Zhao *et al.*
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REVIEW

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Clinical outcome analysis for surgical fixation versus conservative treatment on rib fractures: a systematic evaluation and meta-analysis

Penglong Zhao[1], Qiyue Ge[2], Haotian Zheng[2], Jing Luo[3], Xiaobin Song[1] and Liwen Hu[1*]

Abstract

Background The efficacy of surgical intervention for traumatic rib fractures in improving clinical outcomes remains a subject of considerable debate. Over the past decade, the adoption of surgical stabilization for rib fractures (SSRF) has increased substantially. This study presents a systematic review and meta-analysis of the literature published over the past 20 years, with the objective of comparing the clinical outcomes of adult patients with multiple traumatic rib fractures who underwent SSRF, relative to those treated conservatively.

Methods We searched six online databases (PubMed, Web of Science, Embase, Cochrane Library, and the Sino-American Clinical Trials Database) for literature published between June 2004 and June 2024. The Cochrane Collaboration Risk of Bias 2 (RoB 2) and the Newcastle–Ottawa Scale (NOS) tool were employed to assess methodological quality, and relative risks (RR) with 95% confidence intervals (CI) were calculated to evaluate the outcome measures. The primary outcome was all-cause mortality, while the secondary outcomes included hospital length of stay (HLOS), ICU length of stay (ILOS), duration of mechanical ventilation (DMV), and the incidence of pneumonia. Subgroup analyses were performed to assess the effects of fracture type, age, timing of surgical fixation, and study design on treatment outcomes.

Results A total of 47 studies involving 1,078,795 patients were included, consisting of three randomized controlled trials and 44 case–control studies. The results demonstrated that patients who underwent SSRF experienced better outcomes than those receiving conservative treatment in terms of all-cause mortality. However, SSRF was not superior to conservative treatment regarding HLOS, ILOS, or health care costs. Subgroup analyses revealed that the SSRF group had a lower incidence of pneumonia and shorter DMV in patients with flail chest, and patients older than 60 years may also benefit from SSRF, Furthermore, those who underwent SSRF within 72 h had shorter HLOS and DMV compared to those treated conservatively.

Conclusion SSRF reduces mortality in patients with multiple rib fractures compared to conservative management, particularly in those with flail chest and in patients over 60 years of age. It also offers benefits in terms of pneumonia incidence and DMV for patients with flail chest. Early SSRF may significantly reduce HLOS and DMV. However, careful screening of appropriate candidates is crucial to maximize the benefits of SSRF.

Keywords Chest trauma, Rib fractures, Flail chest, Surgical stabilization for rib fractures, Meta-analysis

*Correspondence:
Liwen Hu
thorax_hoo@163.com
Full list of author information is available at the end of the article

Introduction

Trauma was responsible for approximately 10% of global deaths [1], with chest trauma accounting for 25% of all trauma-related fatalities [2]. Among the various types of chest injuries, rib fractures were particularly common, representing approximately 50% of these cases [3, 4]. Common causes of trauma included road traffic accidents, falls from height, crushing forces[2], and direct violence [3, 5]. Following such trauma, patients with rib fractures may experience complications such as pneumothorax, hemothorax, pulmonary contusion, and pain [3]. These complications may impair ventilation, leading to pneumonia, respiratory failure, and even death [6–8]. Studies had shown that as the number of rib fractures increases, there was a gradual rise in the mortality rate [9]. When these complications occurred in patients with multiple rib fractures, especially those with flail chest, respiratory function is further compromised, escalating the risk of ventilator dependence and mortality by 16% [6, 10–13].

The concept of surgical stabilization has been integral to the history of thoracic trauma for more than 70 years [14, 15]. However, with the widespread use of positive pressure ventilation, it had gradually been neglected in subsequent practice [16]. Traditional conservative treatment typically included multimodal analgesia and pulmonary supportive therapy, incorporating interventions such as tracheal intubation, intermittent positive pressure ventilation, analgesia, pulmonary lavage (if necessary), chest tube drainage, and chest physiotherapy to ensure adequate ventilation [2, 14, 17, 18]. Over the past two decades, clinical studies had identified ventilation-related complications such as ventilator-associated pneumonia [19], lung injury [20], and airway complications [21]. Additionally, prolonged mechanical ventilation may result in thoracic deformities [22]. In contrast, advances in new fixation materials (e.g., custom rib fixation prostheses, bicortical screws) [23] and innovative techniques (e.g., thoracoscopic surgery, 3D-printed rib models, absorbable internal fixation materials) [24–27] had prompted surgeons and researchers to reconsider surgical fixation methods to improve patient outcomes [28, 29]. The primary objective of SSRF was to restore stability to the chest wall, thereby alleviating pain and aiding in respiratory function restoration. This intervention reduced the risk of complications and enhances patient survival [30–32].

Currently, SSRF was not only employed as a remedy following the failure of conservative treatment but is also extensively used in clinical practice as a standalone treatment option [33]. Although recent randomized controlled trials (RCTs) and observational studies had assessed the effectiveness of surgical fixation compared to conservative treatment alone in managing rib fractures, there remained variability in efficacy results across studies and a lack of consistency in defining outcomes for other patient groups [34–38]. Accurately diagnosing the severity of rib fractures and categorizing them based on key characteristics of patients presents a challenge. This study aimed to compare the outcomes of SSRF and conservative treatment for multiple rib fractures, with the objective of providing additional evidence to guide treatment strategy selection. Additionally, stratified analysis was conducted to identify the most suitable candidates for SSRF treatment.

Methods

Search strategies and criteria

We searched six databases (PubMed, Medline, Embase, Cochrane Library, China Clinical Trials Registry, and ClinicalTrials.gov) using Medical Subject Headings (MeSH) terms and free-text terms based on the following keywords: "Rib" OR "Chest," "Fracture," “fixat*,” "Surgery, Operat*," and ""Non*Operat*, conservative". Research literature comparing surgical fixation and conservative treatment for rib fractures (up to June 2024) was collected, followed by a detailed screening of each paper based on predefined inclusion and exclusion criteria. The literature search was conducted independently by two assessors (Penglong Zhao and Qiyue Ge).

