

1 **Integrated Anaesthesia and Physiotherapy Strategies to** 2 **Reduce Post-Thoracotomy Pulmonary Complications**

3
4 **Abstract:** Post-thoracotomy pulmonary complications (PTPCs) remain a major source of
5 postoperative morbidity, prolonged hospitalstay, and mortality following thoracic surgery.
6 These complicationsincluding atelectasis, pneumonia, hypoxemia, and respiratory
7 failureresult from a complex interplay of surgical trauma, one-lung ventilation–induced lung
8 injury, impaired diaphragmatic function, postoperative pain, reduced lung volumes, and
9 ineffective cough. Increasing evidence supports a multidisciplinary, integrated perioperative
10 approach combining optimized anaesthetic management with structured physiotherapy
11 interventions to mitigate these risks. Anaesthetic strategies focus on preoperative risk
12 stratification and optimization, lung-protective ventilation during one-lung ventilation,
13 judicious oxygen use, effective regional and multimodal analgesia to facilitate deep breathing
14 and early mobilization, and opioid-sparing techniques to minimize respiratory depression.
15 Complementary physiotherapy strategies include preoperative pulmonary rehabilitation,
16 early postoperative respiratory exercises, incentive spirometry, positive expiratory pressure
17 therapy, airway clearance techniques, and early, progressive mobilization. Integration of these
18 approaches within enhanced recovery after thoracic surgery (ERATS) pathways has been
19 shown to reduce the incidence and severity of PTPCs, improve oxygenation and functional
20 recovery, and shorten intensive care unit and hospital length of stay. Emerging concepts such
21 as precision ventilation, ultrasound-guided continuous regional analgesia, digital
22 physiotherapy platforms, wearable respiratory monitoring, and artificial intelligence–based
23 risk prediction models offer promising avenues to further improve outcomes. This review
24 highlights current evidence and practical considerations for implementing integrated
25 anaesthesia and physiotherapy strategies, emphasizing the importance of coordinated, patient-
26 centred perioperative care in reducing pulmonary morbidity after thoracotomy.

27 **Keywords:** Atelectasis prevention; Breathing exercises; Chest physiotherapy; Enhanced
28 recovery after surgery (ERAS); Early mobilization; Epidural analgesia; Incentive spirometry;
29 Lung-protective ventilation; Multidisciplinary perioperative care; Multimodal analgesia;
30 Postoperative pain management; Post-thoracotomy pulmonary complications; Pulmonary
31 rehabilitation; Regional anaesthesia; Respiratory physiotherapy; Thoracic anaesthesia

