0 (IQR 3–4). This was significantly higher than both the ESP (2.0, IQR 0–3) and Deep SAP (3.0, IQR 2–4) groups ($p = 0.032$), indicating a shorter duration of action for the superficial technique compared to the deeper planes.

xiii) Dynamic Pain (Exertion/Inspirium):

The disparity was exacerbated during exertion. At 6 hours, the Superficial SAP group exhibited significantly higher median NRS scores (7.0, IQR 6–7) compared to Deep SAP (4.0, IQR 3–5) and ESP (2.0, IQR 1–4) (p = 0.001). This trend indicates an early failure of the superficial block in controlling movement-related pain.

This pattern persisted at 12 hours (p = 0.048), where the Superficial SAP group maintained a fixed median score of 6.0, whereas the ESP group remained the most effective (median 2.0).

7.8.3. 24-Hour Endpoint

By 24 hours, analgesic trajectories tended to converge across groups, with no statistically significant differences recorded in static scores. However, the ESP group displayed the most favorable and consistent trend for both static and dynamic pain throughout the observation period. Conversely, the Superficial SAP block was characterized by higher variability and a significant loss of analgesic coverage in the 6-to-12-hour window.

Table 7: Differences in static pain and dynamic pain between deep SAP, superficial SAP and ESP block groups.

	ESP block **N = 31 (21.4%)**	**deep SAP block** **N= 106 (73.1%)**	**superficial SAP block** **N = 8 (5.5%)**	**p-value**
		Static Pain, NRS		
admission	8 (7, 9)	8 (7, 9)	7 (5, 8)	0.108
15 min	6 (4, 6)	6 (5, 8)	3 (1, 5)	0.005
30 min	4 (3, 5)	5 (4, 6)	3 (1, 5)	0.026
60 min	3 (1, 4)	3 (2, 4)	1 (2, 3)	0.014
6 h	2 (1, 3)	3 (3, 4)	3 (2, 3)	0.016
12 h	2 (0, 3)	3 (2, 4)	4 (3, 4)	0.032

24 h	2 (1, 4)	3 (2, 3)	3 (0, 3)	0.348
		Dynamic Pain, NRS		
admission	8 (7, 9)	8 (8, 10)	10 (8, 10)	0.257
15 min	6 (5, 7)	6 (5, 8)	6 (3, 9)	0.513
30 min	4 (4, 5)	5 (4, 6)	5 (5, 7)	0.099
60 min	3 (2, 4)	3 (3, 4)	5 (2, 5)	0.310
6 h	2 (1, 4)	4 (3, 5)	7 (6, 7)	0.001
12 h	2 (2, 4)	4 (3, 4)	6 (5, 6)	0.048
24 h	3 (2, 4)	3 (2, 4)	5 (4, 8)	0.139