Inclusion and exclusion criteria

To ensure the reliability of this study, rigorous inclusion and exclusion criteria were defined, and the literature was evaluated independently by two assessors (PLZ and QYG). If there were any discrepancies, consensus was reached through consultation with a third assessor (Liwen Hu). Inclusion Criteria: (1) Original articles; (2) Quantitative observational studies, prospective studies, and randomized controlled trials; (3) Published within the last 20 years (2004–2024); (4) English-language literature; (5) Comparative studies on surgical fixation and non-surgical methods for treating rib fractures; (6) Adult cohort (individuals aged 18 years and above). Exclusion Criteria: (1) Incomplete data or lack of primary outcome; (2) Studies lacking clear inclusion and exclusion criteria or featuring non-compliant inclusion subjects or interventions; (3) Case reports, reviews, abstracts, and systematic reviews; (4) Duplicate publications; (5) Low-quality literature; (6) Studies with a different purpose or operationalization than defined for this study; (7) Inclusion criteria not meeting the study’s expectations.

Data selection and quality assessment

Two reviewers (PLZ and QYG) evaluated the quality of all included studies, with any disagreements reevaluated by a third senior reviewer (LWH) to resolve discrepancies. The retrieved data encompassed the article title, first author, publication source, study type, case count, patient age, gender distribution, intervention specifics, follow-up duration, and primary outcome measures. Information on literature not available for data summarization could be obtained by sending an email to the first or corresponding author and excluded if no response was received. If the statistical data description does not align with our requirements, we will modify the format of the data description [39–41]. Any discrepancies in data extraction will be reviewed and resolved through discussion between the two assessors (PLZ and QYG).

Quality assessment of the studies

The methodological quality of each randomized controlled trial (RCT) was assessed using the Cochrane Collaboration Risk of Bias 2 (RoB 2) tool. Evaluators assessed each study as high, unclear, or low risk based on the evaluation criteria. In cohort studies, evaluators used the Newcastle–Ottawa Scale (NOS), employing a star rating system (up to nine stars) to assess selection, comparability, exposure, and outcome determination [42]. A higher star rating indicates a lower risk of bias.

Statistical analysis

The primary outcome measured in this study was all-cause mortality. Secondary outcomes included length of hospital stay, ICU stay, mechanical ventilation, pneumonia incidence, and the need for tracheotomy. Statistical analysis was performed using Review Manager version 5.4 for Windows, a specialized software package, following the criteria established by the Cochrane Collaboration. Pooled effect sizes for continuous variables are presented as weighted mean difference (WMD) or standardized mean difference (SMD) (in cases of inconsistent units of measurement or methods) along with 95% confidence intervals (CI). For the binary variables, the pooled effect sizes are expressed as relative risks (RR) and 95% CI. Heterogeneity between studies was assessed both by visual inspection of the forest plots and statistically by using the *I*-squared (I^2) statistic. A random-effects (RE) model was used for heterogeneity ($I^2 > 50\%$, $P < 0.05$) and a fixed-effects (FE) model for homogeneity ($I^2 < 50\%$, $P > 0.05$). When using the I^2 statistic to assess heterogeneity, ≥ 50% is considered likely to be heterogeneous, and when ≥ 75% it is considered to be considerable. The stability of the results was assessed by conducting sensitivity analyses by omitting one study at a time and noting changes in the combined effect sizes of the main outcome indicators.

Subgroup analyses

Subgroup analyses were conducted to identify the most suitable patient cohort for rib fixation surgery. These analyses considered variables such as the study type (RCT, retrospective, and prospective), rib fracture type (flail chest, non-flail chest), and patient characteristics, including age (≥ 60 years versus mixed age group) and timing of fixation (< 72 h versus physician decision).

Results

Characteristics of enrolled literature

A total of 467 articles were retrieved according to the predefined search strategy, including 49 articles in PubMed, 191 articles in Web of Science, 212 articles in Embase, 12 articles in the Cochrane Library, 0 articles in Chinese clinical trials, and three articles from ClinicalTrials.gov. After excluding duplicates and studies whose titles, abstracts, or content did not meet the inclusion criteria, we included a total of 47 eligible studies, consisting of three randomized controlled trials and 44 cohort studies (Fig. 1).

Data from the included studies were presented in Supplementary Table 1. Of the 44 cohort studies, 12 had six stars or fewer, one was rated as high risk with three stars, and nine were rated as intermediate risk. The remaining 33 studies were rated as low risk (Supplementary Table 2). The quality assessment of the three RCTs is presented in Supplementary Fig. 2.

Primary outcomes

Mortality data were reported in 33 publications (n = 989,707), with SSRF demonstrating superiority over conservative treatment in all the included studies, resulting in a sharp reduction in patient mortality (RR 0.53; 95% CI 0.39 to 0.72; $P < 0.0001$) (Fig. 2). Subgroup analysis showed that surgical fixation improved survival rates compared with conservative treatment for both patients with flail chest and those without flail chest separately (Supplementary Fig. 2a). In addition, surgical fixation proved to be superior to conservative treatment across all age groups, particularly in patients over the age of 60 (RR 0.72; 95% CI 0.55 to 0.94; $P < 0.01$) (Supplementary Fig. 2b). Among patients operated on within 72 h, surgical fixation did not show a significant difference compared to conservative treatment. However, in the subgroup where the timing of surgery was determined by the physician's assessment, surgical fixation showed a lower mortality rate than conservative treatment, with a statistically significant difference (RR 0.43; 95% CI 0.32 to 0.59; P < 0.00001) (Supplementary

