Complete Video-Assisted Thoracoscopic Surgery vs Open Surgery for Rib Fracture: Impacts on Postoperative Inflammation and Foreign Body Sensation

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AIM: This study aims to compare the effects of complete video-assisted thoracoscopic surgery (VATS) rib fracture (RF) fixation with a conventional open procedure on surgical parameters, inflammatory markers, and postoperative discomfort.

METHODS: This multicenter retrospective cohort study enrolled 141 patients with rib fractures, treated at The First People's Hospital of Zunyi, Renhuai People's Hospital, and Sinan People's Hospital between May 2020 and December 2024. Based on the actual procedure performed, as documented in medical charts and operative records, patients were categorized into the VATS group (fully thoracoscopic internal fixation via uniportal or biportal VATS; n = 70) and the open thoracotomy group (open reduction and internal fixation; n = 71). Perioperative variables, complications, and inflammatory biomarkers (white blood cell (WBC) count, neutrophil percentage (NEU%), C-reactive protein (CRP), procalcitonin (PCT), and interleukin-6 (IL-6)) were compared between groups across postoperative 24 h, 72 h, and pre-discharge time points. Furthermore, follow-up outcomes, including implant-related foreign-body sensation and functional status (rib fracture functional scale (RFFS)), were also recorded. Repeated-measures analysis of variance (ANOVA) was used to evaluate time effects and time-by-group interactions, and multivariable logistic regression was performed to identify factors independently associated with an RFFS score $\geq$80.

RESULTS: In both groups, WBC, NEU%, CRP, PCT, and IL-6 peaked at 24 h postoperatively, declined from 72 h onward. Repeated measures ANOVA showed a significant effect of time for all markers (all $p < 0.001$). Compared with the open thoracotomy group, the VATS group had consistently lower WBC, CRP, PCT, and IL-6 levels at 24 h, 72 h, and before discharge, with significant time $\times$ group interaction effects for CRP and IL-6 (both $p < 0.001$), indicating a reduced inflammatory burden under a similar overall downward trend. NEU% changed significantly over time but showed no significant between-group or interaction effects ($p > 0.05$). The incidence of abnormal WBC was high in both groups at 24 h but decreased more rapidly in the VATS group. At 72 h, the proportion of patients with abnormal WBC was significantly lower in the VATS group than in the open thoracotomy group ($p = 0.001$), whereas more patients in the VATS group achieved normal WBC levels by discharge. No patient in the VATS group required implant removal, whereas 2.94% of patients in the open surgery group underwent implant removal due to pronounced foreign-body sensation. Postoperative hemoglobin levels were higher and electrolyte disturbances less frequent in the VATS group (both $p < 0.05$). Multivariable logistic regression showed that VATS (vs open thoracotomy) remained independently associated with achieving a rib fracture functional scale (RFFS) score $\geq$80 ($p = 0.027$). In addition, abnormal WBC status at 24 hours postoperatively showed a borderline association with an RFFS $\geq$80 ($p = 0.049$).

CONCLUSIONS: Complete thoracoscopic rib fracture fixation significantly reduces surgical trauma, improves recovery, and lowers the incidence of postoperative complications.

Keywords: rib fractures; flail chest; open reduction and internal fixation; complete video-assisted thoracoscopic surgery

Introduction

Rib fractures are among the most frequent manifestations of thoracic trauma, occurring in approximately 40% of patients who present with chest injuries, with severity ranging from minor to complex fractures [1]. In patients with multiple or obviously displaced fractures, surgical stabilization has been increasingly applied as a central management strategy. This intervention intends to alleviate chest pain, restore structural stability of the thoracic cage, improve respiratory function, and reduce the risk of pulmonary complications [2].

Although open reduction and internal fixation remain widely used and enable direct exposure of fracture sites with reliable fixation, this approach often requires extensive dissection of chest wall muscles and surrounding soft tissues, resulting in substantial surgical trauma, more pronounced postoperative pain, and prolonged recovery. In some cases,

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implants may be palpable, resulting in a persistent sensation of a foreign body, and in certain cases, secondary surgery may be required for implant removal, thereby potentially compromising long-term benefits.

With advances in minimally invasive surgical techniques and fixation materials, totally thoracoscopic rib fracture fixation using video-assisted thoracoscopic surgery (VATS) has gained increasing focus. This approach uses small incisions and thoracoscopic visualization, usually coupled with imaging guidance, to precisely locate, reduce, and stabilize fractures. By minimizing injury to chest wall soft tissues while maintaining adequate stability, VATS may facilitate rapid recovery [3]. Previous studies indicate that thoracoscopic procedures can reduce postoperative pain, shorten hospital stay, and attenuate perioperative inflammatory responses. However, existing evidence largely focuses on short-term in-hospital outcomes, and there is still a limited study regarding longitudinal changes in inflammatory biomarkers and their associations with long-term functional recovery and patient-reported outcomes, such as foreign-body sensation [4].

Given these gaps, the present study assesses perioperative outcomes in individuals undergoing VATS compared with conventional open surgery for rib fractures. It further evaluates the dynamic changes in postoperative inflammatory markers, such as white blood cell (WBC) count, neutrophil percentage (NEU%), C-reactive protein (CRP), procalcitonin (PCT), and interleukin-6 (IL-6), and provides an integrated assessment incorporating electrolyte imbalances, postoperative complications, and follow-up measures of foreign-body sensation and functional scores. Specifically, the aim is to determine whether VATS is linked to a lower postoperative inflammatory burden and improved perioperative safety, and to examine whether operative approach and postoperative inflammatory responses independently affect long-term functional outcomes and patient experience, thereby contributing more comprehensive evidence to inform surgical decision-making and perioperative management.

Methods

Study Population

This retrospective study initially screened 520 patients with rib fractures admitted to The First People's Hospital of Zunyi, Renhuai People's Hospital, and Sinan People's Hospital, between May 2020 and December 2024. After applying predetermined inclusion and exclusion criteria, 141 patients were included in the final cohort, comprising 90 males and 51 females. This study was an approach-based comparison within a surgical cohort, especially assessing VATS vs traditional open surgery, focusing on differences in perioperative inflammatory responses, postoperative complications, and functional recovery, rather than comparisons with nonoperative management or defining thresholds for surgical indications.

This study received financial support from the Zunyi Science and Technology Program (Grant No. HZ-2022-84) and was approved by the Ethics Committee of the First People's Hospital of Zunyi (Approval No. 2025-1-129). Before study commencement, all three participating centers completed standardized pre-study training to ensure consistency in surgical procedures. Critical intraoperative steps, including anesthesia induction, selection of thoracoscopic approach, and application of fixation devices, were performed as per the unified protocol. All patients were successfully discharged from the hospital and provided informed consent. Based on the operative records, patients were divided into either the VATS group or the open surgery group for comparative analyses.

Flail chest was defined as the presence of fractures involving at least three consecutive ribs, each with two or more fractured sites, resulting in a free-floating segment of the chest wall. Clinically, this condition may have paradoxical chest wall motion. In patients where clinical signs were atypical, particularly after mechanical ventilation or sufficient analgesia, diagnosis was determined in conjunction with chest computed tomography (CT) and three-dimensional reconstruction demonstrating an unstable chest-wall segment formed by multiple adjacent bicortical or multi-site rib fractures.