Figure 1: temporal trend of static pain intensity

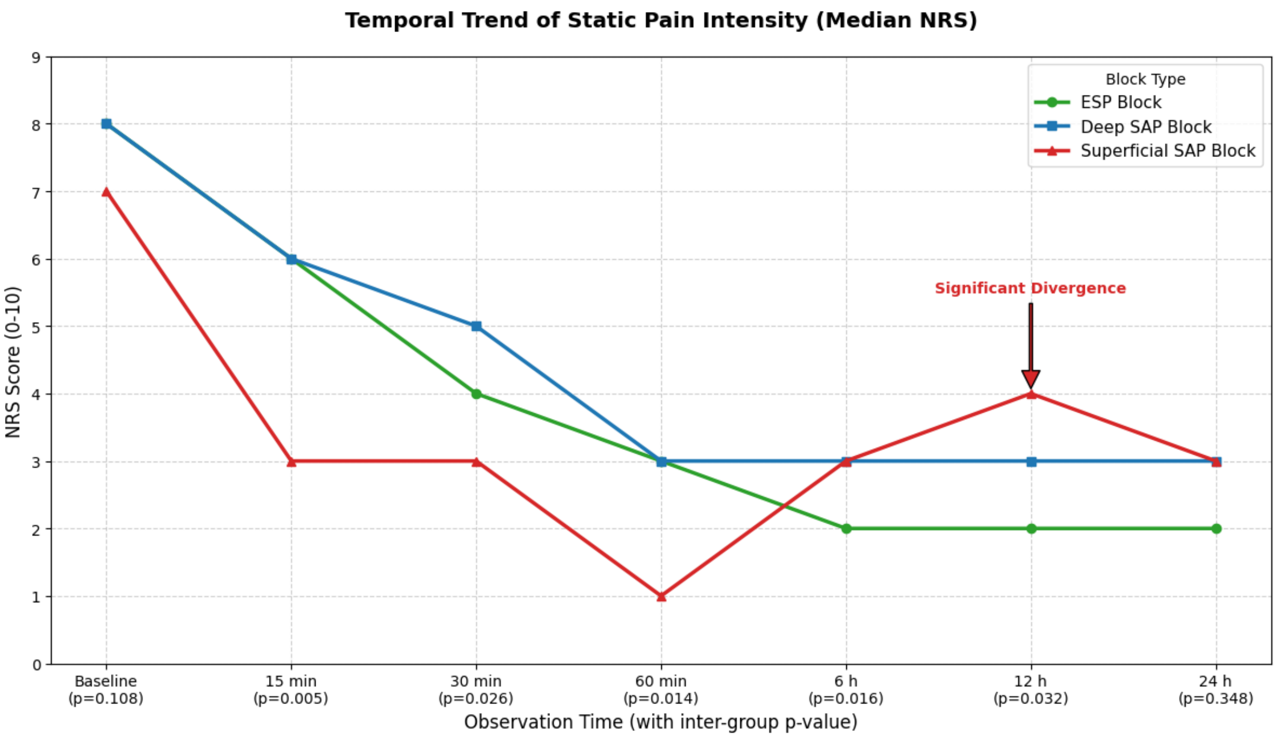
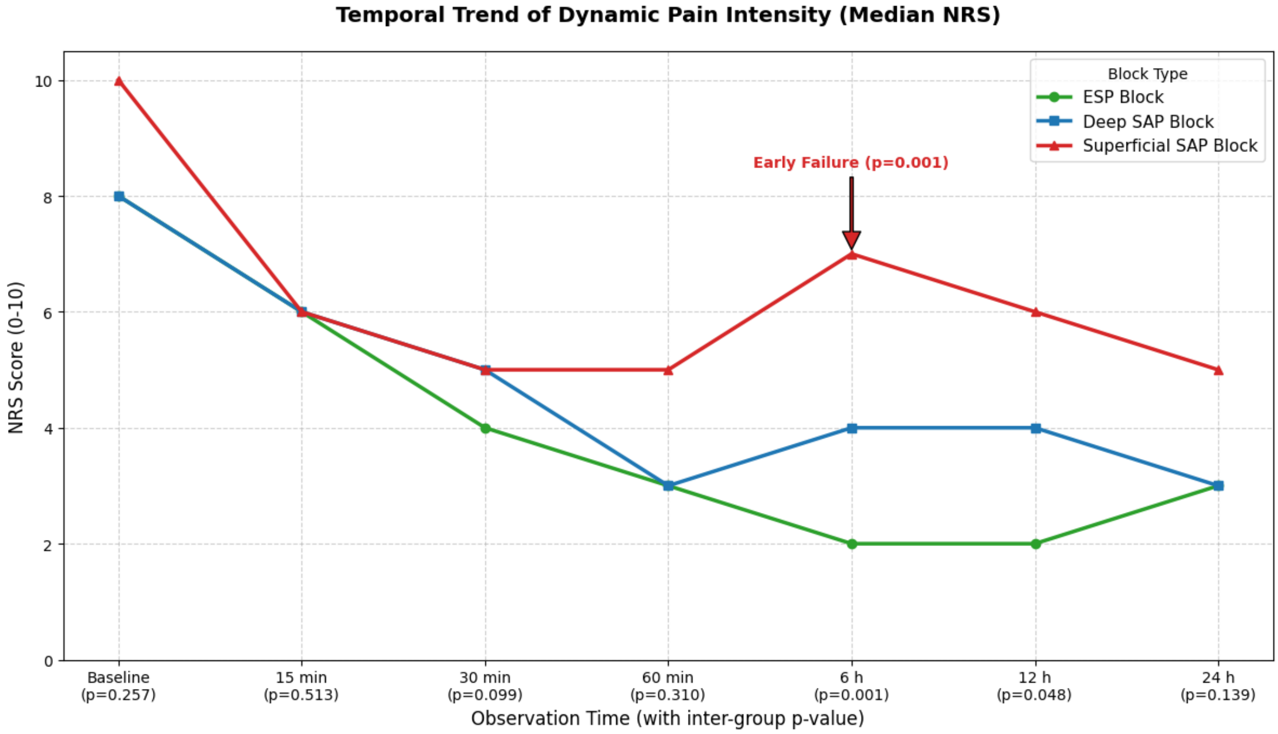


Figure 2: temporal trend of dynamic pain intensity



7.9. Respiratory Mechanics and Gas Exchange

The impact of analgesic intervention on respiratory function was evaluated by monitoring the longitudinal evolution of Respiratory Rate (RR) and the SpO_2/FiO_2 ratio at 6, 12, and 24 hours. Overall, a general trend towards improvement in ventilatory parameters was observed across the entire cohort, although inter-group comparisons did not reach statistical significance.

xiv) Respiratory Rate (RR):

