Fixation of flail chest or multiple rib fractures: current evidence and how to proceed. A systematic review and meta-analysis

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Received: 19 June 2018 / Accepted: 24 September 2018 / Published online: 1 October 2018 © The Author(s) 2018

Abstract

Purpose The aim of this systematic review and meta-analysis was to present current evidence on rib fixation and to compare effect estimates obtained from randomized controlled trials (RCTs) and observational studies.

Methods MEDLINE, Embase, CENTRAL, and CINAHL were searched on June 16th 2017 for both RCTs and observational studies comparing rib fixation versus nonoperative treatment. The MINORS criteria were used to assess study quality. Where possible, data were pooled using random effects meta-analysis. The primary outcome measure was mortality. Secondary outcome measures were hospital length of stay (HLOS), intensive care unit length of stay (ILOS), duration of mechanical ventilation (DMV), pneumonia, and tracheostomy.

Results Thirty-three studies were included resulting in 5874 patients with flail chest or multiple rib fractures: 1255 received rib fixation and 4619 nonoperative treatment. Rib fixation for flail chest reduced mortality compared to nonoperative treatment with a risk ratio of 0.41 (95% CI 0.27, 0.61, \( p < 0.001 \), \( I^2 = 0\% \)). Furthermore, rib fixation resulted in a shorter ILOS, DMV, lower pneumonia rate, and need for tracheostomy. Results from recent studies showed lower mortality and shorter DMV after rib fixation, but there were no significant differences for the other outcome measures. There was insufficient data to perform meta-analyses on rib fixation for multiple rib fractures. Pooled results from RCTs and observational studies were similar for all outcome measures, although results from RCTs showed a larger treatment effect for HLOS, ILOS, and DMV compared to observational studies.

Conclusions Rib fixation for flail chest improves short-term outcome, although the indication and patient subgroup who would benefit most remain unclear. There is insufficient data regarding treatment for multiple rib fractures. Observational studies show similar results compared with RCTs.

keywords Flail chest · Multiple rib fractures · Operative treatment · Nonoperative treatment · Current evidence

Introduction

Rib fractures are very common in patients with thoracic trauma and nowadays still associated with significant morbidity and mortality due to the underlying injuries to the lung and heart resulting in more pulmonary complications [1–4]. Compared to multiple rib fractures, flail chest is associated with a worse outcome due to a higher incidence of respiratory compromise and concomitant injuries [5, 6].

A combination of adequate pain control, respiratory assistance, and physiotherapy is considered the gold standard in management of rib fractures [3]. Over the past decades, there has been a growing interest in rib fixation for flail chest and for multiple rib fractures, however, there is no consensus regarding the indication and patient selection for rib fixation.
In the field of (orthopedic) trauma surgery, there is increasing scientific evidence that inclusion of observational studies could add value to meta-analyses without decreasing quality of the results [7–10]. Adding observational studies result in larger sample sizes and might enable the evaluation of small treatment effects, subgroups, and infrequent outcome measures while also providing information about the generalizability of the results [11].

The aim of this systematic review and meta-analysis was (1) to present current evidence on outcome after rib fixation compared to nonoperative treatment for both flail chest and multiple rib fractures and (2) to compare effect estimates obtained from RCTs and observational studies.

**Methods**

This review was performed according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) and the Meta-analysis of Observational Studies in Epidemiology (MOOSE) guidelines [12, 13]. A published protocol for this review does not exist. Ethical committee approval did not apply to this study.

**Search strategy and eligibility criteria**

A structured literature search was conducted in MEDLINE, Embase, CENTRAL and CINAHL on June 16th, 2017 for both randomized controlled trials (RCTs) and observational studies comparing operative to nonoperative treatment of traumatic rib fractures. The search was not restricted by publication date, language, or other limits. The full search syntax is provided in Appendix 1.

All obtained studies from the literature search were independently screened for eligibility based on title and abstract by two reviewers (RBB, JP). Exclusion criteria were animal studies, abstracts of conferences, case-reports, reviews, inclusion of patients younger than 18 years, and studies written in another language than English, French, Dutch or German. Disagreement regarding study selection was resolved by discussion with a third reviewer (RMH). The full search syntax is provided in Appendix 1.