Surgical indications followed the consensus statement on surgical stabilization of rib fractures (rib fracture colloquium clinical practice guidelines) [5], including: (1) fracture fragments penetrating the lung or other intrathoracic organs with a risk of potential injury; (2) associated severe complications, such as pulmonary laceration or tracheal or major vessel injury; (3) severe multi-rib fractures with obvious displacement identified during thoracotomy for other indications; (4) severe pulmonary contusion requiring prolonged mechanical ventilation; (5) significantly displaced bicortical rib fractures; and (6) persistent, severe chest pain with impaired respiratory or circulatory function despite adequate analgesia and ineffective conservative management.

Inclusion and Exclusion Criteria

Patients were included in the final cohort if they met the following criteria: (1) age $\geq$18 years; (2) a confirmed diagnosis of flail chest (as defined above), or the presence of $\geq$3 rib fractures with significant displacement and/or compromised chest-wall stability, deemed to meet indications for surgical stabilization on clinical assessment; (3) availability of preoperative chest CT with three-dimensional reconstruction, allowing clear evaluation of the fracture segments and degree of displacement, and confirming that surgical intervention was technically feasible; (4) severe pain with poor response to conservative therapy; (5) concomitant thoracic injuries requiring surgical management; and (6) availability of complete clinical data.

However, exclusion criteria included: (1) severe comorbidities, such as cardiac, pulmonary, hepatic, or renal dys-

function, coagulopathy, or any condition making the patient unfit for surgical intervention; (2) severe polytrauma, such as major cranial, abdominal, or other life-threatening injuries requiring immediate management; and (3) injury duration >14 days, particularly in patients where callus formation had already occurred, making fracture reduction technically challenging.

Evaluation of Fracture Reduction

To improve the consistency and reliability of outcome evaluation, the quality of fracture reduction was primarily determined using postoperative chest CT and three-dimensional reconstructions, with clinical symptoms used as supportive information. Representative preoperative chest CT three-dimensional reconstruction images demonstrating multiple rib fractures and displacement are shown in Fig. 1A,B. All patients underwent repeat chest CT within 3–7 days after surgery. Two thoracic surgeons at or above the associate chief physician level independently measured the maximal step-off and gap between fracture fragments using axial, sagittal, or coronal reconstructed images. The average of the two measurements was used as the final value. In cases where a significant discrepancy was observed, a third senior surgeon reviewed the images.

In this study, "chest wall collapse" was defined using radiological criteria: (1) inward displacement of ≥10 mm in the injured chest wall compared with the corresponding intercostal space on the contralateral side, or (2) focal disruption and inward deformation of the chest wall contour observed on inspiratory-phase CT images. When necessary, these radiologic findings were further supported by physical examination to determine the presence of paradoxical chest wall motion.

Based on these definitions, fracture reduction quality was classified into four grades: excellent: postoperative chest pain and dyspnea were almost completely resolved or markedly relieved, and no paradoxical chest wall motion was detected on physical examination. CT imaging showed a symmetrical thoracic cage with anatomical restoration of the fracture ends. Both maximal step-off and gap were ≤2 mm, and no radiological evidence of chest wall collapse was observed (Fig. 1C,D). Good: clinical symptoms were significantly improved, and patients were able to perform daily activities. CT findings demonstrated an essentially symmetrical thoracic contour, with only minor local angulation or irregularities. The maximal step-off or gap was >2 to ≤5 mm, without obvious chest wall collapse or with only minimal deformity. Fair: chest pain and chest tightness were partially relieved, but patients continued to experience discomfort during deep breathing or physical activity. CT images showed incomplete reduction of the fracture, with a maximal step-off or gap of >5 to ≤10 mm, possibly accompanied by mild localized inward deformation. Overall chest wall stability was maintained, and no evident paradoxical motion was observed. Poor: clinical improvement was limited, with persistent or marked chest pain and dyspnea. CT images revealed pronounced displacement of the fracture ends, with a maximal step-off or gap >10 mm, together with clear chest wall collapse or instability. In such cases, reoperation was considered when appropriate.

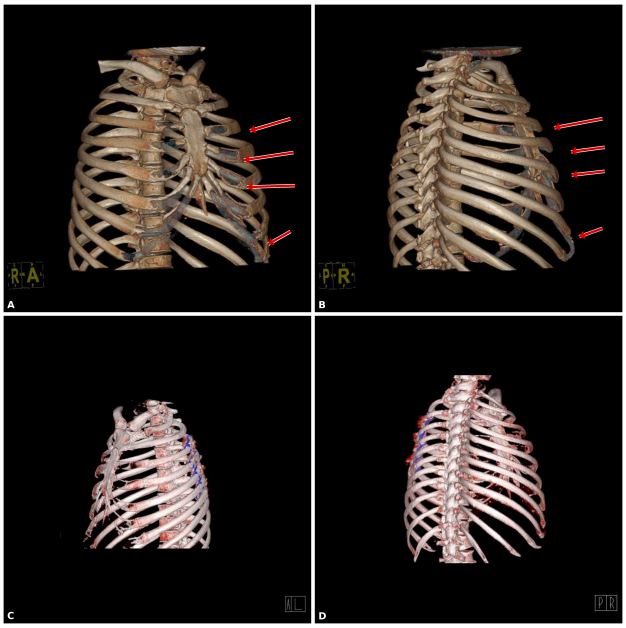

Fig. 1. Imaging evaluation and follow-up of a representative surgical case (example). (A) Preoperative chest computed tomography (CT) three-dimensional reconstruction (volume rendering (VR), posterolateral oblique view, with scapulae included) showing multiple rib fractures and displacement. The red arrows indicate fractured rib segments and displaced fracture sites. (B) Preoperative VR image (with VR threshold/view adjusted to reduce scapular overlap and to more clearly depict the fracture sites) further demonstrating the fractured segments and displacement (with cortical discontinuity/step-off changes at the fracture sites). The red arrows indicate cortical discontinuity and step-off changes at the fracture sites. (C) Chest CT and three-dimensional reconstruction at 3–7 days postoperatively showing satisfactory fracture reduction and stable internal fixation, with no obvious loosening or displacement. (D) Follow-up CT and three-dimensional reconstruction at 3 months postoperatively, indicating favorable fracture-healing progress and stable internal fixation. Note: This figure illustrates a representative case to indicate the imaging assessment workflow and should not be used as the sole basis for determining surgical indications.

The thresholds of 2, 5, and 10 mm for step-off and gap were chosen based on previously published reports on rib fracture fixation and chest wall reconstruction and were further adjusted through institutional experience. These values indicate both biomechanical and clinical significance in maintaining chest wall stability. Overall, this grading system was adapted from previous reports on rib fracture fixation and chest wall reconstruction [6] and modified by incorpo-

rating practical adjustments to enhance its applicability and reproducibility in routine clinical practice.

Surgical Procedures

Procedure for Internal Fixation

In the traditional group (open rib fixation under direct vision using a NiTi embracing fixator), all procedures were conducted under general anesthesia with double-lumen endotracheal intubation. The patient was placed in the lateral decubitus position on the contralateral side. After routine skin preparation and draping, the intercostal space and approximate range of the fractured ribs were identified using preoperative CT and three-dimensional reconstruction, which were then correlated with surface anatomical marking. An arc-shaped incision of approximately 10–15 cm was made along the axis of the affected ribs. The skin, subcutaneous tissue, and superficial fascia were incised sequentially, followed by careful dissection of the chest wall muscles (including partial fibers of the serratus anterior and latissimus dorsi). The intercostal muscles were partially exposed when necessary to visualize the fracture segments. Extensive rib osteotomy was avoided; instead, only limited subperiosteal stripping was performed around the fracture site to protect the intercostal neurovascular bundle and minimize soft tissue trauma.