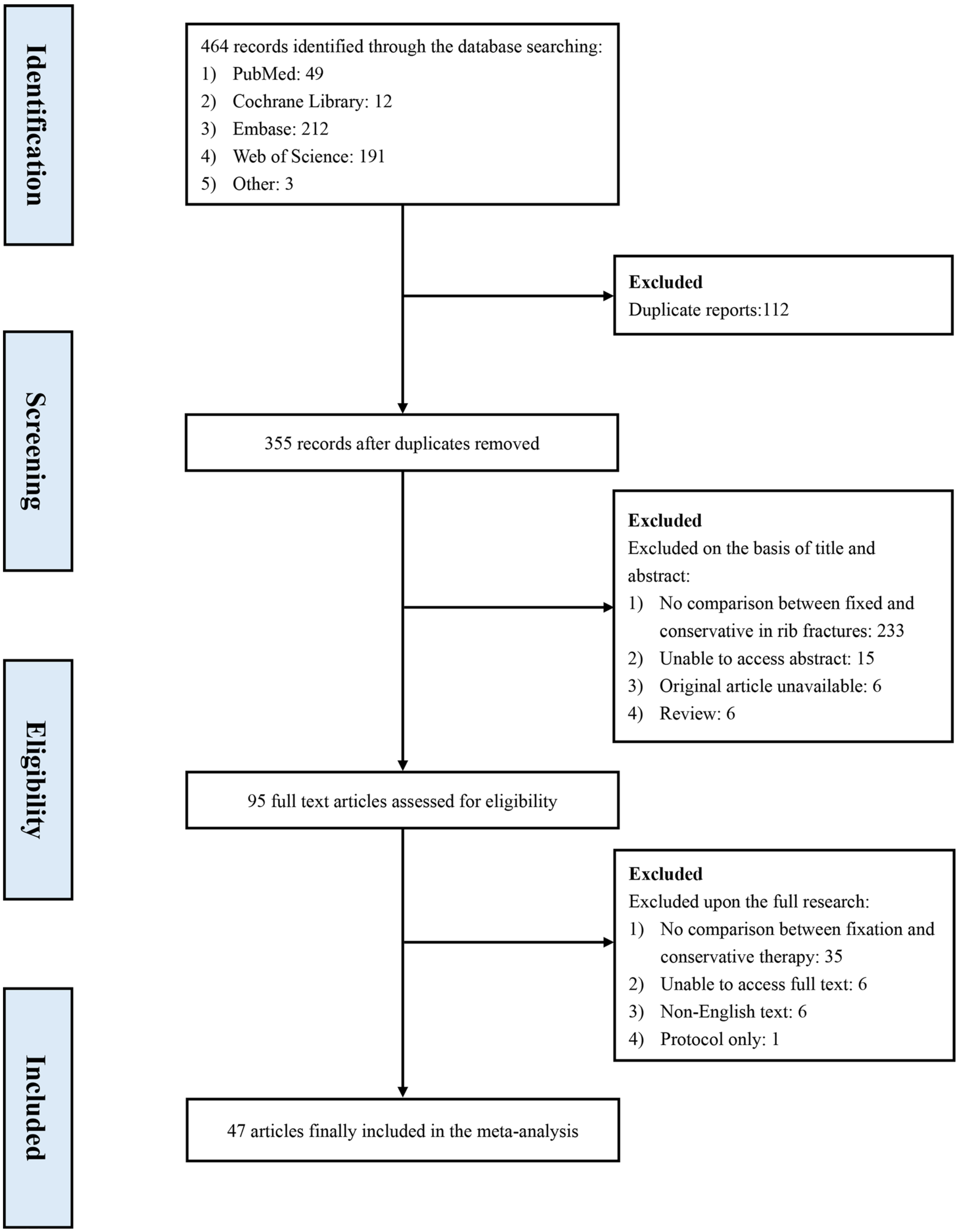

Fig. 1 Flow chart of the systematic literature search

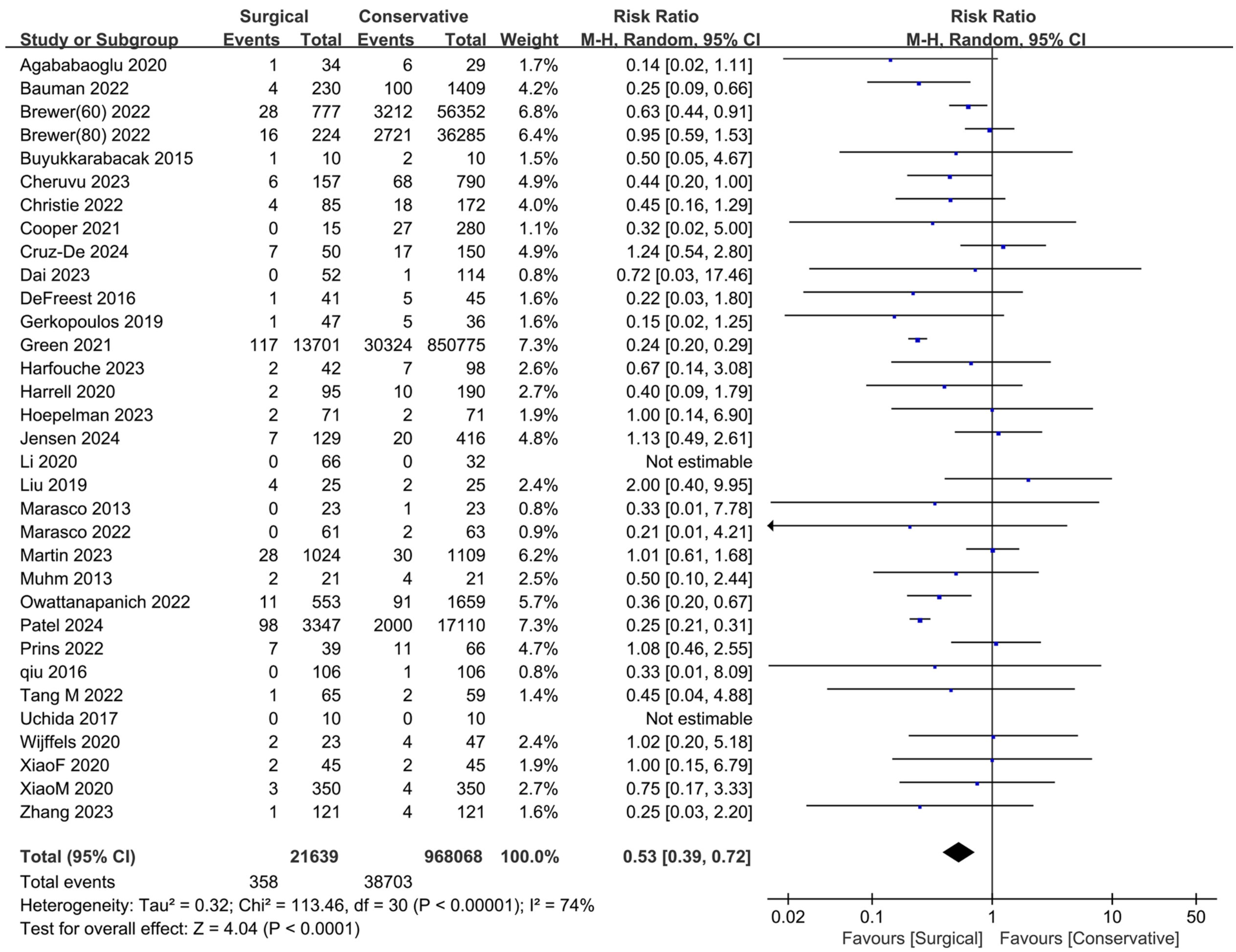

Fig. 2 Forest plot of mortality for SSRF versus conservative treatment

Table 1 Meta-analysis for pooled results of all available primary studies for outcomes