A distinct clinical pattern emerged in the ESP group, characterized by a progressive normalization of respiratory frequency over time (Median: 18.0 breaths/min at 6h, 17.0 b/min at 12h, 16.0 b/min at 24h). In contrast, patients in both the Deep and Superficial SAP groups exhibited stable or slightly elevated respiratory rates throughout the observation period. However, these differences were not statistically significant ($p = 0.332$, $p = 0.864$, and $p = 0.441$ at 6, 12, and 24 hours, respectively).

xv) Oxygenation (SpO_2/FiO_2 Ratio):

The analysis of gas exchange revealed a potentially clinically relevant divergence. The ESP group consistently displayed more favourable oxygenation indices, culminating in a median P/F ratio of 360 at 24 hours. This value was notably higher than those recorded in the Deep SAP group (median 288) and markedly superior to the Superficial SAP group, which showed a median value of 190 (indicative of moderate respiratory impairment).

While statistical significance was not achieved ($p = 0.079$ at 6h; $p = 0.217$ at 12h; $p = 0.230$ at 24h), the substantial difference in median values suggests a strong trend favouring the ESP block in preserving respiratory performance and preventing hypoxic complications in the medium term.

7.10. Analysis of Major Clinical Outcomes and Complications

7.10.1 Major outcomes

In terms of major clinical outcomes, the overall incidence of complications was as follows:

xvi) No LAST related event were recorded.

xvii) Hospital-acquired pneumonia: 8 patients (10%).

xviii) ICU Admission: 4 patients (2.7%) required transfer to the Intensive Care Unit.

xix) In-hospital Mortality: 1 death (1.3%) was recorded.

Statistical comparison across the three treatment groups (ESP, SAP) revealed no significant differences in the incidence of these major outcomes ($p > 0.05$), suggesting a comparable safety profile regarding hard endpoints.

7.10.2. Predictors of Pneumonia

A subgroup analysis was conducted to compare characteristics and outcomes between patients who developed hospital-acquired pneumonia (n=8) and those who did not.

xx) Baseline Characteristics and Trauma Severity

No statistically significant differences were observed between the two groups regarding demographic variables or general trauma severity indices. Specifically, age, Charlson

Comorbidity Index (CCI), Injury Severity Score (ISS), and Thoracic Trauma Severity Score (TTSS) were comparable ($p > 0.05$).

Furthermore, the incidence of pneumonia showed no significant association with the specific fascial block technique performed (ESP vs. Deep SAP vs. Superficial SAP), nor were there differences in the total dose of opioids administered or in the absolute number of rib fractures.

xxi) Fracture Morphology

Significant differences emerged regarding the specific anatomical pattern of the fractures. Patients who developed pneumonia presented a significantly higher prevalence of bifocal fractures (flail segments) located in the lateral sector ($p = 0.022$) and posterior sector ($p = 0.001$).

xxii) Respiratory Support Requirements

The requirement for respiratory support varied between groups:

xxiii) Oxygen Therapy: Oxygen dependency was higher in the pneumonia group (87.5%) compared to the complication-free group (46.3%).

xxiv) Non-Invasive Ventilation (NIV): In the Emergency Department, a trend toward higher NIV use was noted in the pneumonia group (12.5% vs 1.4%), though this did not reach statistical significance ($p = 0.06$). During the in-hospital stay, the difference became statistically significant ($p = 0.001$), with 25% of pneumonia patients requiring NIV compared to 1.5% of the control group. It is noted that these percentages correspond to low absolute numbers (2 patients in the pneumonia group vs 1 in the control group).

xxv) Therapeutic Interventions and Outcomes

A statistically significant difference was recorded in the use of antibiotics ($p < 0.001$): 100% of patients with pneumonia received antibiotic therapy compared to 10% of patients without pneumonia (administered as prophylaxis).

Regarding hospital course, patients with pneumonia had a significantly longer Length of Stay (LOS) ($p = 0.001$). No statistically significant difference was observed regarding in-hospital mortality between the two groups.

Chapter 8: Discussion

8.1. Summary of Key Findings

The present study provides a comprehensive, real-world analysis of the efficacy and safety of ultrasound-guided fascial plane blocks (Deep SAP, Superficial SAP, and ESP) administered by Emergency Physicians for the management of multiple rib fractures.

The comparison of these three techniques reveals a distinct time-dependent divergence in clinical performance, highlighting a clear trade-off between immediate onset and sustained analgesic stability.

1. Universal Acute Efficacy:

In the hyper-acute phase (0–60 minutes post-procedure), all three techniques demonstrated a robust and statistically significant reduction in pain intensity compared to baseline. Interestingly, the Superficial SAP block exhibited the most rapid onset, achieving the lowest median NRS scores at 1 hour. This confirms that, regardless of the specific technique, fascial blocks are highly effective "rescue" tools for immediate stabilization in the Emergency Department.