32 **Introduction:** Thoracic surgery performed through thoracotomy is associated with a high
33 incidence of postoperative pulmonary complications (PTPCs), which remain a leading cause
34 of perioperative morbidity, prolonged hospitalization, increased healthcare costs, and
35 mortality.^{1,2} Despite advances in surgical techniques, anaesthetic management, and
36 perioperative care, PTPCs such as atelectasis, pneumonia, hypoxemia, respiratory failure,
37 bronchospasm, and the need for prolonged mechanical ventilation continue to affect a
38 substantial proportion of patients undergoing thoracotomy.^{3,4} These complications not only
39 delay postoperative recovery but also adversely influence long-term respiratory function,
40 functional capacity, and overall quality of life.⁵ The development of PTPCs is multifactorial
41 and reflects the cumulative impact of surgical, anaesthetic, and patient-related factors.⁶
42 Surgical incision, rib retraction, and disruption of the thoracic musculature impair chest wall
43 compliance and diaphragmatic excursion, leading to reduced lung volumes and ventilation–
44 perfusion mismatch.⁷ The routine requirement for one-lung ventilation during thoracic surgery
45 further predisposes patients to atelectasis, oxidative stress, and ventilator-induced lung
46 injury.^{8,9} General anaesthesia exacerbates these effects by reducing functional residual
47 capacity, impairing mucociliary clearance, and suppressing protective airway reflexes.¹⁰ In
48 the postoperative period, inadequate pain control limits deep inspiration and effective
49 coughing, while excessive opioid use contributes to respiratory depression, compounding the
50 risk of pulmonary dysfunction.^{11,12} Historically, efforts to reduce PTPCs have focused on
51 isolated interventions, such as postoperative chest physiotherapy or refinements in
52 anaesthetic technique. However, growing evidence suggests that these single-modality
53 approaches are insufficient to address the complex and interrelated mechanisms underlying
54 postoperative pulmonary impairment.¹³ Instead, there is increasing recognition that effective
55 prevention of PTPCs requires a coordinated, multidisciplinary strategy that spans the entire
56 perioperative continuum.¹⁴ Anaesthesiologists play a central role in minimizing perioperative
57 lung injury through careful preoperative risk stratification, lung-protective ventilation
58 strategies during one-lung ventilation, judicious oxygen administration, and the use of
59 regional and multimodal analgesia to facilitate early mobilisation and effective respiratory
60 effort.^{15,16} Concurrently, physiotherapists are essential in optimizing respiratory mechanics
61 and airway clearance through preoperative pulmonary prehabilitation, early postoperative
62 breathing exercises, incentive spirometry, positive expiratory pressure therapy, and structured
63 early mobilisation programs.^{17,18} The integration of anaesthesia and physiotherapy strategies
64 within enhanced recovery after thoracic surgery (ERATS) pathways represents a paradigm
65 shift toward proactive, patient-centred perioperative care.^{19,20} Such integrated pathways

66 emphasize early intervention, interdisciplinary collaboration, and individualized treatment
 67 plans, and have been shown to reduce the incidence and severity of PTPCs, improve
 68 functional recovery, and shorten intensive care unit and hospital length of stay.^{21,22} this
 69 review aims to synthesize current evidence and practical considerations for implementing
 70 integrated anaesthesia and physiotherapy strategies to reduce pulmonary complications
 71 following thoracotomy, while also highlighting emerging innovations and future directions in
 72 this evolving field.

73 **Materials and Methods:** The data for this review were compiled from a wide range of
 74 articles published which sourced from multiple academic journals. These papers were
 75 carefully selected and reviewed to extract relevant information applicable to the focus
 76 of this study.

77 **2.PathophysiologyofPost-Thoracotomy Pulmonary Complications:** (PTPCs) arise from a
 78 complex interaction of surgical trauma, anaesthesia-related physiological changes, and
 79 patient-specific factors. These mechanisms collectively impair respiratory mechanics, gas
 80 exchange, and airway clearance, predisposing patients to atelectasis, pneumonia, hypoxemia,
 81 and respiratory failure.

| Pathophysiological Domain | Mechanisms | Pulmonary Consequences |
|---|---|---|
| Surgical Trauma & Chest Wall Dysfunction | <ul style="list-style-type: none"> •Thoracotomy incision and rib retraction • Division of chest wall muscles • Severe postoperative pain | <ul style="list-style-type: none"> • Reduced chest wall compliance • Shallow breathing and reduced tidal volume • Decreased functional residual capacity (FRC) •Dependent airway closure and atelectasis.^{23,24} |
| One-Lung Ventilation–Induced Lung Injury | <ul style="list-style-type: none"> •Collapse of non-ventilated lung with surfactant loss •Increased airway pressures in ventilated lung •Repetitive alveolar opening and closing • High inspired oxygen | <ul style="list-style-type: none"> •Atelectasis •Volotrauma, barotrauma, atelectotrauma • Oxidative stress •Ventilator-induced lung injury •Ischemia–reperfusion injury on lung re-expansion.^{25,26} |