Once 1 to 3 fractured ribs were adequately exposed, reduction was performed under direct vision. A nickel-titanium memory alloy embracing fixator (model 4HW10-40, Lanzhou Ximai Memory Alloy Co., Ltd., Lanzhou, China) was applied to stabilize the ribs. The fixator was positioned away from the rib angle and excessively curved segments. After fixation, stability was ensured by assessing the interface between the device and the rib to confirm there was no obvious loosening or displacement. The operative field was then inspected for intercostal oozing or active bleeding, which was controlled by electrocautery or ligation where necessary.

When thoracic exploration was required, the pleural cavity was accessed through the same incision, allowing direct evaluation and management of lung contusion, retained blood clots, and other intrathoracic conditions. At the end of the procedure, a single closed thoracic drainage tube was placed through an appropriate intercostal space as required. After confirming complete lung re-expansion, the intercostal muscles, chest wall muscles, and subcutaneous tissue were closed in layers, followed by skin closure. All procedures in this group were performed under direct visualization without the assistance of thoracoscopy or other endoscopic devices.

In the VATS group (complete thoracoscopic intrathoracic rib fixation), all procedures were conducted under general anesthesia with double-lumen endotracheal intubation and one-lung ventilation. Patients were placed in the lateral decubitus position with the affected side upward. Preoperative CT and three-dimensional reconstruction were used to evaluate the number, location, and extent of rib fractures, and corresponding intercostal spaces were marked on the skin. Based on patient habitus, number of fractured ribs, and surgical preferences, either a single-port or two-port thoracoscopic approach was selected.

The single-port approach was preferred for patients with relatively clustered fracture segments and sufficient intrathoracic working space. A 4–6 cm incision was made along the rib axis at the 4th or 5th intercostal space along the mid-axillary line (Fig. 2A). The exact incision length was adjusted according to patient characteristics such as body mass index (BMI), chest-wall thickness, and fracture distribution. In patients with a lower BMI, a thinner chest wall, and more localized fractures, the incision was typically maintained at approximately 4 cm. In contrast, in patients with a higher BMI and/or thicker chest wall, or when additional working space was required, the incision could be appropriately extended to $\leq$6 cm to facilitate instrument handling and maintain adequate visualization without adding additional ports and minimize repeated instrument compression and traction on the intercostal soft tissues. This practice is consistent with the uniportal VATS, stating that incision size may be individualized according to patient body habitus (including BMI) and procedural requirements [7]. After incising, the chest wall muscles were dissected along the direction of their fibers, and a soft-tissue protector was inserted. Both the thoracoscope and operative instruments were introduced through the same incision.

The two-port approach was used when fracture segments were more widely distributed, when pleural adhesions were suspected, or when greater flexibility in instrument movement was required. A 3 to 4 cm "working port" was created along the anterior or mid-axillary line, while a 1–1.5 cm "viewing port" was placed along the posterior axillary or scapular line. The thoracoscope was inserted through the viewing port, and all specialized instruments were introduced via the working port.

After entering the thoracic cavity, accumulated blood clots and effusions were removed, and the lung parenchyma and surrounding structures were inspected. Fractured ribs were identified under thoracoscopy, combined with preoperative surface markings and intraoperative transillumination. When necessary, an additional 0.5–1.0 cm auxiliary incision was made at the corresponding intercostal space, through which a hook-shaped probe or traction wire was passed around the outer surface of the rib to the fracture segment, thereby creating a body-surface tunnel for subsequent placement of the embracing fixator.

Using specialized instruments (Fig. 2B), fracture ends were distracted, reduced, and temporarily stabilized. Once a satisfactory reduction was achieved, a preselected nickel-titanium memory alloy embracing fixator (same model as in the open thoracotomy group) was introduced through the working port and advanced along the auxiliary tunnel or traction wire to the lateral surface of the target rib under tho-

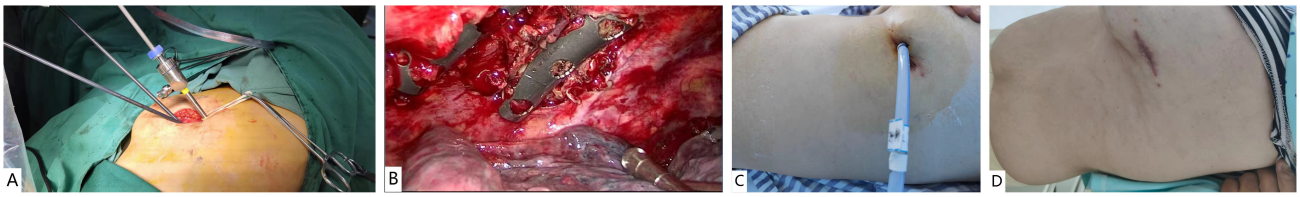

Fig. 2. Key operative steps of fully thoracoscopic-assisted internal fixation for rib fractures (example). (A) Minimally invasive single-incision thoracoscopic approach, with a single working port of approximately 4–6 cm in length. (B) Intraoperative use of a specially designed patented instrument for thoracic internal fixation of the fracture ends. (C) Removal of the closed thoracic drainage tube on postoperative day 3. (D) Follow-up at 3 months postoperatively, with Grade A wound healing with a small scar.

racoscopic guidance. The device was then deployed to encircle the fractured rib, ensuring that the placement avoided highly curved portions such as the rib angle. Stability was confirmed after locking to ensure proper seating without rotation or loosening.

After fixation of all fractured segments, the thoracic cavity was re-examined for active bleeding, intercostal vascular injury, or device-related compression, and complete lung re-expansion was confirmed. A single closed thoracic drainage tube was then placed under thoracoscopic guidance, and its position was adjusted appropriately (Fig. 2C). All instruments were then removed, and the incisions were closed in layers. As shown in Fig. 2D, at 3-month postoperative follow-up, wound healing was generally satisfactory (Grade A), with minimal scarring found.

Postoperative Management

Both groups underwent postoperative management, including pain control, respiratory care, rehabilitation, and careful assessment of antibiotic use. Pain in both groups was managed with a perioperative multimodal analgesia approach. Postoperatively, the baseline analgesic regimen consisted of patient-controlled analgesia (PCA) and/or intravenous or oral nonsteroidal anti-inflammatory drugs (NSAIDs). Based on the visual analogue scale (VAS) scores and patient-reported discomfort, additional analgesics, such as weak opioids or short courses of strong opioids, were used when needed. The aim was to maintain a resting VAS $\leq$3, rather than simply relying on a stepwise manner. All medications were administered within recommended doses and durations, and patients were closely monitored for adverse events such as respiratory depression, nausea, vomiting, and constipation. Non-pharmacological analgesia was also incorporated, including ice application, postural adjustment, chest wall support, and relaxation techniques. Early postoperative use of heat over the incision site was avoided to reduce the risk of local congestion and swelling. All these interventions were individualized according to patient tolerance.