2. The "Rebound Pain" Phenomenon at 12 Hours:

A critical turning point emerged in the subacute phase. While the ESP block maintained consistent analgesia throughout the 24-hour observation period (acting as a "deposito" thanks to paravertebral spread), the Superficial SAP block was characterized by a dramatic loss of efficacy between 6 and 12 hours. At the 12-hour mark, patients in the superficial group experienced a higher recurrence of pain, significantly higher than those in the ESP or Deep SAP groups ($p = 0.021$). This "rebound pain" highlights a major limitation of the superficial approach for prolonged coverage.

3. Impact on Therapeutic Burden (The "Hidden Cost"):

Although hard outcomes (mortality, pneumonia incidence) did not reach statistical significance due to sample size, the failure of sustained analgesia in the Superficial SAP group translated into a measurable increase in therapeutic burden. A statistically significant difference was found in the need for adjunctive respiratory physiotherapy ($p = 0.004$) and antibiotic therapy ($p = 0.027$). Specifically, 50% of patients in the Superficial SAP group required these interventions to manage developing complications, compared to a minority in the Deep SAP and ESP groups.

4. Respiratory Protection:

A trend toward superior respiratory preservation was observed in the ESP group, which maintained the highest SpO_2/FiO_2 ratio at 24 hours (Median 360) compared to the notable respiratory deterioration observed in the Superficial SAP group (Median 190). While not statistically definitive ($p > 0.05$), this clinical gap suggests that the ESP block offers superior protection against hypoxic decline.

Conclusion:

Our data suggest a hierarchical model of utility: while the Superficial SAP is an excellent, rapid-onset technique for short-term procedural analgesia, the ESP block (and to a lesser extent the Deep SAP) demonstrates superior stability and a stronger protective effect against the clinical cascade of complications in the hospitalized trauma patient.

8.2. Pain Reduction

8.2.1 Baseline Homogeneity and Acute Efficacy

In our sample, the median pain scores recorded at baseline were comparable across the three groups (ESP: 8, Deep SAP: 8, and Superficial SAP: 8), indicating a homogeneous distribution of data at admission that allowed for an unbiased evaluation of the analgesic techniques.

Specifically, the Superficial SAP block showed superior analgesic efficacy in the hyper-acute phase (first hour), demonstrating the most marked reduction in pain scores. This data on early efficacy is consistent with literature findings: Schnekenburger et al. described a reduction in NRS score from 6.5 to 3.0 in the first four hours post-block, while Serra et al.

highlighted a significant reduction as early as 3 and 6 hours after administration (Schnekenburger et al., 2021; Serra et al., 2024, 2025)

8.2.2 Mid-Term Efficacy and Systemic Impact

Regarding medium-term control (6–12 hours), the ESP block demonstrated greater stability, consistent with findings by Finnerty et al. (Finnerty et al., 2020). Although no statistically significant differences were found at the 24-hour endpoint in our study—contrary to Finnerty's observation of long-term superiority—the clinical trend favored the ESP.

These findings align with the recent systematic review and meta-analysis by Gamberini et al. (Gamberini et al., 2025), which highlighted the superiority of ESP not only in pain reduction but also in "hard outcomes," such as reducing hospital length of stay by 1.8 days compared to intravenous therapy (95% CrI: −3.1; −0.4). While our study did not replicate the reduction in length of stay due to sample size, it reinforces the concept that locoregional blocks, particularly ESP, are associated with better outcomes compared to systemic analgesia alone.

8.2.3 The "Rebound Pain" Phenomenon

However, this initial benefit of the superficial approach did not persist over time. A critical finding of our study is the divergence in efficacy observed in remote measurements (6, 12, and 24 hours). The ESP block proved to be significantly more effective in controlling pain both at rest and, crucially, under exertion (deep inspiration). Conversely, the Superficial SAP group exhibited a phenomenon of "rebound pain," characterized by a drastic return of symptoms at 12 hours (Median NRS rising to 8), a difference that reached statistical significance compared to the other groups ($p=0.021$). Furthermore, the effectiveness of Superficial SAP appeared limited to resting pain, failing to control dynamic pain during exertion as early as 6 hours post-procedure ($p=0.001$) compared to Deep SAP and ESP.

8.2.4 Anatomical and Technical Determinants

The mechanism underlying this early failure likely relates to sonographic visibility and pharmacokinetics. The Superficial SAP block was the technique where incomplete visualization of the fascial plane was most frequently observed (50% of cases), suggesting possible anesthetic dispersion within the serratus anterior muscle rather than the fascial plane. This condition explains the rapid initial relief—likely due to direct bathing of the long thoracic nerve fibers and intercostal nerves, structures not immediately affected by a deep SAP block (Serra et al., 2024). However, this intramuscular spread facilitates rapid vascular absorption ("washout"), resulting in a loss of effectiveness in later stages. This pharmacokinetic profile justifies why lower NRS scores were maintained over time in the groups treated with ESP and Deep SAP, which benefit from a "depot effect."