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|---|---|--|
| | <p>concentrations</p> <ul style="list-style-type: none"> •Cytokine-mediated inflammation | |
| Effects of General Anaesthesia | <ul style="list-style-type: none"> • Reduced muscle tone and diaphragmatic function • Loss of hypoxic pulmonary vasoconstriction • Suppressed airway reflexes •Impaired mucociliary clearance | <ul style="list-style-type: none"> • 20–30% reduction in FRC •Ventilation–perfusion mismatch • Secretion retention •Increased risk of infection.²⁷ |
| Pain-Induced Respiratory Dysfunction | <ul style="list-style-type: none"> • Intercostal nerve injury • Pleural and muscular pain • Splinting due to pain | <ul style="list-style-type: none"> • Reduced inspiratory effort • Ineffective cough • Sputum retention • Increased risk of atelectasis and pneumonia.²⁸ |
| Diaphragmatic Dysfunction | <ul style="list-style-type: none"> • Phrenic nerve irritation • Reflex inhibition •Pain-related diaphragmatic splinting | <ul style="list-style-type: none"> •Reduced diaphragmatic excursion • Basal atelectasis • Impaired ventilation–perfusion matching.²³ |
| Impaired Airway Clearance | <ul style="list-style-type: none"> • Opioid-induced cough suppression • Pain-limited expiratory effort • Reduced mucociliary transport | <ul style="list-style-type: none"> •Secretion accumulation • Increased airway resistance •Higher risk of postoperative pneumonia.²⁴ |
| Systemic & Patient-Related Factors | <ul style="list-style-type: none"> • COPD, obesity, smoking • Advanced age • Poor nutritional status • Systemic inflammatory response • Blood transfusion | <ul style="list-style-type: none"> • Reduced respiratory reserve •Interstitial pulmonary edema •Increased susceptibility to hypoxemia and infection.^{28,29} |
| Overall Pathophysiological Outcome | <p>Combined effects of surgical, anaesthetic, and patient factors</p> | <ul style="list-style-type: none"> • Reduced lung volumes and compliance •Ventilation–perfusion mismatch |

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|--|--|---|
| | | <ul style="list-style-type: none"> • Impaired gas exchange • Increased work of breathing • Development of PTPCs.^{23,24} |
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83 **3. Risk Factors for Post-Thoracotomy Pulmonary Complications (PTPCs):** Result from a
84 complex interplay of patient-related, surgical, and anaesthesia-related factors. Identifying
85 these risk factors preoperatively is critical for stratifying risk, tailoring perioperative
86 management, and implementing targeted preventive strategies.

| Category | Risk Factor | Mechanism / Impact |
|-------------------------|------------------------------------|---|
| Patient-Related | Advanced Age | Reduced lung compliance and chest wall elasticity; diminished respiratory muscle strength; higher prevalence of comorbidities. ^{30,31,32} |
| | COPD / ILD | Pre-existing airflow limitation increases susceptibility to atelectasis and hypoxemia; reduced pulmonary reserve complicates one-lung ventilation. ^{31,32,33} |
| | Smoking History | Impaired mucociliary clearance and increased mucus production; chronic airway inflammation predisposing to infection. ^{31,32} |
| | Obesity | Reduced functional residual capacity (FRC) and lung volumes; increased work of breathing and risk of hypoventilation. ^{31,34} |
| | Poor Nutritional Status | Weak respiratory muscles; impaired immune response, increasing infection risk. ³⁴ |
| | Limited Functional Capacity | Poor exercise tolerance; reduced cardiorespiratory reserve |
| | Comorbidities | Cardiovascular disease (heart failure, ischemic heart disease); diabetes mellitus (impaired immune response, delayed recovery); chronic renal insufficiency (fluid overload, electrolyte imbalances). ³⁴ |
| Surgical-Related | Extent and Type of Surgery | Open thoracotomy carries higher risk than minimally invasive thoroscopic approaches; upper lobectomy reduces pulmonary reserve. ^{30,31,35} |
| | Duration of Surgery | Prolonged surgery increases exposure to mechanical ventilation and anaesthesia-related lung injury. ^{30,31} |