Outcomes	Sample size (S, C)	Treatment favoring	MD/SMD (95%CI)	RR (95%)	I^2	P
Mortality	(21,639,968,068)	Surgical	–	0.53[0.39,0.72]	74%	< 0.0001
Hospital LOS	(19,802,1,053,534)	Conservative	1.92 [0.82, 3.01]	–	97%	0.0006
ICU LOS	(8885, 201,883)	Conservative	1.01[0.08, 1.94]	–	98%	0.03
Mechanical ventilation	(7904,117,199)	Not significant	−0.03[−0.26,0.21]	–	98%	0.81
Pneumonia	(7441,115,791)	Not significant	–	1.06[0.81,1.39]	85%	0.66
Tracheostomy	(19,594,964,357)	Not significant	–	1.37[0.97,1.93]	91%	0.07
Medical cost	(13,982,851,203)	Conservative	0.90 [0.25, 1.55]		97%	0.007

RR = relative risk; CI = confidence intervals

Fig. 2c). Furthermore, surgical stabilization was found to be superior in retrospective studies (RR 0.50; 95% CI 0.36 to 0.70; P < 0.0001) (Supplementary Fig. 2d).

Secondary outcomes

Hospital length of stay (HLOS)

Forty-two publications (n = 1,073,336) reported on HLOS (Table 1). Surgical fixation was associated with a longer hospital stay than conservative treatment (MD 1.92; 95% CI 0.82 to 3.01; P = 0.0006) (Fig. 3a). Subgroup analyses

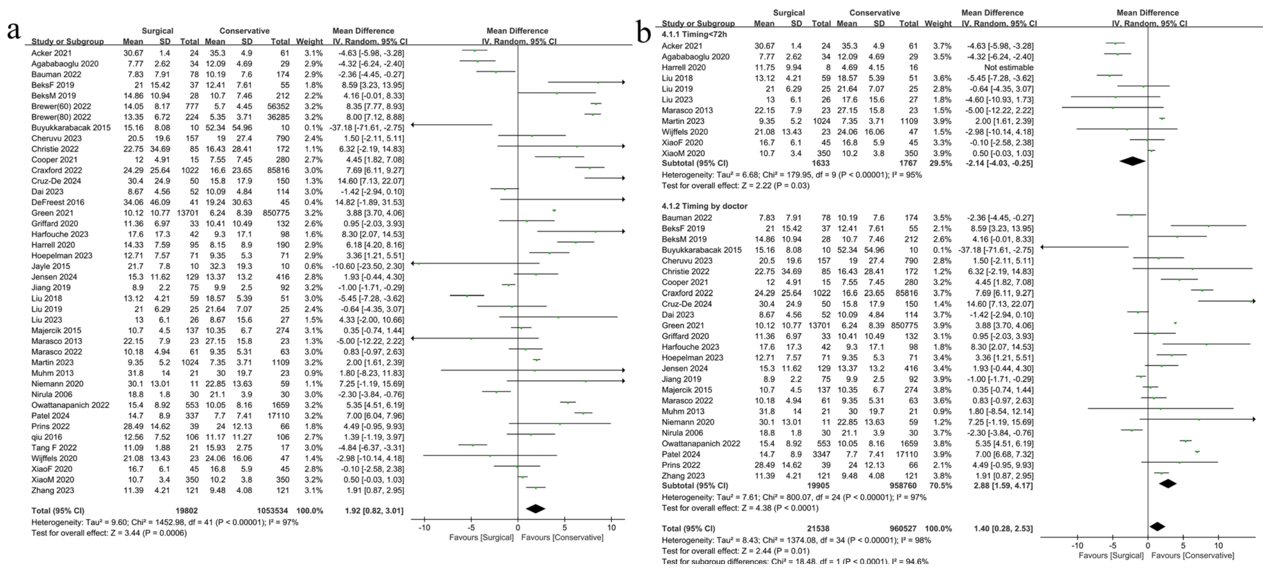

Fig. 3 Forest plot of HLOS for SSRF versus conservative treatment. (**a**) Comparison of HLOS in all studies; (**b**) Comparison of HLOS in different surgical time subgroups

revealed that conservative treatment was associated with a shorter hospital stay compared to surgical fixation in patients over 60 years of age, those whose physicians determined the timing of surgery, and patients included in the retrospective studies (Table 2). However, within 72 h of injury, HLOS for surgical fixation was superior to conservative treatment (MD −2.14; 95% CI −4.03 to −0.25; $P=0.03$) (Fig. 3b).

ICU length of stay (ILOS)

Forty publications (n = 210,768) reported on ILOS, and analysis across all included studies showed no discernible difference between the two groups. After excluding two studies displaying significant heterogeneity [41, 42], it was observed that ILOS was longer in the surgical group compared to the conservative treatment group (MD 1.01; 95% CI 0.08 to 1.94; P = 0.03) (Fig. 4a). Similar findings were observed in patients over 60 years of age and those whose physicians determined the timing of surgery (Table 2). In addition, surgical fixation in patients with flail chest reduced ILOS compared to conservative treatment (SMD −0.37; 95% CI −0.73 to −0.01; P = 0.04) (Fig. 4b).

Duration of mechanical ventilation (DMV)

Thirty-six articles (n = 125,103) reported DMV, and none of the included studies showed a statistically significant difference between surgical fixation and conservative treatment (SMD −0.03; 95% CI −0.26 to 0.21; $P=0.81$) (Supplementary Fig. 3). Subgroup analysis found that surgical fixation shortened the duration of mechanical ventilation in patients with flail chest, across all age groups, and in patients who underwent surgery within 72 h (Table 2). However, in patients over 60 years of age, conservative treatment showed greater benefits (MD 3.13; 95% CI 0.35 to 5.91; $P=0.03$) (Fig. 5).

Pneumonia

The incidence of pneumonia was reported in 29 studies (n = 123,232), and the results showed no statistical difference (RR 1.06; 95% CI 0.81 to 1.39; P = 0.66) (Supplementary Fig. 4). Subgroup analysis found that surgical fixation was a favorable factor in reducing pneumonia occurrence in patients with flail chest (RR 0.79; 95% CI 0.64 to 0.98; P = 0.03) (Fig. 6a). In contrast, the surgical treatment group showed a higher incidence of pneumonia complications than conservative treatment among patients over 60 years of age (RR 3.43; 95% CI 1.34 to 8.76; $P=0.01$), but there was no statistical difference between surgical fixation and conservative treatment in the overall age group (RR 0.92; 95% CI 0.78 to 1.33; P = 0.49) (Fig. 6b).