8.2.5 Volume and Feasibility

A significant aspect of our observation is that the analgesic efficacy of the ESP block was evident despite the volume of local anesthetic administered being at the lower limit of recommended ranges (median 20 mL vs. the recommended 30 mL) (Serra et al., 2024). Literature suggests that fascial block effectiveness is volume-dependent (Chin & El-Boghdadly, 2021); however, our data indicate that correct anatomical placement may be more critical than volume for the ESP technique.

Finally, the lower utilization rate of ESP blocks in our population compared to Deep SAP is attributable to logistical constraints. The need for sitting or lateral positioning for ESP is not always feasible in the Emergency Department for polytrauma patients, making the Deep SAP a more versatile "supine-friendly" option despite the superior stability of the ESP

8.2.6 Comparison with Literature

Evidence regarding the comparison of SAP block variants remains conflicting. Some studies, such as Qiu et al. (2020), highlight an overall superiority of the superficial SAP block even up to 24 hours, though in a different population (thoracic surgery) (Qiu et al., 2021). Conversely, other authors, including Piracha et al. and Edwards et al., support the superior efficacy of the deep SAP block (Edwards et al., 2021; Piracha et al., 2017).

A plausible explanation for the lower effectiveness of the superficial technique in our emergency cohort lies in procedural complexity. Unlike Deep SAP and ESP, which rely on static bony landmarks (rib and transverse process), the Superficial SAP requires precise identification of a dynamic inter-muscular plane. This technical challenge, evidenced by our lower visualization rates, presupposes greater operator expertise and may compromise efficacy in the acute setting (Serra et al., 2024).

8.2.7 Clinical Take-Home Messages: A Pharmacokinetic Hierarchy

Based on the analgesic trajectories observed in this study, the choice of fascial block should be guided by a specific understanding of their temporal limitations and advantages. We propose the following conceptual framework for the Emergency Physician:

xxvi) <u>The "Washout" of the Superficial Plane:</u> The inter-muscular space between the latissimus dorsi and serratus anterior is a highly vascularized and dynamic plane. While this facilitates immediate drug uptake (rapid onset), it also accelerates absorption. Consequently, the Superficial SAP block functions effectively as a short-term procedural analgesic but lacks the durability required for definitive trauma management without continuous catheterization.

xxvii) <u>The "Rebound" Paradox:</u> Clinicians must be vigilant regarding the biphasic nature of the Superficial SAP block. The initial profound relief often masks a precipitous drop in analgesic coverage at 6–12 hours. This "rebound pain" leaves the patient vulnerable during the critical night-time or ward transfer window, necessitating aggressive rescue analgesia to prevent respiratory deterioration.

xxviii) <u>The "Depot Effect" of the ESP:</u> The injection deep to the erector spinae muscle creates a protected reservoir of local anesthetic that slowly diffuses into the paravertebral space. This "depot effect" insulates the drug from rapid washout, ensuring the stable, 24-hour coverage required to support respiratory physiotherapy and reduce opioid dependency.

xxix) <u>Deep SAP: The "Pragmatic Compromise":</u> For the undifferentiated polytrauma patient where posterior positioning for an ESP block is unsafe, the Deep SAP block represents the optimal trade-off. By utilizing the rib as a safety backstop and depositing the anesthetic deep to the serratus muscle, it offers a safety profile superior to the superficial approach and a duration profile that—while shorter than the ESP—avoids the catastrophic failure of the superficial plane. It is, therefore, the recommended first-line "workhorse" for the supine trauma patient.

8.2.8 The "Anatomical-Procedural Mismatch": A Critical Reflection on the "One-Size-Fits-All" Bias

A pivotal, unexpected finding of our updated analysis concerns the relationship between fracture localization and procedural selection.

While anatomical logic dictates that posterior fractures should be targeted by paravertebral or ESP blocks, and anterolateral fractures by SAP blocks, our data revealed no statistically significant correlation between the fracture site and the choice of block ($p > 0.05$).In other words, the distribution of ESP, Deep SAP, and Superficial SAP was homogeneous regardless of whether the injuries were posterior, lateral, or anterior.

This lack of selectivity raises a critical question regarding the internal validity of "real-world" studies. It suggests that operator choice was likely driven by habit, confidence with a specific technique, or patient positioning constraints (e.g., inability to sit up for ESP) rather than by strictly targeting the injury site.

This introduces the hypothesis of an "Anatomical Mismatch": a patient with posterior rib fractures receiving a Superficial SAP block (which covers the lateral cutaneous branches) essentially receives a "missed block" for the primary injury site. This potential mismatch could significantly contribute to the high failure rate and "rebound pain" observed in the Superficial SAP group. If a subset of these patients had posterior injuries not covered by the serratus plane, the rapid washout of local anesthetic would leave the fracture site exposed, explaining the dramatic rise in NRS scores at 12 hours.