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|----------------------------|---|--|
| | Repeat Thoracotomy | Scar tissue, adhesions, and prolonged operative time increase pulmonary stress. ^{30,36} |
| | Surgical Trauma | Extensive rib retraction and intercostal nerve injury cause severe postoperative pain and splinting. ^{31,33} |
| Anaesthesia-Related | One-Lung Ventilation (OLV) | Lung collapse, hypoxia, and ventilator-induced lung injury. ^{31,33,36} |
| | High Tidal Volumes / High Airway Pressures | Barotrauma, volutrauma, and atelectotrauma. |
| | Excessive Oxygen Concentration (FiO₂) | Promotes oxidative stress and absorption atelectasis. |
| | Prolonged Neuromuscular Blockade | Delays spontaneous breathing and cough, increasing secretion retention. ^{31,36} |
| | Inadequate Analgesia | Prevents deep inspiration and effective coughing; opioid overuse can cause respiratory depression. ^{31,33,34} |

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88 **4. Anaesthetic Strategies to Reduce Post-Thoracotomy Pulmonary Complications**

89 Anaesthetic management plays a pivotal role in minimizing (PTPCs). The perioperative
90 period preoperative, intraoperative, and postoperative presents multiple opportunities for
91 intervention to preserve pulmonary function, prevent atelectasis, reduce infection risk, and
92 facilitate early recovery. The strategies involve careful patient assessment, optimized
93 ventilation, pain management, fluid therapy, and judicious drug selection.³⁷⁻⁴²

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| Phase | Strategy / Intervention | Key Points / Recommendations |
|--|---|---|
| Preoperative Anaesthetic Optimization | Risk Stratification & Pulmonary Assessment | Evaluate comorbidities (COPD, ILD, heart disease); perform PFTs, DLCO, ABGs; identify high-risk patients for perioperative monitoring. ^{37,41} |
| | Preoperative Pulmonary Optimization | Smoking cessation $\geq 2-4$ weeks pre-op; incentive spirometry and respiratory muscle training; treat infections/airway inflammation; optimize bronchodilator therapy and steroids if indicated. ^{37,38} |
| | Preoperative Analgesia Planning | Consider regional techniques (thoracic epidural, paravertebral block); multimodal analgesia to minimize opioid-induced respiratory depression. ^{38,39} |
| Intraoperative Anaesthetic Strategies | Airway & Ventilation Management | Lung-Protective Ventilation: low tidal volume 4–6 mL/kg PBW, limit peak airway pressure <30 cm H ₂ O, maintain PEEP; OLV Considerations: minimize duration, judicious recruitment maneuvers, avoid hyperoxia (FiO ₂ titrated to SpO ₂ >92%); Monitoring: pulse oximetry, ABG, capnography, advanced hemodynamics in high-risk patients. ^{37,42} |
| | Analgesia | Thoracic Epidural Analgesia (TEA): gold standard, excellent segmental analgesia, reduces systemic opioids; Paravertebral Block (PVB): alternative for unilateral analgesia, preserves hemodynamic stability; Multimodal Analgesia: acetaminophen, NSAIDs (if renal function allows), adjuncts (gabapentinoids, ketamine) ^{38,39} |
| | Fluid & Hemodynamic Management | Avoid fluid overload; use goal-directed therapy (stroke volume variation, cardiac output); prefer vasopressors for hypotension rather than excessive fluids. ^{41,42} |
| | Pharmacologic Considerations | Minimize sedative-hypnotics and opioids; use short-acting, organ-independent agents (propofol, cis-atracurium); avoid high-dose benzodiazepines and long-acting opioids in high-risk patients. ^{37,42} |
| Postoperative Anaesthetic Strategies | Continued Regional Analgesia | Maintain epidural or paravertebral infusion 48–72 hours; adjust local anaesthetic to balance analgesia and motor function. ^{38,39} |
| | Early Extubation & Ventilation Support | Aim for early extubation if hemodynamically stable; consider non-invasive ventilation or high-flow nasal oxygen in borderline respiratory function. ^{37,38} |
| | Pulmonary Care Integration | Encourage deep breathing, incentive spirometry, and airway clearance; coordinate with physiotherapy for early mobilization. ^{37,40} |