Tracheotomy

Tracheotomy was reported in 23 publications (n = 983,951), and the included studies did not identify a statistically significant difference between the two groups (RR 1.37; 95% CI 0.97 to 1.93; P = 0.07) (Supplementary Fig. 5). Fewer tracheotomies were found in the conservative group among patients over 60 years of age, those whose physicians decided the timing of surgery, and in retrospective studies (Table 2). No significant difference was found between SSRF and conservative treatment

Table 2 Outcomes of subgroup analysis of SSRF versus conservative treatment

Subgroup Analysis	Mortality			HLOS			ILOS		
	RR (95% CI)	**P**	***n***	**MD/SMD (95% CI)**	**P**	***n***	**MD/SMD (95% CI)**	**P**	***n***
Fracture Type									
Non-flail	0.52 [0.32, 0.84]	0.007	11	1.15[−0.33 2.62]	0.13	23	0.17[−0.04, 0.37]	0.11	23
Flail	0.39 [0.24, 0.63]	0.001	9	1.07[−2.20, 4.35]	0.52	12	−0.37[−0.73,0.01]	0.04	10
Age									
Mixed age	0.49 [0.35, 0.67]	0.0001	18	1.12[−0.04, 2.27]	0.06	37	0.52 [−0.42, 1.47]	0.28	36
≥ 60 y	0.72 [0.55, 0.94]	0.01	6	5.82 [3.20, 8.44]	< 0.0001	6	3.77 [0.82, 6.73]	0.01	5
Timing of fixation									
Timing < 72 h	0.92 [0.61, 1.39]	0.69	8	−2.14[−4.03, −0.25]	0.03	10	−0.04[−0.43,0.36]	0.86	12
Timing by doctor	0.43 [0.32, 0.59]	0.00001	20	2.88 [1.59, 4.17]	0.0001	25	0.21 [0.03, 0.40]	0.02	24
Study design									
Prospective	0.68 [0.28, 1.64]	0.39	8	−0.72 [−2.86, 1.42]	0.51	11	0.34 [−0.16, 0.84]	0.18	10
Retrospective	0.50 [0.36, 0.70]	0.0001	23	2.50 [1.27, 3.72]	0.0001	31	0.15 [−0.21, 0.52]	0.41	30
Subgroup Analysis	**DMV**			**Pneumonia**			**Tracheostomy**		
	MD/SMD (95% CI)	**P**	**n**	**RR (95% CI)**	**P**	**n**	**RR (95% CI)**	**P**	**n**
Fracture Type									
Non-fail	−0.03[−0.26,0.20]	0.81	18	0.81 [0.60, 1.09]	0.16	15	1.24 [0.77, 2.00]	0.38	9
Flail	−0.26[−0.47,0.04]	0.02	10	0.79 [0.64, 0.98]	0.03	9	1.06 [0.68, 1.65]	0.79	8
Age									
Mixed age	−0.76[−1.21, −0.31]	0.0009	30	0.92 [0.74, 1.16]	0.49	26	1.27[0.77, 2.10]	0.35	12
≥ 60 y	3.13 [0.35, 5.91]	0.03	5	3.43[1.34, 8.76]	0.01	3	5.31[3.98, 7.08]	0.00001	3
Timing of fixation									
Timing < 72 h	−0.27[−0.51, −0.03]	0.03	7	0.88 [0.66, 1.16]	0.37	10	0.81 [0.30, 2.16]	0.67	4
Timing by doctor	−0.02 [−0.35, 0.31]	0.92	22	0.89 [0.64, 1.23]	0.48	15	1.43 [1.05, 1.94]	0.02	14
Study design									
Prospective	−0.11 [−0.45, 0.24]	0.53	7	0.91 [0.65, 1.28]	0.60	8	0.93 [0.51, 1.70]	0.83	6
Retrospective	0.05 [−0.22, 0.32]	0.70	27	1.06 [0.80, 1.42]	0.68	22	1.64 [1.06, 2.54]	0.03	16

HLOS: Hospital length of stay; ILOS: ICU length of stay; DMV: Duration of mechanical ventilation

regarding the need for tracheotomy in the mixed age group. No statistically significant differences were observed between the two groups in other classifications.

Medical costs

Medical costs were reported in five studies (n = 865,185), with the analysis revealing higher costs in the surgical fixation group compared to the conservative treatment group (MD 0.90; 95% CI 0.25 to 1.55; P = 0.007) (Fig. 7).

Discussion

Rib fracture was a major risk factor for mortality in humans [43], with multiple rib fractures being particularly severe, especially in the case of flail chest, which was associated with an exceptionally high mortality rate. Studies had shown that the incidence of pneumonia in patients with flail chest ranges from 21% to 43.9%, with a mortality rate as high as 25% [44]. Treatment options for rib fractures were generally categorized into two types: surgical and conservative treatment. In recent years, advancements in fixation materials and the significant improvement of minimally invasive surgical techniques had made surgical internal fixation the preferred treatment for many patients [23, 45, 46]. Despite these advancements, there remained an ongoing debate in the medical community regarding the optimal approach [44, 47, 48].

Our study demonstrated that surgical treatment significantly reduced the mortality rate in patients with multiple rib fractures compared to conservative treatment, thereby confirming the superiority of SSRF. However, with respect to the HLOS and ICU stay, the SSRF group had longer durations, which may be attributed to the patients' initial conditions and comorbidities [47]. It is widely accepted that patients with relatively mild conditions are more likely to undergo conservative treatment [49, 50]. The absence of data on injury severity scores (ISS) and the patients' underlying physical conditions in