This finding implies that the efficacy of fascial blocks may have been underestimated in our cohort due to suboptimal targeting. It strongly supports the need for a shift from a "provider-centric" model (doing the block the doctor knows best) to a "lesion-centric" protocol, where the choice of technique is algorithmically dictated by the CT-verified location of the fractures (e.g., Posterior → ESP; Lateral → Deep SAP; Anterior → Pectoral/Parasternal).

8.3. Respiratory Function and Safety Profile

8.3.1 Ventilatory Mechanics

Current literature establishes that peripheral nerve blocks contribute significantly to improving respiratory mechanics in chest trauma, primarily by interrupting the pain-splinting cycle and restoring tidal volume (Durant et al., 2017; El Malla et al., 2022; Serra et al., 2024). Our findings align with this physiologic rationale, particularly regarding the ESP block, which demonstrated a progressively favourable trend in both Respiratory Rate (RR) and gas exchange indices (SpO2/FiO2) in the hours following the procedure.

Specifically, patients treated with the ESP block exhibited a consistent reduction in respiratory rate over the 24-hour observation period, indicative of improved ventilatory adaptation and the normalization of compensatory tachypnea. Conversely, in the Deep SAP and Superficial SAP groups, respiratory rates remained essentially stable or slightly elevated, suggesting a persistent respiratory drive potentially linked to less effective late-stage analgesia.

8.3.2 Gas Exchange (SpO2/FiO2 Ratio)

The trajectory of the SpO2/FiO2 ratio revealed a clinically relevant divergence. The ESP group showed a marked improvement over time, reaching median values compatible with normal oxygenation at 24 hours. This stands in contrast to the Superficial SAP group, which exhibited lower median values (trending towards moderate respiratory impairment), likely reflecting the "rebound pain" and subsequent hypoventilation discussed previously. Although these inter-group differences did not reach formal statistical significance—likely due to sample size limitations and high variability—the observed trend suggests a distinct clinical advantage of the ESP block in preserving lung function, attributable to its superior analgesic stability and potential visceral coverage.

8.3.4 Safety and Trauma Severity

These functional data, combined with the total absence of immediate procedural complications, support the hypothesis that fascial blocks—and particularly the ESP block—represent a safe and beneficial strategy even in critical settings.

The analysis of trauma severity indices (TTSS score) and baseline characteristics confirmed that the safety profile of these techniques remains robust regardless of injury complexity. Our data indicate that fascial blocks can be applied effectively not only in patients with minor, isolated trauma but also in those with complex injury patterns (e.g., pulmonary contusion, pneumothorax), which were prevalent in our Deep SAP cohort. This consistency agrees with recent literature (Durant et al., 2017; Edwards et al., 2021; Partyka et al., 2024; Paul et al., 2020; Serra et al., 2024), confirming that the safety of the procedure is not compromised by the severity of the thoracic trauma

8.4. Major Clinical Outcomes

8.4.1. Anatomical Determinism vs. Baseline Frailty

A critical and unexpected finding of our analysis concerns the predictors of hospital-acquired pneumonia. Contrary to established literature, which identifies advanced age, clinical frailty, and a high Charlson Comorbidity Index (CCI) as the primary drivers of respiratory complications (Bergeron et al., 2003; Brattström et al., 2010; Laporta et al., 2021; MacLeod et al., 2004; Pape et al., 2000; Serag, 2007; Sirmali et al., 2003; Zhao et al., 2023), our data revealed no statistically significant differences in these baseline characteristics between patients who developed pneumonia and those who did not ($p > 0.05$). Similarly, general trauma severity indices (ISS, TTSS) and the total number of rib fractures failed to predict the infectious outcome. Instead, the determinant factor in our cohort appeared to be strictly anatomical. Patients developing pneumonia exhibited a significantly higher prevalence of bifocal ("flail") fractures located in the lateral ($p = 0.022$) and posterior ($p = 0.001$) sectors. This suggests that mechanical chest wall instability in dependent lung zones plays a dominant role in the pathogenesis of pneumonia, potentially outweighing the impact of baseline comorbidities in this specific trauma population.

8.4.2. The Dissociation of Analgesia and Complications

Our analysis challenges the linear assumption that "better pain control equals fewer complications." We observed no significant differences in NRS pain scores (at 12 hours or other time points) or in the total dose of opioids administered between the pneumonia and non-pneumonia groups ($p > 0.05$). Furthermore, the incidence of pneumonia was independent of the fascial block technique employed (ESP vs. SAP). This indicates a dissociation between symptomatic relief and physiological outcome: while fascial blocks effectively reduced pain scores across the board, effective analgesia alone was insufficient to negate the risk of consolidation driven by mechanical disruption (flail segments).