102 **5. Physiotherapy Strategies in PTPC Prevention**

103 Physiotherapy is crucial for preventing post-thoracotomy pulmonary complications (PTPCs)
104 by maintaining lung volumes, improving ventilation, enhancing airway clearance, and
105 facilitating early mobilization. Both preoperative and postoperative interventions are essential
106 components of an integrated perioperative care pathway.^{43,44}

107 **5.1 Preoperative Physiotherapy (Prehabilitation)**

108 Preoperative physiotherapy, or pulmonary prehabilitation, aims to optimize respiratory
109 function, strengthen inspiratory muscles, and educate patients regarding postoperative
110 exercises. Interventions include:

- 111 1. **Breathing exercises:** Diaphragmatic and segmental breathing to improve lung
112 expansion and functional residual capacity (FRC)^{44,45}
- 113 2. **Incentive spirometry:** Encourages sustained maximal inspiration to prevent
114 atelectasis and improve alveolar recruitment.^{45,46}
- 115 3. **Inspiratory muscle training (IMT):** Strengthens respiratory muscles, increases
116 ventilatory capacity, and improves endurance during postoperative recovery.^{46,47}
- 117 4. **Patient education:** Instruction on deep breathing, coughing techniques, and early
118 mobilization to enhance postoperative compliance.^{44,46}

119 Prehabilitation has been shown to reduce the incidence of postoperative pulmonary
120 complications, shorten hospital stay, and improve functional recovery, particularly in high-
121 risk patients with COPD or limited baseline pulmonary reserve.^{44,47}

122 **5.2 Postoperative Physiotherapy Interventions**

123 **5.2.1 Respiratory Physiotherapy**

- 124 1. **Deep breathing exercises & Sustained Maximal Inspiration (SMI):** Promote
125 alveolar recruitment and reduce atelectasis.^{45,47}
- 126 2. **Positive Expiratory Pressure (PEP) devices:** Facilitate airway opening and improve
127 secretion clearance.
- 128 3. **Directed coughing and huffing:** Enhance effective sputum clearance and prevent
129 mucus plugging.⁴⁸

130 **5.2.2 Early Mobilization**

131 **Sitting out of bed within 24 hours:** Stimulates lung expansion, improves ventilation-
132 perfusion matching, and reduces venous stasis.

133 **Progressive ambulation:** Enhances functional capacity, promotes diaphragmatic movement,
134 and reduces risk of pneumonia.

135 **Upper limb and thoracic mobility exercises:** Prevent shoulder stiffness and maintain chest
136 wall compliance.⁴⁹

137 **5.2.3 Airway Clearance Techniques**

138 1. **Manual chest physiotherapy:** Percussion and vibration to mobilize secretions.

139 2. **Active Cycle of Breathing Technique (ACBT):** Combines breathing control,
140 thoracic expansion exercises, and forced expiratory techniques to optimize secretion
141 clearance.⁴⁸

142 **6. Integrated Anaesthesia–Physiotherapy Pathway**

143 A coordinated, multidisciplinary pathway that integrates optimized anaesthetic care with
144 structured physiotherapy has been shown to reduce post-thoracotomy pulmonary
145 complications (PTPCs) and improve recovery. Key components include:

146 1. **Preoperative physiotherapy assessment:** Identifies baseline respiratory function and
147 establishes individualized exercise programs to enhance pulmonary reserve and
148 minimize PTPC risk.⁵⁰

149 2. **Regional anaesthesia (epidural or paravertebral block):** Effective pain control
150 allows patients to deep breathe, cough effectively, and mobilize early, reducing
151 splinting-related complications.⁵¹

152 3. **Standardized postoperative respiratory protocols:** Structured regimens of deep
153 breathing exercises, incentive spirometry, and airway clearance techniques help
154 maintain functional residual capacity and prevent atelectasis.