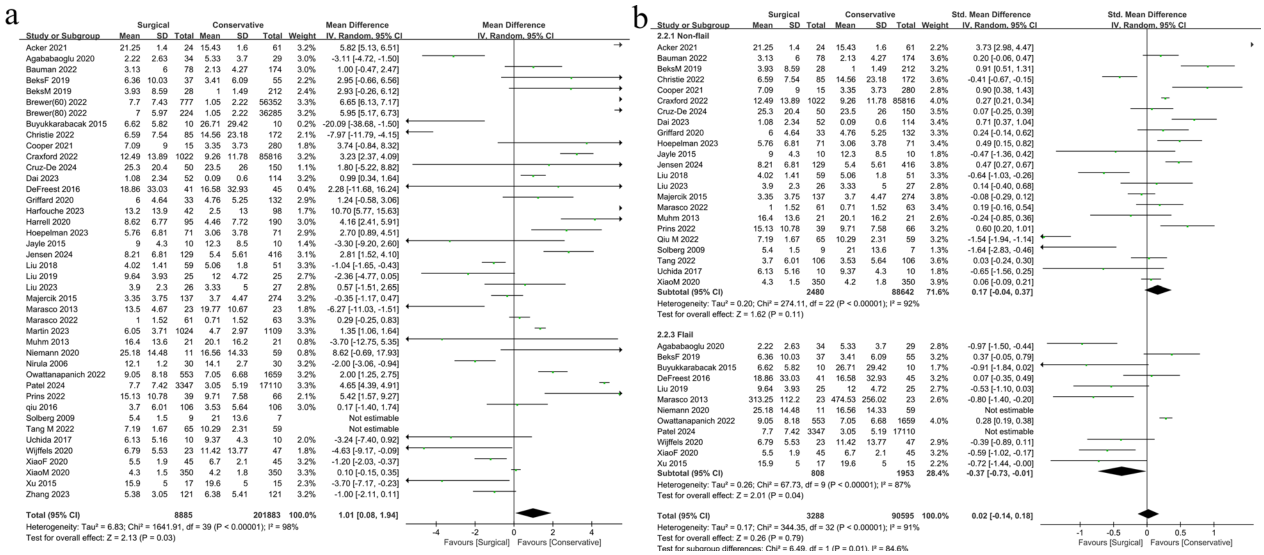

Fig. 4 Forest plot of ILOS for SSRF versus conservative treatment. (**a**) Comparison of ILOS in all studies; (**b**) Comparison of ILOS in different rib fracture subtypes

the studies included in our review complicates the further analysis of the factors contributing to the increased HLOS and ILOS in the SSRF group. Furthermore, surgical treatment increases the overall cost of hospitalization, likely due to the additional expenses associated with anesthesia, surgery, and materials used in SSRF procedures.

Subgroup analysis indicated that flail chest is the most appropriate condition for SSRF. Previous studies had suggested that flail chest was an indication for SSRF [23], and our findings supported these earlier conclusions, demonstrating that patients with flail chest benefit significantly from SSRF [51]. Specifically, we observed that the mortality rate in flail chest patients treated with SSRF was significantly lower than in those receiving conservative treatment. Additionally, the SSRF group exhibited shorter ILOS, reduced mechanical ventilation duration, and a lower incidence of pneumonia compared to the conservative treatment group. These results emphasized the appropriateness of SSRF for flail chest patients, underscoring the pivotal role of SSRF surgery in their treatment.

A key finding of this study was the significance of early SSRF within 72 h. Our results demonstrated that patients who received SSRF within 72 h had shorter overall hospitalization and mechanical ventilation durations. This may be attributed to lower levels of inflammatory markers and a reduced risk of infection at the time of early intervention [52, 53]. Additionally, we proposed that delayed treatment of multiple rib fractures can exacerbate the patient's condition [54]. For example, multiple rib fractures can lead to respiratory distress, hemopneumothorax, and lung injury [1]. If left untreated, patients may develop acute respiratory distress syndrome (ARDS) [55], hemorrhagic shock [56], and severe infections [57], all of which contribute to prolonged treatment and recovery periods.

Subgroup analysis indicated that SSRF treatment significantly improved survival outcomes in patients with multiple rib fractures aged over 60 years. Rib fractures are usually associated with severe pain, which can hinder sputum clearance [58]. Additionally, prolonged bed rest following rib fractures further elevates the risk of complications such as atelectasis and deep vein thrombosis, particularly among elderly patients [59, 60]. Several studies have demonstrated that SSRF surgery significantly alleviates pain and promotes early mobilization, offering key advantages over conservative treatment [61]. Reduced pain improves sputum expectoration, thereby enhancing lung function recovery, while early mobilization mitigates the risk of complications such as deep vein thrombosis and pressure ulcers [62]. We proposed that these factors contribute to the lower mortality rate observed among elderly patients undergoing SSRF surgery.

Based on the above findings, we concluded that patients with flail chest are the most appropriate candidates for SSRF treatment. Additionally, SSRF is particularly beneficial for patients with multiple rib fractures when performed within 72 h of injury, as well as for elderly patients aged over 60 years. Despite its significant findings, our study was subjected to the following limitations. (1) The included literature lacked standardized