8.4.3. Therapeutic Escalation and Resource Consumption

The development of pneumonia triggered a distinct divergence in the clinical trajectory, characterized by a rapid escalation of therapeutic support.

xxx) Ventilatory Support: A trend toward higher Non-Invasive Ventilation (NIV) requirements was already evident in the Emergency Department ($p = 0.06$) and became statistically significant during hospitalization ($p = 0.001$). As confirmed by Serra et al. and Durant et al., fascial blocks theoretically facilitate NIV tolerance by sparing opioids (Serra S, et al 2024, Durant E, et al., 2017); however, our data suggest that in patients with posterior flail segments, NIV becomes an inevitable requirement regardless of the block's success.

xxxi) Antibiotic Stewardship: The most dramatic difference was observed in antimicrobial management ($p < 0.001$). While only 10% of the complication-free cohort received prophylaxis, 100% of patients with pneumonia required therapeutic antibiotics.

xxxii) Oxygen Dependency: Similarly, oxygen dependency was markedly higher in the pneumonia group (87.5% vs 46.3%), reflecting the functional impairment imposed by the infection.

8.4.4. Mortality

Regarding hard outcomes, no significant difference was found in in-hospital mortality between groups. The single mortality recorded involved a patient with extreme values of CCI and ISS, suggesting that fatal outcomes were driven by global polytrauma severity rather than the failure of locoregional management. While this observation remains speculative due to the limited sample size, it aligns with the recurrent methodological challenge in regional anesthesia literature, where mortality is often a rare endpoint, as noted by Marhofer et al. (Marhofer et al., 2020)

8.4.5. Safety Conclusion

Crucially, none of the major adverse outcomes—pneumonia, NIV requirement, or death—showed a statistically significant association with the specific type of fascial block performed. This confirms the excellent safety profile of ESP, Deep SAP, and Superficial SAP blocks in the emergency setting. However, it also underscores that while these blocks are safe and effective for pain, they are not a panacea: high-risk anatomical patterns (posterior flail chest) require aggressive, multimodal respiratory management beyond analgesia alone, aligning with the complexity of care chest trauma being worthy of.

8.5. Study Limitations

Our findings must be interpreted within the context of several methodological constraints inherent to the observational design and the "real-world" emergency setting.

1. Sample Size Imbalance and Statistical Fragility

The most significant limitation of this study lies in the grossly unbalanced distribution of the study population (N=145). While the Deep SAP group is robust (n=106, 73.1%), the Superficial SAP group comprises only 8 patients (5.5%).From a statistical perspective, such a small denominator renders the subgroup analysis highly volatile; a variation in outcomes for a single patient can disproportionately skew the percentages. Consequently, the statistically significant findings regarding the "failure" of the superficial technique (e.g., the high rate of respiratory physiotherapy) carry a risk of Type I error (overestimation of the effect) and must be interpreted as descriptive trends rather than definitive clinical axioms.

2. Underpowering for Hard Outcomes (Type II Error)

The validity of our analysis regarding "hard outcomes" (pneumonia, mortality) is constrained by the low overall incidence of these events. With a hospital-acquired pneumonia rate of roughly 5-10% and negligible mortality, the study is statistically underpowered to detect modest differences between block techniques. The finding that pneumonia incidence was independent of the block type may essentially represent a Type II error (false negative); we cannot confidently exclude that a specific block might offer a protective benefit that our sample size was simply too small to detect.

3. The "Anatomical-Procedural Mismatch"

A crucial retrospective finding is the lack of correlation ($p > 0.05$) between the fracture localization and the type of block performed. In an ideal setting, posterior fractures would trigger an ESP block and lateral fractures a SAP block. In our cohort, this alignment was absent, suggesting that operator choice was driven by proficiency or positioning constraints rather than anatomical targeting.This introduces a significant confounder: the high failure rate and "rebound pain" observed in the Superficial SAP group might not reflect an intrinsic weakness of the technique, but rather its application to anatomically mismatched injuries (e.g., posterior fractures not covered by the serratus plane)

.4. The "Mechanical Ceiling" Effect

Our multivariate analysis revealed that pneumonia was primarily driven by bifocal (flail) fractures, independent of pain scores or block type. This highlights an intrinsic limitation of regional anesthesia: fascial blocks can mitigate nociception, but they cannot reverse the mechanical paradox and chest wall instability of a flail segment. Our study design did not stratify for this "mechanical ceiling," potentially confounding the assessment of analgesic efficacy in patients with severe structural disruption

5. Selection Bias and Standardization

As an observational study, treatment allocation was non-randomized. The prevalence of the Deep SAP technique reflects a proficiency bias, where operators preferentially utilized the technique they were most comfortable with. Furthermore, the restriction to single-shot injections limits the generalizability of our results to settings where continuous catheter-based analgesia is the standard of care, directly influencing the "rebound pain" phenomenon observed at 12 hours

Conclusion on Limitations

In summary, while this study offers valuable real-world insights, the extreme sample size imbalance and the lack of anatomical standardization mandate that our comparative conclusions—particularly those disfavoring the Superficial SAP block—be viewed as hypothesis-generating. Definitive confirmation requires randomized controlled trials with balanced cohorts stratified by fracture anatomy.