155 4. **Daily physiotherapist-led interventions:** Regular physiotherapy ensures adherence
156 to protocols, progression of exercises, and early detection of respiratory
157 deterioration.⁵⁰

158 5. **Close monitoring of oxygenation and lung volumes:** Continuous assessment of
159 SpO₂ and ventilatory metrics enables early intervention for hypoxemia or early signs
160 of atelectasis.⁵²

161 By integrating these strategies, patients maintain better pulmonary mechanics, enhance
162 secretion clearance, and achieve faster functional recovery. This approach has been associated
163 with lower rates of PTPCs, reduced intensive care and hospital length of stay, and improved
164 overall postoperative outcomes.⁵³

165 **7. Enhanced Recovery After Thoracic Surgery (ERATS)**

166 **ERATS** is a structured, evidence-based perioperative framework combining surgical,
167 anaesthetic, and physiotherapy strategies to optimize outcomes after thoracic surgery.
168 Components include:

- 169 1. **Minimal fasting and carbohydrate loading:** Reduces postoperative insulin
170 resistance and preserves metabolic reserve.⁵⁴
- 171 2. **Regional analgesia:** Thoracic epidural or paravertebral blocks provide superior pain
172 control, reduce opioid consumption, and support early mobilization.⁵¹
- 173 3. **Lung-protective ventilation:** Low tidal volumes and optimized positive end-
174 expiratory pressure (PEEP) during one-lung ventilation reduce ventilator-induced
175 lung stress.⁵⁴
- 176 4. **Early postoperative feeding and mobilization:** Enhances gut function, respiratory
177 mechanics, and reduces muscle wasting.⁵⁵
- 178 5. **Structured physiotherapy:** Integration of deep breathing, airway clearance, and
179 progressive mobilization reduces atelectasis and pneumonia risk.⁵⁰

180 **Evidence Supporting ERATS**

- 181 • ERATS implementation is associated with significantly fewer pulmonary
182 complications, shorter ICU and hospital stay, and reduced pneumonia rates compared
183 to standard care.⁵³
- 184 • Systematic reviews show ERATS reduces overall morbidity and hospital length of
185 stay.^{55,56}

186 • ERATS also improves pain control and decreases opioid use, indirectly supporting
187 respiratory function and facilitating early physiotherapy.⁵⁷

188 Integrating ERATS principles with targeted physiotherapy and optimized anaesthetic
189 management creates a comprehensive perioperative pathway that reduces pulmonary
190 complications, enhances recovery, and improves outcomes following thoracotomy.^{50,53,54}

191 **8. Emerging and Future Directions**

192 Despite advances in perioperative care, postoperative pulmonary complications remain a
193 leading contributor to morbidity and mortality after thoracic surgery. Current evidence
194 supports established strategies such as lung-protective ventilation, risk stratification,
195 multimodal analgesia, and perioperative physiotherapy, while highlighting gaps that novel
196 precision, digital, and AI-based approaches may help address.^{58,59}

197 **8.1 Precision Perioperative Care**

198 **Individualized Ventilation Strategies**

199
200 Tailored ventilatory management (low tidal volumes, PEEP, recruitment maneuvers) has been
201 associated with reduced incidence of postoperative pulmonary complications in noncardiac
202 and thoracicsurgicalpopulations.
203 Optimizing parameters such as driving pressure and compliance may further reduce
204 ventilator-induced lung injury, but requires individualized titration and advanced
205 monitoring.⁵⁹

206 **Personalized Analgesic Regimens**

207
208 Multimodal opioid-sparing analgesia preserves respiratory drive while achieving pain control,
209 an important protective factor against PPCs.⁶⁰
210 Regional techniques (e.g., paravertebral, erector spinae plane blocks) show promise in
211 reducing opioid requirements and enhancing respiratory function, especially when applied
212 continuously or guided by ultrasound.⁶¹

213 **Impact:** Individualized strategies aim to reduce atelectasis, hypoxemia, and opioid-related
214 respiratory depression, and to enable earlier mobilization.

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216 **8.2 Digital and Remote Physiotherapy**

217 **Wearable Respiratory Monitoring & App-Based Adherence**

218 Remote monitoring technologies (e.g., wearables, spirometry apps) can track respiratory
219 parameters continuously and may facilitate early detection of shallow breathing or
220 hypoventilation, although high-quality clinical evidence remains limited.
221 Digital platforms that prompt exercise adherence and integrate data into EMRs can enhance
222 provider oversight and support engagement in incentive spirometry and breathing exercises.⁵⁸

223 **Impact:** Digital tools have potential to improve exercise compliance, reduce atelectasis risk,
224 and enable early intervention for high-risk patients.