Both the study groups received structured respiratory care. In line with enhanced recovery after surgery (ERAS) principles, early mobilization was encouraged, generally within 1–3 days after surgery. From the immediate postoperative period, patients were instructed in conducting deep-breathing exercises, effective coughing strategies, and pursed-lip breathing. Incentive spirometry was used when available to support lung expansion. Nebulized inhalation therapy was provided as required to humidify the airways and facilitate sputum secretions. For patients with viscous sputum or impaired spontaneous expectoration, bronchoscopic suctioning was performed with assistance from respiratory or anesthesia specialists to minimize the risk of atelectasis and pneumonia [8].

Once adequate pain control was achieved, early rehabilitation was initiated, including pulmonary function training and bedside limb exercises. Patients gradually progressed to sitting, standing, and ambulation. As fracture healing progressed, resistance training targeting the upper limbs and chest wall muscles was incrementally increased, while avoiding premature vigorous rotational and heavy loading to promote chest wall stability and support overall functional recovery [9].

Further, patients in both groups received short-term prophylactic antibiotics according to the standard perioperative prophylaxis principles. The first dose was administered 30–60 minutes before anesthesia induction, and postoperative antibiotics were continued for 24–72 hours, depending on the degree of wound contamination and concomitant injuries, generally not exceeding 3 days. If postoperative clinical signs such as fever, persistently elevated inflammatory markers, or suspected infection were found, the antibiotic regimen was adjusted or extended accordingly.

Routine laboratory examinations, including blood counts and biochemical profiles, were repeated on postoperative days 2–3. Particular attention was paid to white blood cell count, neutrophil percentage (NEU%), hemoglobin, albumin, and electrolytes to assess inflammatory response and overall homeostasis. Imaging follow-up involved bedside chest radiography to evaluate lung re-expansion, pleural effusion, and the position of the chest drain. Chest CT was reserved for patients with respiratory distress, recurrent pneumothorax or hemothorax, suspected malposition, or failure of the internal fixation.

As part of the study design, all enrolled patients underwent an additional chest CT scan with three-dimensional reconstruction at 3–7 days postoperatively to enable objective as-

sessment of fracture reduction and device positioning. The imaging step was specifically conducted for research purposes and was not part of the routine clinical practice. A decision regarding repeat CT imaging before discharge was made by the attending surgeon based on the clinical symptoms and prior imaging results.

Primary Outcome Measures

Perioperative Inflammatory, Hematologic, and Internal Environment Parameters

For assessing postoperative inflammatory markers, peripheral venous blood samples were obtained at 24 h, 72 h, and before discharge (typically postoperative days 5–7). The following indicators were evaluated: WBC, NEU%, CRP, PCT, and IL-6. According to the laboratory reference ranges, WBC $<3.5 \times 10^9$/L or $>9.5 \times 10^9$/L was considered abnormal, while NEU% <40% or >75% was considered an abnormal neutrophil range. The number and proportion of patients with abnormal values at each time point were recorded.

Patients were also assessed for postoperative hematologic and internal environment parameters. At the same time points, hemoglobin (Hb) and serum albumin (Alb) levels were recorded. Furthermore, electrolyte disturbances were defined as any deviation of serum sodium, potassium, or chloride levels beyond the normal reference range.

Follow-up Efficacy Indicators

Long-term functional outcomes were assessed using a modified rib fracture functional scale (RFFS), developed by our research team based on previous studies. This is a disease-specific assessment tool that incorporates domains typically used in the evaluation of rib fractures and chest wall injuries, along with established principles of health-related scale development [10,11]. The preliminary version of the scale was drafted through multidisciplinary collaboration involving thoracic surgeons, rehabilitation physicians, and nursing staff, and was then refined through pilot testing, with semantic revision and structural optimization of the items.

The RFFS consists of three domains: pain (0–40 points), respiratory function (0–30 points), and activities of daily living (0–30 points). Each item is rated on a 0–4 scale (from "no symptoms to no difficulty" to "extremely severe impairment or inability to perform the activity"). Total scores range from 0 to 100, with higher scores indicating better functional status and less disability. In the present study, the RFFS showed good internal consistency (Cronbach's $\alpha = 0.857$).

For functional grading, functional status was categorized into three levels using cut-off values of 60–80, informed by expert clinical consensus and previous literature on chest wall injury outcomes, including the approach described by Fornasiero *et al*. [12], as well as commonly used grouping methods in 0–100 functional scales such as the 36-Item Short Form Health Survey (SF-36). Scores of <60 points indicate severe functional impairment, characterized by significant limitation in daily activities and a need for continuous analgesic support with inadequate relief, 60–80 points represent moderate functional impairment, with mild-to-moderate activity limitation and intermittent need for analgesics, and 80–100 points show mild or no functional impairment, indicating independence in daily activities and minimal or no reliance on analgesics.

This grading scheme was designed to indicate three clinically meaningful recovery states—"markedly limited and needing long-term analgesia", "partially limited but improvable with analgesia", and "essentially returned to normal activity" —so as to provide a more intuitive reflection of the impact of different operative approaches on medium- to long-term functional recovery. The grading is intended primarily to facilitate clinical interpretation rather than to be used for diagnostic purposes.

RFFS assessments were performed at least 6 months after surgery to reflect longer-term functional recovery. Follow-up was conducted by trained staff using standardized procedures, either through outpatient visits or telephone interviews. For patients with multiple follow-up records, the most recent RFFS assessment at or beyond 6 months after surgery was included in the analysis. Patients who did not complete follow-up at ≥6 months were excluded from RFFS-related analyses, and missing data were not imputed.

Secondary Outcome Measures

Secondary outcome measures included subjective discomfort and foreign-body sensation among patients. Subjective or patient-reported discomfort related to the implanted fixation devices was systematically collected through outpatient visits or telephone follow-up. The questionnaire covered symptoms such as persistent or intermittent local chest wall pain, numbness, pruritus, swelling, and the patient's experience or awareness.

Furthermore, foreign-body sensation was defined as a persistent awareness or discomfort associated with the implant, either at rest or during activity. This includes feelings of tightness, pulling, or pressure; a clear perception or palpation of the implant device; or symptom aggravation during movements (e.g., turning over in bed, raising the arm, deep breathing) or with weather changes.

To improve the quantifiability and reproducibility of this subjective indicator, discomfort was graded using a 4-point Likert scale where 0 points indicated no discomfort; 1 point mild discomfort, occasional awareness without interference with daily activities; 2 points showed moderate discomfort, obvious aggravation of discomfort during activity or with weather changes, with partial limitation of daily activities; 3 points indicated severe discomfort, persistent or pronounced symptoms requiring long-term analgesics or a clear desire of implant removal.

Table 1. Comparison of baseline information between groups.

Variable	VATS group (n = 70)	Open thoracotomy (n = 71)	χ^2/t	p-value
Age (years)	45.65 ± 9.86	46.03 ± 10.13	0.225	0.822
Gender (male/female)	45/25	45/26	0.013	0.911
Preoperative albumin (g/L)	39.10 ± 4.20	38.60 ± 4.50	0.690	0.490
BMI (kg/m^2)	22.75 ± 1.40	22.35 ± 1.53	1.619	0.108
ASA classification (I–II/III and above)	52/18	50/21	0.263	0.608
Injury to surgery time (days)	4.15 ± 1.40	3.80 ± 1.55	1.369	0.173
Flail chest	24 (34.29)	25 (35.21)	0.013	0.908

BMI, body mass index; ASA, American Society of Anesthesiologists; VATS, video-assisted thoracoscopic surgery.