Chapter 9 Conclusion

9.1. Synthesis of Findings: Beyond the "One-Block-Fits-All" Concept

The results of this multicenter prospective study confirm that ultrasound-guided fascial plane blocks represent a transformative tool for the management of blunt chest trauma in the Emergency Department. Our data solidify the role of the Emergency Physician as a primary provider of advanced analgesia, demonstrating that these procedures are feasible, devoid of immediate major complications, and universally effective in the hyper-acute stabilization of pain symptoms.

However, this research goes beyond merely validating the safety of locoregional anesthesia. By granularly comparing three distinct techniques (ESP, Deep SAP, and Superficial SAP), we have challenged the notion that all chest wall blocks are clinically equivalent. The central finding of this thesis is the identification of a pharmacokinetic and clinical hierarchy, interpreted through the lens of anatomical determinism:

xxxiii) The "Rebound" Liability: While the Superficial SAP block offered rapid onset, our data suggest it is burdened by a significant "washout" phenomenon. In our cohort, this correlated with a failure of maintenance analgesia at 12 hours ($p < 0.05$ for static pain) and a consequent increase in the therapeutic burden, specifically regarding the need for respiratory physiotherapy and bronchial hygiene. However, given the limited sample size of this subgroup (n=8), this finding should be interpreted as a strong signal of lower stability rather than definitive proof of futility.

xxxiv) The Stability of Deep Layers: Conversely, the ESP and Deep SAP blocks utilize anatomical "depots" (paravertebral and retro-serratus spaces) that ensure sustained coverage. The ESP block, in particular, demonstrated the most consistent analgesic profile over 24 hours.

xxxv) The Dissociation of Outcome: Crucially, our analysis revealed that effective analgesia does not automatically translate to the prevention of complications. The development of pneumonia was independent of the block technique and was instead driven by fracture morphology (posterior flail segments). This indicates that while blocks are essential for comfort, they cannot solely overcome the mechanical instability of severe chest trauma.

9.2. Clinical Implications: A New Operational Standard

Based on these findings, and acknowledging the retrospective evidence of an "anatomical-procedural mismatch" in our cohort, we propose a paradigm shift in the operational protocols of the Emergency Department:

xxxvi) The Pragmatic Standard (Deep SAP): The Deep SAP block should be considered the first-line intervention for the undifferentiated, supine polytrauma patient. With a success rate of visualization nearing 96% and a robust safety profile (rib backstop), it represents the optimal balance between efficacy and feasibility for the vast majority of ED presentations (n=106 in our study).

xxxvii) The Protective Standard (ESP): The ESP block should be prioritized for patients with posterior fractures or those at high risk of respiratory decline. Its ability to cover dorsal rami makes it the theoretical gold standard for posterior rib injuries, provided patient positioning is safe.

From "Provider-Centric" to "Lesion-Centric": We advocate moving away from selecting blocks based solely on operator proficiency. The high failure rate of the superficial approach in our study suggests that "matching the block to the fracture" (e.g., avoiding SAP for posterior injuries) is as critical as the execution of the block itself.

9.3. Toward the "Pain-Free Hospital"

These clinical insights fit into a broader vision of healthcare humanization. As envisioned by the Italian Law 38/2010, the relief of suffering is a fundamental right. Integrating early, effective locoregional analgesia into the trauma pathway does more than improve numbers on a chart; it restores the patient's capacity to breathe, rest, and recover with dignity.The complete feasibility of these techniques in dynamic environments like the Emergency Department paves the way for a systematic cultural change. By moving from a reactive, opioid-centred model to a proactive, multimodal strategy, we offer a more humane and comprehensive approach to trauma care, even if the prevention of "hard outcomes" requires a multidisciplinary effort beyond analgesia alone.

9.4. Future Directions and Limitations

While this study establishes a strong foundation, the conclusions must be tempered by the sample size imbalance (predominance of Deep SAP) and the observational nature of the design. The lack of statistical significance regarding mortality or pneumonia rates may reflect a Type II error due to the low incidence of these events.Future efforts should focus on

xxxviii) Randomized Controlled Trials (RCTs) with balanced cohorts to definitively compare the Superficial vs. Deep SAP efficacy.

xxxix) Standardized Training Curricula for Emergency Physicians to ensure proficiency in posterior techniques (ESP).

xl) Catheter-Based Solutions: Implementation of continuous infusions to bridge the "analgesic gap" observed at 12 hours in single-shot techniques.

In conclusion, the adoption of a rationally selected fascial block—preferencing the Deep SAP or ESP based on fracture anatomy—must become a core competency in modern Emergency Medicine, serving as the cornerstone of a multimodal strategy that bridges the gap between acute resuscitation and long-term functional recovery.

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