225 **8.3 Artificial Intelligence (AI) Applications**

226 **Risk Prediction Models**

227 Predictive analytics using electronic health record data have demonstrated improved
228 stratification of postoperative risk compared with clinical judgment alone in non-thoracic
229 contexts.

230 Custom PPC prediction models remain an active area of research, integrating demographic,
231 comorbidity, and intraoperative data to better tailor perioperative planning.⁶²

232 **Automated Ventilation Optimization**

233 AI-assisted adjustment of ventilator settings (e.g., tidal volume, PEEP) promises real-time
234 optimization of lung protection, though clinical deployment is still emerging.⁶²

235 **Impact:** AI systems may support risk stratification, early detection of pulmonary compromise,
236 and dynamic intraoperative decision-making.

237 **8.4 Novel Analgesic Techniques**

238 **Fascial Plane Catheters & Ultrasound-Guided Blocks**

239 Continuous fascial plane catheters (such as erector spinae and serratus plane blocks) provide
240 prolonged regional analgesia with minimal hemodynamic impact.

241 Ultrasound-guided regional anaesthesia enhances precision and safety, enabling reduced local
242 anaesthetic doses and supporting early participation in physiotherapy.⁶¹

243 **Impact:** These techniques achieve superior pain control while preserving respiratory
244 mechanics and reducing opioid consumption.

245 **8.5 Integration of Emerging Technologies into Clinical Pathways**

246 A future perioperative pathway may integrate precision medicine, digital monitoring, AI, and
247 advanced analgesia across the surgical timeline:

- 248 1. Preoperative Assessment: AI-based risk stratification identifies high-risk individuals.⁶²
249 2. Intraoperative Management: Precision ventilation and opioid-sparing analgesia reduce
250 pulmonary stress.^{59,60}
251 3. Postoperative Physiotherapy: Wearables and app-based engagement enhance
252 compliance with respiratory exercises.⁵⁸
253 4. Analgesic Optimization: Continuous regional techniques sustain effective analgesia
254 without respiratory compromise.⁶¹

255 **Expected Outcomes:**

- 256 • **Reduced incidence of atelectasis, pneumonia, and hypoxemia**
257 • **Accelerated functional recovery and mobilization**
258 • **Shorter ICU and hospital length of stay**
259 • **Improved patient satisfaction and quality of life**

260 **9. Outcomes and Evidence Summary**

261 **Integrated anaesthesia–physiotherapy strategies consistently demonstrate:**

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| Outcome Domain | Intervention / Strategy | Evidence / Study Type | Key Findings / Impact |
|---------------------------|---|------------------------------|---|
| Reduction in PTPCs | Thoracic epidural analgesia (TEA) + early physiotherapy | RCTs, Meta-analyses | ↓ Atelectasis, ↓ Pneumonia, ↓ Hypoxemia by 30–50% compared to conventional care |
| | Lung-protective ventilation during one-lung ventilation | Prospective cohort studies | ↓ Barotrauma, ↓ Volutrauma, ↓ Oxidative stress, ↓ Pulmonary complications |
| | Preoperative inspiratory muscle training + incentive spirometry | RCTs | ↓ Basal and dependent-lung atelectasis, ↑ Lung expansion |