For statistical analysis, a foreign-body discomfort score of ≥2 was defined as "clinically significant foreign-body sensation". In addition, the number and proportion of patients undergoing implant removal specifically due to foreign-body discomfort were recorded.

All patients were followed according to a standardized schedule, with outpatient visits arranged at 1, 3, and 6 months postoperatively, and every 6 months thereafter. When in-person follow-up was not feasible, a trained staff nurse conducted the assessment via telephone or video consultation. The minimum follow-up duration was 6 months after surgery, and data from the most recent available follow-up were used for analysis. For patients with multiple follow-up records, the most recent follow-up assessment at or beyond 6 months was considered as a long-term outcome.

Statistical Analysis

Data were analyzed using SPSS version 29.0 (IBM Corp, Armonk, NY, USA). Categorical variables were expressed as numbers (percentages) and compared using the χ^2 test. For continuous variables, normality was assessed using the Shapiro-Wilk test in combination with Q-Q plots, and homogeneity of variance was evaluated with Levene's test. Continuous variables conforming to the assumption of normality and homogeneity of variance were expressed as mean ± standard deviation ($\bar{x} \pm s$), and intergroup comparisons were conducted using the independent-samples t test. Skewed continuous data were expressed as median and interquartile range [M (Q1, Q3)] and analyzed using the Mann-Whitney U test.

To account for potential confounders, logistic regression analysis was performed using an RFFS score ≥80 points (coded as yes = 1, no = 0) as the dependent variable. Initially, univariable logistic regression was conducted to calculate unadjusted odds ratios (ORs) with corresponding 95% confidence intervals (CIs). Variables with a p-value < 0.10 in the univariable analysis, as well as clinically important covariates (such as age, sex, body mass index, number of fractured ribs, presence of concomitant thoracic injuries, and American Society of Anesthesiologists (ASA) classification), were then entered into a multivariable logistic regression model.

The operative approach (thoracoscopic vs open surgery) was set as the primary independent variable. Adjusted ORs with 95% CI were estimated to evaluate the independent association between thoracoscopic surgery and long-term functional outcome (RFFS ≥80 points). All tests were two-sided, and a p-value < 0.05 was considered statistically significant.

Results

Comparison of Baseline Characteristics Between the Two Groups

The baseline characteristics were broadly similar between the VATS and open thoracotomy groups, with no statistically significant differences observed (all $p > 0.05$, Table 1), indicating good comparability.

Comparison of Perioperative Laboratory Parameters and Intraoperative Blood Loss Between Groups

Postoperative laboratory results indicated that patients treated with VATS maintained better postoperative hematologic stability. Particularly, hemoglobin levels were significantly higher in the VATS group, and changes in electrolyte balance occurred less frequently compared with the open thoracotomy group, with both differences achieving statistical significance ($p < 0.05$). In contrast, serum albumin levels were comparable between the two groups ($p > 0.05$, Table 2). Additionally, intraoperative blood loss was significantly lower in the VATS group than in the open surgery group ($p < 0.001$, Table 3). Overall, these results suggest a less invasive physiological effect associated with the thoracoscopic method.

Perioperative Dynamic Changes in Inflammatory Markers

From 72 h onward, these markers began to reduce. The effect of time was statistically significant for all indicators ($p < 0.001$, Table 4), indicating that the postoperative inflammatory response showed an overall trend of remission over time.

The lack of a significant time × group interaction indicates that, although the initial level was different, the overall trend of reduction in WBC was similar between the two groups. NEU% showed a relatively simple pattern, with a transient increase early after surgery and a gradual decrease

Table 2. Comparison of postoperative hemoglobin, albumin, and electrolyte disturbances between groups.

Variable	VATS group (n = 70)	Open thoracotomy (n = 71)	χ^2/t	*p*-value
Hemoglobin ($\bar{x} \pm s$, g/L)	113.24 ± 16.17	106.20 ± 18.41	2.414^b	0.020
Albumin ($\bar{x} \pm s$, g/L)	32.28 ± 4.23	32.16 ± 3.55	-0.180^b	0.860
Electrolyte disturbances [example (%)]	4 (5.7%)	13 (18.3%)	5.274^a	0.022

Note: "a" denotes the χ^2 value and "b" denotes the *t* value.

Table 3. Comparison of intraoperative blood loss between the two groups ($\bar{x} \pm s$).

Variable	VATS group (n = 70)	Open thoracotomy (n = 71)	*t*	*p*-value
Intraoperative blood loss (mL)	102.50 ± 40.25	190.10 ± 68.50	9.273	<0.001

Table 4. Time variation of dynamic inflammatory indicators ($\bar{x} \pm s$).

Group	WBC ($\times 10^9$/L)			*F* (time × group)	*p*-value (time × group)
	24 hours after surgery	72 hours after surgery	Before discharge		
VATS group (n = 70)	11.51 ± 3.04	9.29 ± 3.17	7.52 ± 2.05	0.472	0.624
Open thoracotomy (n = 71)	12.83 ± 3.50	10.59 ± 3.68	8.21 ± 2.37		
F (time)		69.144			
p (time)		<0.001			
Group	NEU%			*F* (time × group)	*p*-value (time × group)
	24 hours after surgery	72 hours after surgery	Before discharge		
VATS group (n = 70)	81.20 ± 6.25	78.99 ± 7.29	68.75 ± 8.10	0.020	0.980
Open thoracotomy (n = 71)	82.50 ± 7.10	79.99 ± 9.26	70.10 ± 9.25		
F (time)		94.449			
p (time)		<0.001			
Group	CRP (mg/L)			*F* (time × group)	*p*-value (time × group)
	24 hours after surgery	72 hours after surgery	Before discharge		
VATS group (n = 70)	80.76 ± 10.09	61.25 ± 8.50	11.35 ± 3.20	35.785	<0.001
Open thoracotomy (n = 71)	105.20 ± 15.75	85.24 ± 11.32	18.10 ± 6.32		
F (time)		2331.644			
p (time)		<0.001			
Group	PCT (ng/mL)			*F* (time × group)	*p*-value (time × group)
	24 hours after surgery	72 hours after surgery	Before discharge		
VATS group (n = 70)	0.20 ± 0.05	0.13 ± 0.03	0.08 ± 0.02	2.242	0.118
Open thoracotomy (n = 71)	0.28 ± 0.12	0.20 ± 0.08	0.17 ± 0.05		
F (time)		64.864			
p (time)		<0.001			
Group	IL-6 (pg/mL)			*F* (time × group)	*p*-value (time × group)
	24 hours after surgery	72 hours after surgery	Before discharge		
VATS group (n = 70)	80.10 ± 12.25	40.52 ± 8.75	13.20 ± 3.15	85.435	<0.001
Open thoracotomy (n = 71)	120.54 ± 20.20	60.36 ± 10.85	17.50 ± 7.20		
F (time)		1895.896			
p (time)		<0.001			

WBC, white blood cell; CRP, C-reactive protein; PCT, procalcitonin; IL-6, interleukin-6; NEU%, neutrophil percentage.

thereafter. There was no substantial interaction between time and treatment group ($p > 0.05$).

In contrast, CRP and IL-6 levels were consistently lower in the VATS group than in the open thoracotomy group at all three time points. Furthermore, significant time × group interactions were observed (both $p < 0.001$), indicating that, under an overall similar downward trend in both groups, the inflammatory response in the VATS group was milder in the early postoperative stage and recovered more quickly. While the effect of time was significant, no interaction was found. Although PCT levels were slightly lower in the VATS group at each time point than in the open thoracotomy group, the overall patterns of change were similar.