**Data extraction**

Data were extracted by two independent reviewers (RBB, JP), using a data extraction file. Extracted data included first author, year of publication, study period, study design, country, fracture type, number of fractured ribs, number of included patients, number of patients with flail chest or multiple rib fractures (according to the definition used by the original study), age, gender, type of operative treatment, type of nonoperative treatment, duration of follow-up, loss to follow-up, Injury Severity Score (ISS), Abbreviated Injury Scale (AIS), Glasgow Coma Scale (GCS), hemothorax, pneumothorax, pulmonary contusion, type of implant in operative group, mortality during hospitalization, hospital length of stay (HLOS), intensive care unit length of stay (ILOS), duration of mechanical ventilation (DMV), incidence of pneumonia, need for tracheostomy, complications, revision surgery, and implant removal.

**Outcome measures**

The primary outcome measure was mortality during hospitalization. Secondary outcome measures were HLOS, ILOS, DMV, incidence of pneumonia, need for tracheostomy, complications, revision surgery, and implant removal.

**Quality assessment**

The Methodological Index for Non-Randomized Studies (MINORS) score was used to assess the included studies [14]. The MINORS is a critical appraisal instrument developed to assess the methodological quality of observational surgical studies. Other quality assessment tools focus on a specific study design while the MINORS is externally validated on RCTs and is therefore a suitable instrument for meta-analyses of different study designs. The MINORS score ranges from 0 to 24 and a higher score reflects better quality. Studies were independently assessed by two reviewers (RBB, JP) using the MINORS criteria and disagreement was resolved by discussion with a third reviewer (RMH). Additional details on the MINORS criteria and scoring system are set out in Appendix 2.

**Statistical analysis**

Statistical analyses were performed using Review Manager (RevMan, Version 5.3.5 Copenhagen: The Nordic Cochrane Centre, The Cochrane Collaboration, 2014). Data were converted to a mean with standard deviation (SD) using different methods as described in the Cochrane Handbook for Systematic Reviews of Interventions [15].

Different studies based on the same patient cohort were included only once in the analysis [16, 17]. Studies reporting on specific patient subgroups were split and included separately for meta-analysis, provided sufficient information was reported; Qiu et al. distinguished between the presence or absence of a flail chest and Voggenreiter et al. made subgroups based on the presence or absence of pulmonary contusion [18, 19]. Results from both RCTs and observational studies were pooled in the primary analysis.
Meta-analysis was performed if outcome measures of two or more studies were available. For continuous outcome measures, the inverse variance weighted random effects model was used to estimate the pooled difference in the outcome measure for fixation versus no fixation, with corresponding 95% confidence interval (CI). For dichotomous outcomes, we applied the Mantel–Haenszel method and pooled results are presented as risk ratios (RR) with 95% CI. Heterogeneity between studies was assessed by visual inspection of the forest plots and by estimating statistical measure for heterogeneity, i.e., the $I^2$ statistic. Inspection of a funnel plot of the study-specific difference in the primary outcome measure against its standard error was done to detect potential publication bias. A two-sided $p$ value $< 0.05$ was considered statistically significant.

**Subgroup and sensitivity analyses**

In subgroup analysis, we stratified by study design and pooled effects of RCTs were compared with pooled effects of observational studies. For the analysis of study quality only studies with an arbitrarily chosen MINORS score of 16 or higher were included, similar to previously published meta-analyses in orthopedic trauma surgery studying both study designs [8, 10, 20]. To assess the impact of improvement in intensive care management over time, we performed a sensitivity analysis including only studies published in the last 5 years. Different methods were used to include studies with zero events in one or both arms of the outcome measure. To assess the sensitivity of the analyses to the choice of the method of analysis, also the crude methods, DerSimonian–Laird method with correction, the inverse variance with and without correction for zero event data, and the Peto method were applied and results were compared for consistency [21].

**Fig. 1 Flowchart of the literature search**
Results

Search

The flowchart of the literature search is presented in Fig. 1. Ultimately, 33 studies were included [16–19, 22–50]. There were three RCTs, two prospective cohort studies, 14 retrospective cohort studies, and 14 case–control studies.

Patient characteristics

The studies included for meta-analysis included 5874 patients; 1255 received rib fixation and 4619 received nonoperative treatment. In the majority of the studies (n = 20), patients were surgically treated with plates (Tables 1, 2). Other surgical methods were K-wires and Judet or Adkins struts. Nonoperative treatment consisted generally of ‘best medical treatment’ and included adequate pain management, lung physiotherapy and respiratory support. The weighted average age was 52.9 years and 73% of patients were male. The weighted average of the number of rib fractures was 6.9 in the rib fixation group and 6.0 in the nonoperative group with a weighted mean ISS of 21.2 and 22.4, respectively.