| | | | |
|---------------------------------------|--|-------------------------------|---|
| | Early postoperative mobilization | ERATS protocols | Accelerated lung re-expansion, improved functional recovery |
| Functional Recovery | Integrated physiotherapy + effective analgesia | Clinical trials | ↑ FVC & FEV1, preserved FRC, improved exercise tolerance |
| | Early ambulation within 24 hours | ERATS pathways | ↓ Muscle deconditioning, enhanced participation in physiotherapy |
| Length of Stay / ICU Use | Integrated ERATS protocols | Systematic reviews | ↓ ICU stay by 1–2 days, ↓ Hospital stay by 2–5 days, earlier return to self-care |
| Pain Control / Opioid-Sparing | TEA, paravertebral blocks, fascial plane catheters | RCTs & Cohort studies | ↓ Opioid requirement, ↓ Respiratory depression, improved airway clearance and deep breathing |
| Mortality / Long-Term Outcomes | Prehabilitation + structured ERATS | Cohort studies, observational | Improved postoperative oxygenation, functional recovery, and long-term quality of life; indirect reduction in morbidity-related mortality |

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264 **Key Outcomes**

| Intervention | Evidence/Study Type | Key Outcomes |
|--|----------------------------|---|
| Thoracic Epidural Analgesia + Early Physiotherapy | RCTs, meta-analyses | ↓ Atelectasis, ↓ Pneumonia, ↑ Deep breathing capacity |
| Lung-Protective Ventilation | Prospective cohort studies | ↓ Ventilator-induced lung injury, ↓ hypoxemia, ↑ oxygenation |
| Inspiratory Muscle Training | RCTs | ↑ FVC & FEV1, ↓ PTPC incidence, improved postoperative endurance |
| Early Mobilization | ERATS protocols | ↓ ICU & hospital stay, ↑ functional recovery, ↓ PTPC incidence |
| Multimodal Opioid-Sparing Analgesia | Clinical trials | ↓ opioid consumption, preserved respiratory drive, ↑ cough efficacy |
| Integrated ERATS Pathways | Systematic reviews | ↓ PTPC incidence by 30–50%, ↓ hospital LOS, ↑ patient satisfaction |

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266 **Conclusion:** Post-thoracotomy pulmonary complications (PTPCs) remain a significant
267 source of perioperative morbidity, prolonged hospitalization, and impaired functional
268 recovery following thoracic surgery. Their development is multifactorial, involving surgical
269 trauma, one-lung ventilation–related lung injury, general anaesthesia–induced respiratory
270 changes, pain-related splinting, diaphragmatic dysfunction, impaired airway clearance, and
271 patient-specific vulnerabilities such as advanced age, chronic lung disease, or poor nutritional
272 status. Recognition of these complex pathophysiological mechanisms underscores the
273 inadequacy of isolated interventions and highlights the need for a coordinated,
274 multidisciplinary approach. Integrated anaesthesia and physiotherapy strategies have emerged
275 as the cornerstone for preventing PTPCs. Optimized perioperative anaesthetic
276 management including lung-protective ventilation, judicious oxygen administration,
277 multimodal and regional analgesia, and goal-directed fluid therapy preserves pulmonary
278 mechanics, minimizes ventilator-induced lung injury, and facilitates effective respiratory
279 effort. Concurrently, structured physiotherapy interventions encompassing preoperative
280 pulmonary rehabilitation, incentive spirometry, inspiratory muscle training, early
281 postoperative mobilization, and airway clearance techniques maintain lung volumes, enhance
282 secretion clearance, and accelerate functional recovery. The incorporation of these strategies
283 within Enhanced Recovery After Thoracic Surgery (ERATS) pathways has demonstrated
284 significant reductions in the incidence and severity of PTPCs, improved oxygenation,
285 enhanced functional outcomes, and shorter ICU and hospital lengths of stay. Emerging
286 approaches including precision perioperative care, wearable digital monitoring, AI-based risk
287 prediction, and novel ultrasound-guided regional analgesic techniques promise further
288 refinement of individualized, patient-centered care, enabling earlier detection of pulmonary
289 compromise and tailored interventions. In summary, prevention of PTPCs requires a
290 proactive, integrated perioperative strategy that combines evidence-based anaesthetic and
291 physiotherapy interventions with emerging technologies. Such a multidisciplinary, patient-
292 centered approach not only reduces pulmonary complications but also enhances postoperative
293 recovery, improves long-term functional outcomes, and represents the future direction of
294 thoracic surgical care.

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