Table 5. Comparison of abnormal proportions of WBC at different time points [n (%)].

Variable	Time point	VATS group (n = 70)	Open thoracotomy (n = 71)	χ^2	*p*-value
WBC abnormality	24 hours after surgery	52 (74.29%)	54 (76.06%)	0.059	0.808
	72 hours after surgery	32 (45.71%)	52 (73.24%)	11.089	0.001
	Before discharge	12 (17.14%)	18 (25.35%)	1.418	0.234

In addition to differences in mean values, the proportion of patients with abnormal WBC levels was also assessed. At 72 hours postoperatively, the incidence of abnormal WBC was significantly lower in the VATS group than in the open thoracotomy group (45.71% vs 73.24%, $p = 0.001$, Table 5), suggesting that VATS may be associated with a faster resolution of the postoperative inflammatory response.

Follow-up RFFS Scores and Subjective Discomfort/Foreign-Body Sensation

Among the 141 initially enrolled patients, 136 completed functional follow-up at ≥6 months after surgery and were included in the RFFS analysis, corresponding to an overall follow-up completion rate of 96.45% (136/141). The final study cohort included 68 patients in the VATS group and 68 patients in the open surgery group, with no significant difference in follow-up completion rates between groups ($p > 0.05$). Five patients were excluded from functional outcome assessment due to incomplete follow-up. The primary reasons included loss of contact after changes in personal information, follow-up performed at other institutions without return of the assessment data, and refusal to participate. Details of the follow-up completion are given in Table 6.

RFFS grading results are shown in Table 6. In the VATS group, none of the patients had a total RFFS score below 60; 11 patients (16.2%) scored 60–79 and 57 patients (83.8%) scored 80–100. Similarly, no patient in the open surgery group scored below <60; however, 24 patients (35.3%) scored 60–79 and 44 patients (64.7%) scored 80–100. The distribution of RFFS grades differed significantly between the two groups ($p = 0.011$). These results indicate that patients in the VATS group experienced better mid- to long-term functional recovery, with fewer patients demonstrating moderate to severe functional limitation (RFFS <80). Notably, severe functional impairment (RFFS <60) was not observed in either group.

Postoperative Subjective Discomfort/Foreign Body Sensation

During follow-up, patient-related discomfort associated with fixation devices was compared between the groups using Pearson chi-square test. In the open surgery group, two patients reported severe foreign-body discomfort requiring removal of fixation devices. Moreover, two patients experienced weather-related pain, one reported incision-site numbness, one pruritus, and one a local sensation of swelling.

Table 6. Distribution of RFFS scores at ≥6-month postoperative follow-up [n (%)].

Index	<60 points	60–79 points	80–100 points
VATS group (n = 68)	0	11 (16.2)	57 (83.8)
Open thoracotomy group (n = 68)	0	24 (35.3)	44 (64.7)
χ^2		6.502	
p-value		0.011	

Note: As there were zero cases with scores <60 in both groups, the statistical comparison was performed using a chi-square test based on the 2 × 2 distribution of scores in the 60–79 versus 80–100 categories. RFFS, rib fracture functional scale.

However, symptoms in the VATS group were generally milder and less frequent. One patient reported weather-related pain, two reported numbness, and one experienced a mild sensation of swelling. No patients in the VATS group required implant removal during the follow-up period. Overall, the proportion of patients without any abnormal postoperative discomfort was higher in the VATS group (94.12%) compared with the open thoracotomy group (89.71%, Table 7).

Univariate Regression Analysis

For univariate analysis, variables were coded in a binary format as follows: operative approach (thoracotomy = 0, VATS = 1); gender (female = 0, male = 1); number of fractured ribs (≥3 ribs = 1, <3 ribs = 0); flail chest (no = 0, yes = 1); concomitant thoracic injury (no = 0, yes = 1); ASA classification (I–II = 0, ≥III = 1); abnormal WBC at 24 h postoperatively (normal = 0, abnormal = 1); abnormal WBC at 72 h postoperatively (normal = 0, abnormal = 1); and postoperative electrolyte disturbance (no = 0, yes = 1). A univariate logistic regression analysis was performed using an RFFS score ≥80 (yes = 1, no = 0) as the dependent variable. The results showed that the operative approach (VATS vs open surgery) and the presence of abnormal WBC levels at 24 h postoperatively were associated with a higher likelihood of achieving an RFFS score ≥80 ($p < 0.10$). Other variables, such as age, sex, BMI, number of fractured ribs, presence of flail chest, concomitant thoracic injuries, ASA classification, time from injury to surgery, intraoperative blood loss, abnormal WBC at 72 h postoperatively, and postoperative electrolyte disturbance, were not statistically significant in the univariate analysis ($p > 0.10$, Table 8).

Table 7. Details of abnormal postoperative discomfort during follow-up [n (%)].

Index	No special feedback	Request for removal	Weather-related pain	Incision-site numbness	Incision-site pruritus	Local swelling sensation
VATS group (n = 68)	64 (94.12%)	0 (0%)	1 (1.47%)	2 (2.94%)	0 (0%)	1 (1.47%)
Open thoracotomy group (n = 68)	61 (89.71%)	2 (2.94%)	2 (2.94%)	1 (1.47%)	1 (1.47%)	1 (1.47%)
χ^2			0.890			
p-value			0.345			

Table 8. Single-factor logistic regression analysis using an RFFS score ≥80.

Variable	OR (95% CI)	*p*-value
Operative approach	2.793 (1.271~6.135)	0.011
Age (years)	1.019 (0.982~1.058)	0.323
Gender	1.214 (0.564~2.612)	0.620
BMI (kg/m^2)	1.026 (0.796~1.321)	0.845
Number of fractured ribs	0.465 (0.098~2.200)	0.334
Presence of flail chest	0.540 (0.237~1.230)	0.142
Concomitant thoracic injuries	0.635 (0.299~1.346)	0.236
ASA classification	0.770 (0.341~1.735)	0.528
Injury-to-surgery interval (days)	1.209 (0.932~1.569)	0.154
Intraoperative blood loss (mL)	0.996 (0.991~1.002)	0.172
Abnormal (vs normal) WBC 24 hours after surgery	2.278 (1.008~5.146)	0.048
Abnormal (vs normal) WBC 72 hours after surgery	1.477 (0.697~3.130)	0.309
Postoperative electrolyte disturbances	1.228 (0.374~4.028)	0.735

Note: With RFFS score ≥80 as the dependent variable (yes = 1, no = 0), an OR >1 indicates increased odds of achieving RFFS ≥80 (a favorable functional outcome). Unless otherwise specified, categorical variables used code 0 as the reference category: operative approach (thoracotomy = 0, VATS = 1); gender (female = 0, male = 1); number of rib fractures (<3 = 0, ≥3 = 1); flail chest (no = 0, yes = 1); concomitant thoracic injury (no = 0, yes = 1); ASA class (I–II = 0, ≥III = 1); abnormal WBC at 24 h postoperatively (normal = 0, abnormal = 1); abnormal WBC at 72 h postoperatively (normal = 0, abnormal = 1); postoperative electrolyte disturbance (no = 0, yes = 1). Continuous variables were entered into the model per unit increase: age (per 1-year increase), BMI (per 1 kg/m^2 increase), time from injury to surgery (per 1-day increase), and intraoperative blood loss (per 1-mL increase). WBC "normal/abnormal" was defined according to the reference ranges of The First People's Hospital of Zunyi laboratory. OR, odds ratio.