Study or Subgroup	Surgical Mean	Surgical SD	Surgical Total	Conservative Mean	Conservative SD	Conservative Total	Weight	Mean Difference IV, Random, 95% CI
3.3.1 ⩾60								
Brewer(60) 2022	10.05	5.2	777	6.4	5.93	56352	4.5%	3.65 [3.28, 4.02]
Brewer(80) 2022	11.35	5.2	224	5	2.97	36285	4.3%	6.35 [5.67, 7.03]
Cooper 2021	15.27	22.08	15	6.4	7.45	280	0.3%	8.87 [-2.34, 20.08]
Jensen 2024	3.35	7.77	70	1	4.88	230	3.2%	2.35 [0.42, 4.28]
Zhang 2023	3.22	2.31	121	4.34	4.17	121	4.2%	-1.12 [-1.97, -0.27]
Subtotal (95% CI)			**1207**			**93268**	**16.4%**	**3.13 [0.35, 5.91]**
Heterogeneity: Tau² = 8.15; Chi² = 183.58, df = 4 (P < 0.00001); I² = 98%								
Test for overall effect: Z = 2.20 (P = 0.03)								
3.3.2 Mixed age								
Acker 2021	22.2	2.3	24	25.2	4.2	61	3.7%	-3.00 [-4.40, -1.60]
Agababaoglu 2020	2.22	2.63	34	4.45	3.95	29	3.4%	-2.23 [-3.92, -0.54]
Bauman 2022	1.68	4.87	78	1.25	4.58	174	3.8%	0.43 [-0.85, 1.71]
Bauman 2023	5.4	2.3	230	7.2	3.6	1409	4.5%	-1.80 [-2.15, -1.45]
BeksF 2019	4.07	6.94	37	2.47	5.33	55	2.5%	1.60 [-1.04, 4.24]
BeksM 2019	3.21	7.03	28	0.35	0.75	212	2.5%	2.86 [0.25, 5.47]
Buyukkarabacak 2015	4.16	6.47	10	19.47	23.92	10	0.2%	-15.31 [-30.67, 0.05]
Cruz-De 2024	24.3	18	50	22.1	27	150	0.7%	2.20 [-4.40, 8.80]
Dai 2023	0.1	0.31	52	0.12	0.7	114	4.5%	-0.02 [-0.17, 0.13]
DeFreest 2016	15.58	29.96	41	14.34	29.87	45	0.2%	1.24 [-11.42, 13.90]
Griffard 2020	1.42	3.1	33	1.42	3.1	132	3.9%	0.00 [-1.18, 1.18]
Harfouche 2023	8	15	42	2	9	98	1.2%	6.00 [1.13, 10.87]
Harrell 2020	5	7.92	95	2.58	7.09	190	3.2%	2.42 [0.54, 4.30]
Hoepelman 2023	7.23	7.19	71	3.65	2.27	71	3.3%	3.58 [1.83, 5.33]
Jayle 2015	73.5	124.7	10	141.6	224.4	10	0.0%	-68.10 [-227.21, 91.01]
Liu 2019	7.72	3.14	25	9.36	3.93	25	3.1%	-1.64 [-3.61, 0.33]
Majercik 2015	1.05	2.25	137	1.4	2.98	274	4.4%	-0.35 [-0.87, 0.17]
Martin 2023	5.05	5.2	1024	4.7	4.45	1109	4.4%	0.35 [-0.06, 0.76]
Muhm 2013	10.6	10.2	21	13.2	13.7	21	0.6%	-2.60 [-9.91, 4.71]
Niemann 2020	7.1	6.14	11	8.17	9.85	59	1.4%	-1.07 [-5.48, 3.34]
Nirula 2006	6.5	1.3	30	11.2	2.6	30	4.0%	-4.70 [-5.74, -3.66]
Owattanapanich 2022	7.35	6.69	553	8.35	8.16	1659	4.3%	-1.00 [-1.68, -0.32]
Patel 2024	3.4	5.93	3347	0.7	1.48	17110		Not estimable
Prins 2022	16.65	10.01	39	17.65	9.85	66	1.6%	-1.00 [-4.94, 2.94]
qiu 2016	2.7	4.51	106	3.45	7.37	106	3.4%	-0.75 [-2.39, 0.89]
Tang M 2022	5.71	1.35	65	9.06	3.58	59	4.1%	-3.35 [-4.32, -2.38]
Uchida 2017	6.13	5.16	10	11.26	5.16	10	1.3%	-5.13 [-9.65, -0.61]
Wijffels 2020	5.08	5.53	23	12	9.18	47	1.9%	-6.92 [-10.38, -3.46]
XiaoF 2020	4.7	0.85	45	4.63	0.81	45	4.5%	0.07 [-0.27, 0.41]
XiaoM 2020	4.17	0.57	350	4.15	0.86	350	4.5%	0.02 [-0.09, 0.13]
Xu 2015	10.5	3.7	17	13.7	4.4	15	2.3%	-3.20 [-6.04, -0.36]
Subtotal (95% CI)			**3291**			**6635**	**83.6%**	**-0.76 [-1.20, -0.31]**
Heterogeneity: Tau² = 0.72; Chi² = 318.13, df = 29 (P < 0.00001); I² = 91%								
Test for overall effect: Z = 3.33 (P = 0.0009)								
Total (95% CI)			**4498**			**99903**	**100.0%**	**-0.15 [-0.77, 0.47]**
Heterogeneity: Tau² = 2.21; Chi² = 1050.22, df = 34 (P < 0.00001); I² = 97%								
Test for overall effect: Z = 0.47 (P = 0.64)								
Test for subgroup differences: Chi² = 7.30, df = 1 (P = 0.007), I² = 86.3%								

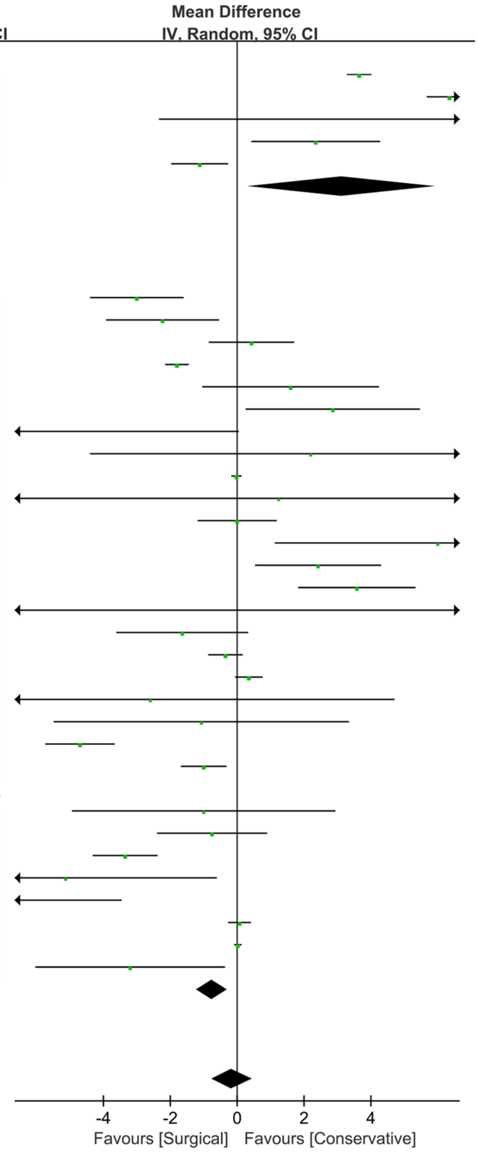

Fig. 5 Forest plot of DMV for SSRF versus conservative treatment in age subgroup

criteria for recording patient conditions, such as pain levels, comorbidities, generalized multiple injuries, and the involvement of multiple surgical sites. Consequently, we were unable to stratify patients in greater detail, which may have resulted in the omission of important risk factors and hindered the assessment of different treatment options. This lack of critical information further complicates the interpretation of results, particularly for patients aged over 60 years. For example, although SSRF treatment was associated with lower mortality in this age group, it was also linked to higher rates of pneumonia, tracheotomy, and longer durations of hospitalization, ICU stays, and mechanical ventilation. This discrepancy may stem from the lack of consideration for key factors, such as underlying diseases and baseline vital signs, in elderly patients. Moreover, only five publications analyzed patients aged 60 years or older as a distinct subgroup, while others included mixed-age cohorts, complicating the evaluation of whether elderly patients truly benefited from SSRF. (2) The inconsistent inclusion criteria and taxonomy for rib fractures, particularly regarding the degree of displacement, introduced heterogeneity into the conclusions. (3) Most studies were retrospective in nature and lacked rigorous design, with variable treatment protocols that may have influenced the outcomes. (4) Furthermore, there was a 20-year gap