Multivariate Regression Analysis

In the multivariate logistic regression model, variables with $p < 0.10$ in the univariate analysis (operative approach and abnormal WBC at 24 h postoperatively), were included together with covariates preselected based on clinical relevance (age, sex, BMI, number of fractured ribs, presence of flail chest, concomitant thoracic injuries, ASA classification, time from injury to surgery, intraoperative blood loss, abnormal WBC at 72 h postoperatively, and postoperative electrolyte disturbance). The results showed that the operative approach (VATS vs open thoracotomy) remained an independent factor associated with achieving a favorable functional outcome (RFFS score ≥80). Particularly, patients who underwent VATS demonstrated a significantly higher likelihood of achieving this threshold compared to those treated with open surgery (odds ratio (OR) = 3.587, 95% CI: 1.157–11.119, $p = 0.027$). Similarly, an abnormal WBC count at 24 h postoperatively showed a borderline association with an improved functional outcome (OR = 2.512, 95% CI: 1.006-6.273, $p = 0.049$). As the direction of this association is not in line with clinical expectations, it may be influenced by residual confounding, timing-related effects, and biases inherent to retrospective study design. Therefore, it is reported only as an exploratory observation, with further clinical interpretation provided in the discussion section.

Other variables, including age, sex, BMI, number of fractured ribs, presence of flail chest, concomitant thoracic injuries, ASA classification, injury-to-surgery interval, intraoperative blood loss, abnormal WBC at 72 h, and postoperative electrolyte disturbances, were not significantly associated with an RFFS score ≥80 ($p > 0.05$, Table 9). Furthermore, the model was calibrated using the Hosmer–Lemeshow goodness-of-fit test, which yielded a *p*-value > 0.05, indicating a good fit between the model and the observed data.

Table 9. Multivariate logistic regression analysis (Outcome variable: RFFS score ≥80 points (yes = 1, no = 0)).

Variable	OR (95% CI)	*p*-value
Operative approach	3.587 (1.157~11.119)	0.027
Age (years)	1.027 (0.984~1.072)	0.224
Gender	1.163 (0.491~2.757)	0.731
BMI (kg/m^2)	0.991 (0.739~1.330)	0.954
Number of fractured ribs	0.572 (0.106~3.097)	0.517
Presence of flail chest	0.640 (0.258~1.585)	0.335
Concomitant thoracic injuries	0.776 (0.331~1.822)	0.560
ASA classification	0.809 (0.328~1.995)	0.646
Injury-to-surgery interval (days)	1.186 (0.896~1.570)	0.233
Intraoperative blood loss (mL)	1.000 (0.992~1.007)	0.909
Abnormal (vs normal) WBC 24 hours after surgery	2.512 (1.006~6.273)	0.049
Abnormal (vs normal) WBC 72 hours after surgery	2.104 (0.861~5.142)	0.103
Postoperative electrolyte disturbances	1.997 (0.528~7.552)	0.308

Variable coding and reference categories were the same as in Table 8. Outcome coded as RFFS ≥80 (yes = 1); categorical variables used 0 as the reference unless specified. Model fit was assessed using the Hosmer–Lemeshow test, with $p > 0.05$ indicating good fit. WBC status ("abnormal/normal") was determined according to the reference ranges of The First People's Hospital of Zunyi laboratory; "abnormal" included values either above or below the reference range.

Discussion

Key Findings and Overall Framework

This retrospective multicenter study compared VATS-assisted versus conventional open fixation for rib fractures, focusing on perioperative inflammatory responses, hematologic and electrolyte stability, patient-reported implant-related discomfort, and long-term functional recovery. Both groups showed an early postoperative rise in inflammatory markers followed by a gradual decline, consistent with a transient systemic stress response associated with trauma and surgical intervention. Compared with open fixation, VATS was associated with a lower perioperative inflammatory burden, less intraoperative blood loss with higher postoperative hemoglobin, and fewer electrolyte disturbances.

At follow-up, patients treated with VATS more often achieved favorable functional outcomes and reported fewer implant-related discomfort events. In multivariable logistic regression, the operative approach (VATS vs open fixation) remained independently associated with achieving an RFFS score ≥80. In addition, an abnormal WBC count at 24 h postoperatively showed only a borderline association with RFFS ≥80 ($p = 0.049$). Given its counterintuitive direction and the potential influence of residual confounding, effects of timing, and biases inherent to retrospective studies, the finding should be interpreted cautiously and regarded as exploratory.

Interpretation of Differences in Perioperative Inflammatory Responses

Across thoracic and trauma surgery studies, inflammatory markers typically peak around postoperative day 1 and then decline as the acute stress response resolves [13–16]. In our cohort, both groups followed this trajectory. Compared with open fixation, patients undergoing VATS consistently showed lower WBC, CRP, PCT, and IL-6 levels, whereas NEU% did not clearly differentiate between the groups. This suggests that cytokines and acute-phase reactants may better capture approach-related differences in inflammatory burden than leukocyte differentials alone.

From a mechanistic standpoint, the advantages of VATS are more plausibly attributable to reduced chest-wall soft-tissue injury and minimized non-productive traction. Conventional open fixation typically requires a larger incision and broader muscle dissection; adequate exposure of fracture segments may entail traction and compression of intercostal muscles, periosteum, and the intercostal neurovascular bundle. Such maneuvers can trigger local ischemia–reperfusion injury, interstitial exudation, and neurogenic inflammation, thereby amplifying systemic inflammatory response [17–19]. In comparison, VATS leverages the magnified thoracoscopic field to accomplish localization, reduction, and fixation through smaller incisions and limited access channels, avoiding or mitigating retractor-related chest-wall contusion while enabling more meticulous hemostasis and less extensive subperiosteal stripping. These features may reduce the release of pro-inflammatory cytokines (e.g., IL-6) and dampen the acute-phase response [20]. In addition, less postoperative pain may indirectly shape inflammatory kinetics. Better postoperative analgesia can facilitate early mobilization, effective coughing, and improved ventilation. This may reduce secondary inflammatory stimuli, such as secretion retention and atelectasis, thereby promoting a favorable cycle of "less tissue injury—lower inflammation—more active functional engagement".

Hematologic and Internal Milieu Stability: Bleeding, Fluid Therapy, and Stress

In this study, VATS was associated with less intraoperative blood loss and higher postoperative hemoglobin, whereas serum albumin showed no meaningful between-group difference. Lower blood loss may reduce the need for transfusion and limit fluctuations in intravascular volume; both substantial hemorrhage and transfusion-related immunomodulation have been linked to increased inflammatory responses and delayed recovery [21]. Clinically, higher postoperative hemoglobin may also support oxygen delivery and improve tolerance to early rehabilitation. However, given the observational design, these relationships should be interpreted as associations rather than causal effects.

Electrolyte abnormalities are frequent after trauma and surgery, reflecting the combined effects of stress responses, fluid shifts, and perioperative fluid management [22]. Compared with VATS, open thoracotomy generally involves broader tissue dissection and may be accompanied by greater exudation and a higher demand for resuscitation, which can increase the risk of dysnatremia or dyskalemia. In our cohort, the lower incidence of electrolyte disturbances in the VATS group is consistent with a more stable postoperative internal milieu, which may help patients adhere to ERAS-based recovery protocols, such as early ambulation and respiratory training. Future studies incorporating detailed transfusion data, fluid balance records, and physiologic indices (e.g., blood gas and metabolic parameters) are needed to elucidate whether "homeostatic stability" mediates the link between operative approach and functional recovery, rather than inferring this pathway from limited perioperative snapshots.

Functional Outcomes and Foreign-Body Sensation: A Patient-Centered Mechanistic Interpretation

Using the modified Rib Fracture Functional Scale (RFFS) to assess function at $\geq$6 months, we observed favorable recovery in both groups, with few patients showing severe impairment. However, a higher proportion of patients in the VATS group reached a favorable functional score, indicating better overall recovery. In multivariable analyses, operative approach and leukocyte status at 24 hours postoperatively remained independently associated with functional outcomes after adjustment for clinical covariates. These findings suggest that the operative approach and early postoperative hematologic/stress-response profile may be associated with long-term chest wall functional recovery. However, their clinical implications and underlying mechanisms require further investigation.

Notably, an abnormal WBC count at 24 h postoperatively showed a borderline association with achieving an RFFS score $\geq$80 (OR $\approx$ 2.5, p = 0.049). Because the direction of this association is inconsistent with the conventional expectation that greater inflammation predicts poorer recovery, causal inference is not warranted; thus, it should be regarded as an exploratory finding.

First, "abnormal WBC" was treated as a binary variable in this study, with both leukocytosis and leukopenia classified as abnormal. Because these two directions may carry opposite clinical implications, this approach may lead to information loss and potential misclassification. Second, the 24-h time point reflects the early stress-response window; WBC changes may be driven more by perioperative stress-related leukocyte mobilization, bone marrow reserve/immune responsiveness, hemodilution from fluid resuscitation, and differences in analgesic, steroid, or anti-infective use, rather than by infection or sustained inflammatory burden per se. Therefore, the observed association may represent a marker of early physiologic stress-response characteristics rather than implying that "higher inflammation is better". Third, given the retrospective cohort design, operative selection and perioperative management were not randomized, and residual confounding and selection bias may persist (e.g., unmeasured injury severity scores, grading of pulmonary contusion, transfusion/fluid volumes, and analgesic strategies). Moreover, the statistical significance of this finding was borderline, suggesting limited stability.

Accordingly, future studies should evaluate this association within a prospective framework by: (1) separating WBC abnormalities into elevations versus reductions and stratifying by magnitude; (2) adjusting for dynamic inflammatory biomarkers (e.g., CRP and IL-6) together with fluid management, transfusion, and medication-related variables; and (3) conducting sensitivity analyses and/or validation cohort analyses to assess reproducibility and clinical interpretability.

Foreign-body sensation and incision-related discomfort are patient-relevant concerns after rib fixation. In our cohort, implant-related discomfort was less frequent in the VATS group, and secondary procedures attributed to foreign-body sensation were uncommon. This likely reflects multiple contributing factors. First, smaller incisions and less muscle dissection may reduce chronic chest-wall pain and sensory disturbance. Open exposure often involves greater traction on intercostal tissues and more extensive scarring, which may predispose to PTPS-like symptoms such as persistent pain, numbness, or pruritus [23]. Second, implant "awareness" is influenced by implant position and soft-tissue coverage. With less extensive dissection, the plate may be less palpable and less likely to cause tethering sensations during posture changes, which could reduce persistent foreign-body awareness [24]. Third, pain and rehabilitation are closely linked. Lower pain may facilitate early deep breathing, upper-limb range of motion, and thoracic expansion exercises, whereas higher pain and persistent discomfort may lead to activity avoidance and stiffness, potentially worsening perceived implant-related symptoms. Overall, the observed advantages of VATS in function and foreign-body sensation likely reflect the combined effects

of surgical exposure, postoperative pain, and rehabilitation engagement rather than a single dominant mechanism.

Limitations, Implementation Implications, and Future Directions

This study is limited by its retrospective, non-randomized design, and residual confounding is likely despite multivariable adjustment, particularly for factors difficult to quantify retrospectively (e.g., detailed injury severity, pulmonary contusion extent, baseline cardiopulmonary reserve, and analgesic adherence). Moreover, this study compared two operative approaches (VATS vs open fixation) within an operative cohort and did not include a nonoperative control group. Therefore, our findings should not be extrapolated to define surgical indication thresholds or to infer whether mildly displaced fractures warrant surgical stabilization. In real-world practice, operative decision-making and approach selection may also be influenced by injury patterns, center expertise, and surgeon preference, introducing potential indication-related bias. Dichotomizing WBC (abnormal/normal) may obscure leukocytosis vs leukopenia and is vulnerable to perioperative management factors; therefore, causal interpretation is not warranted. Accordingly, the borderline association between abnormal WBC at 24 h and achieving RFFS $\geq$80 should be considered exploratory, because our definition combined elevations and reductions, and the measurement was obtained within an early stress-response window. This finding may reflect unmeasured confounding and indication-related bias and requires confirmation in prospective studies or independent validation cohorts.

The sample size may limit the detection of less common outcomes, and external validity to centers with different expertise and resources remains uncertain. Biomarker evaluation was mainly confined to the first postoperative period, and functional outcomes relied primarily on the modified RFFS, which warrants further psychometric validation and corroboration with objective tests.

Within these constraints, the findings consistently favored VATS across perioperative inflammatory burden, hematologic/electrolyte stability, and patient-centered outcomes. Prospective multicenter studies with standardized perioperative and rehabilitation protocols, stratification by injury severity, objective functional endpoints, and longer follow-up are needed to confirm these findings and refine patient selection.

Conclusions

Compared with conventional open thoracotomy, complete thoracoscopic rib fracture fixation offers distinct advantages. It is associated with reduced surgical trauma and a lower systemic inflammatory response, resulting in a more stable postoperative physiological state. Reduced intraoperative blood loss preserves higher postoperative hemoglobin levels and may support early recovery. The intrathoracic placement of fixation devices eliminates implant palpability, reducing both subjective and objective sensations of foreign-body discomfort. Overall, thoracoscopic fixation effectively reduces procedure-related trauma, enhances recovery, and improves patient comfort, making it a clinically valuable and promotable technique for the management of rib fractures.

Availability of Data and Materials

All data supporting the findings of this study are available within the paper, and any raw data can be obtained from the corresponding author upon request.

Author Contributions

JYT conceived and designed the study, supervised the overall research process, and defined the main research objectives. BQ contributed to the study design and methodology, performed data verification and interpretation, and drafted the manuscript. DJS and ZMF collected and organized data, performed statistical analyses, and prepared figures and tables. GLY contributed to the study conception and methodological refinement, and interpreted the results. WFZ conceived and designed the study and provided overall supervision and quality control. All authors have been involved in revising the manuscript critically for important intellectual content. All authors gave final approval of the version to be published. All authors have participated sufficiently in the work to take public responsibility for appropriate portions of the content and agreed to be accountable for all aspects of the work in ensuring that questions related to its accuracy or integrity.

Ethics Approval and Consent to Participate

This study was conducted in accordance with the principles of the Declaration of Helsinki. The study protocol was reviewed and approved by the Ethics Committee of the First People's Hospital of Zunyi (Approval No. 2025-1-129). All patients provided informed consent.

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Conflict of Interest

The authors declare no conflict of interest.

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