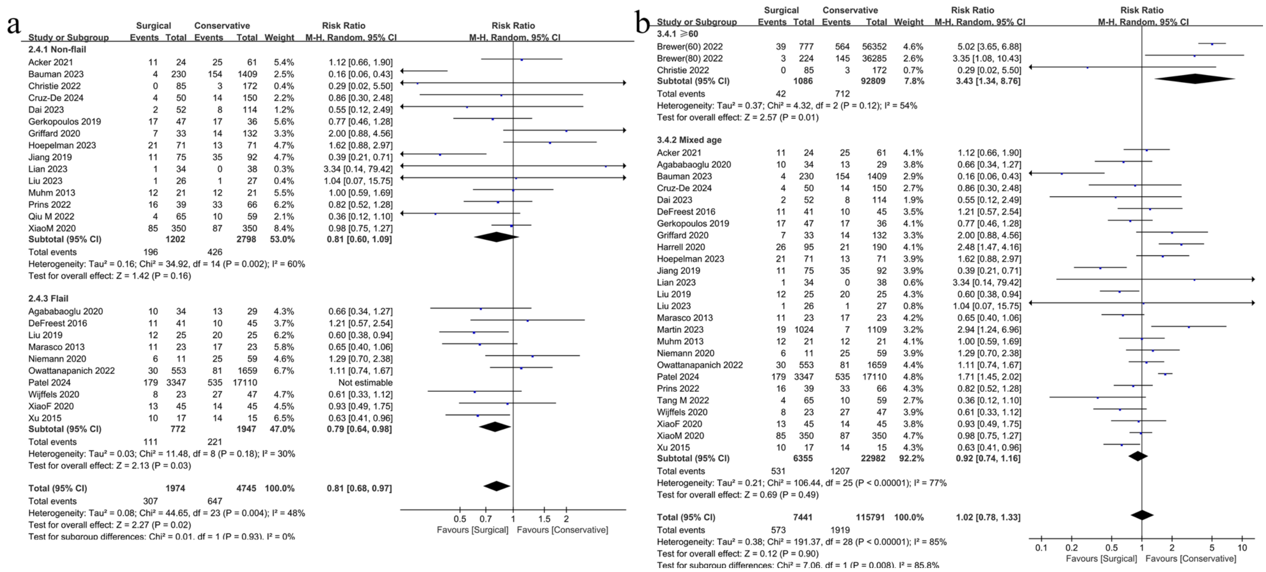

Fig. 6 Forest plot of pneumonia for SSRF versus conservative treatment. (**a**) Differences in pneumonia among different rib fracture types; (**b**) Differences in pneumonia among age groups

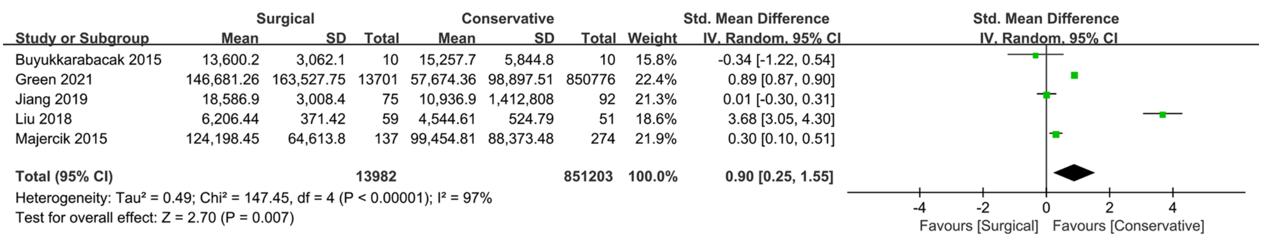

Fig. 7 Meta-analysis of the effect on hospital costs

between the earliest and most recent studies included in this analysis, and surgical techniques from two decades ago may have been outdated, potentially leading to suboptimal outcomes. Regarding the limitations of both our study and the existing literature on SSRF, it is necessary to identify more appropriate indications for SSRF in our future studies.

To draw more reliable conclusions, future research should prioritize large-scale, multicenter studies with rigorous designs. Since the number of fractures and the degree of displacement are established predictors of mortality and pulmonary complications, it is crucial to establish a standardized definition for non-flail chest rib fractures. Recently, Sermonesi et al. proposed a novel classification system for rib fractures that incorporates the degree of displacement and fracture location, potentially offering valuable guidance for future studies [23]. Additionally, as patients placing increasing emphasis on quality of life, the emergence of minimally invasive procedures has resulted in greater clinical benefits and improved survival outcomes, such as minimally invasive plate osteosynthesis (MIPO). This technique not only minimizes surgical trauma but also significantly improves patient outcomes by enhancing quality of life and reducing the risk of postoperative complications [63]. Therefore, minimally invasive plate osteosynthesis is anticipated to further enhancing the role of surgical treatment in managing rib fractures in clinical practice.

Conclusion

The meta-analysis results demonstrated that surgical fixation significantly reduces mortality in patients with multiple rib fractures. Additionally, patients with flail chest were identified as the most appropriate candidates for this intervention. Furthermore, the study highlighted the importance of performing SSRF within 72 h of injury, especially in patients with multiple rib fractures and those aged over 60 years.

Abbreviations

SSRF Surgical stabilization for rib fractures
MIPO Minimally invasive plate osteosynthesis
ARDS Acute respiratory distress syndrome

HLOS	Hospital length of stay
ILOS	ICU length of stay
DMV	Duration of mechanical ventilation
RCT	Randomized controlled trial
CI	Confidence intervals
RR	Relative risks
WMD	Weighted mean difference
SMD	Standardized mean difference
NOS	The Newcastle–Ottawa Scale
RoB	Risk of bias
RE	Random-effects
FE	Fixed-effects

Supplementary Information

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Additional file 1.

Additional file 2.

Additional file 3.

Author Contribution

Penglong Zhao, Qiyue Ge, Haotian Zheng, Xiaobin Song, Jing Luo and Liwen Hu contributed to the study conception and design. Penglong Zhao, Qiyue Ge, and Liwen Hu performed data collection and analysis. The first draft of the manuscript was written by Penglong Zhao. All authors have reviewed the initial manuscript content and exchanged opinions. All authors read and approved the final manuscript.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Human Ethics and Consent to Participate

Not applicable

Competing interests

The authors declare no competing interests.

Author details

[1]Department of Cardiothoracic Surgery, Jinling Clinical Medical College, Nanjing University of Chinese Medicine, Nanjing, China. [2]Department of Cardiothoracic Surgery, Jinling Hospital, School of Medicine, Southeast University, Nanjing, China. [3]Department of Cardiothoracic Surgery, Jinling Hospital, Affiliated Hospital of Medical School, Nanjing University, Nanjing, China.

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