Quality assessment

The average MINORS score of the included studies was 15.4 (SD 2.7; range 9–21). The MINORS score for RCTs was 20 (SD 1.0; range 19–21) and for observational studies 14.9 (SD 2.4; range 9–21). An overview of the study-specific MINORS score is provided in Appendix 3.

Mortality

Twenty-five studies (n = 4826) reported on mortality (Online Appendix 4) [16, 18, 22–26, 28, 30–33, 35–44, 47, 50, 51]. Rib fixation resulted in a significant reduction of mortality compared to nonoperative treatment with a risk ratio (RR) of 0.41 (95% CI 0.27, 0.61, p < 0.001, $I^2 = 0\%$) (Fig. 2). Different methods of incorporating studies in the meta-analysis with zero-event data in one or both arms yielded similar results (Online Appendix 5). When stratified by study design, RCTs showed a RR 0.57 (95% CI 0.13, 2.52, p = 0.46, $I^2 = 0\%$) vs. RR 0.40 (95% CI 0.26, 0.60, p < 0.001, $I^2 = 0\%$) in observational studies (Table 3). Figure 3 shows a funnel plot of the odds ratio and standard error of the included studies using the mortality rate; there was no important asymmetry observed.

Hospital stay length of stay

Twenty-one studies (n = 4770) reported on length of hospital stay (Online Appendix 4) [16, 17, 23, 25, 26, 31–35, 37–45, 47, 50, 51]. Rib fixation did not result in a significant reduction of HLOS compared to nonoperative treatment with a mean difference of −1.46 days (95% CI −4.31, 1.39, p = 0.32, $I^2 = 96\%$) (Online Appendix 6). When stratified by study design, the pooled mean difference of RCTs (−8.33 days; 95% CI −14.6, −2.1; p < 0.001, $I^2 = 46\%$) was greater compared to observational studies (−0.77; 95% CI −3.72, 2.18; p = 0.61, $I^2 = 97\%$) (Table 3).

ICU length of stay

Twenty-six studies (n = 4520) reported on length of ICU stay (Online Appendix 4) [16–18, 22–26, 28, 30–33, 35–44, 47, 50, 51]. Rib fixation resulted in a significant reduction of ILOS compared to nonoperative treatment with a mean difference of −2.0 (95% CI −3.61, −0.38, p = 0.02, $I^2 = 85\%$) (Online Appendix 7). When stratified by study design, RCTs showed a greater difference compared to observational studies (Table 3).

Duration of mechanical ventilation

Twenty-seven studies (n = 2063) reported on duration of mechanical ventilation (Online Appendix 4) [16–19, 22–28, 30–32, 35–42, 45–47, 49–51]. Rib fixation resulted in a significant reduction of days on mechanical ventilation compared to nonoperative treatment with a mean difference of −4.01 (95% CI −5.58, −2.45, p < 0.001, $I^2 = 91\%$) (Online Appendix 8). When stratified by study design, RCTs showed a greater difference compared to observational studies (Table 3).

Pneumonia

Twenty-five studies (n = 4485) reported on the incidence of pneumonia (Online Appendix 4) [16–19, 22, 24–26, 28, 30–33, 37–39, 41–44, 47, 50, 51]. Rib fixation resulted in a significant reduction of pneumonia compared to nonoperative treatment with a risk ratio of 0.59 (95% CI 0.42, 0.83, p = 0.002, $I^2 = 79\%$) (Online Appendix 9). When stratified by study design both subgroups showed similar results (Table 3).

Tracheostomy

Fourteen studies (n = 1541) reported on the need of tracheostomy (Online Appendix 4) [16–18, 22, 25, 26, 28, 30, 32, 34, 36–38, 45, 50]. Rib fixation resulted in a significant
Table 1  Baseline characteristics of the included studies comparing rib fixation versus nonoperative treatment of traumatic rib fractures

| Study          | Study design | Country   | Number of patients | Follow-up (months) | Age (years, range or ±SD) | Male (%) | Number of fractured ribs | ISS score |
|----------------|--------------|-----------|--------------------|--------------------|---------------------------|----------|--------------------------|-----------|
| Dehghan et al. (2018) [43] | RC           | Canada    | RF 77              | NR                 | 52 ± 18                   | 55 (76)  | NR                       | NR        |
|                | NOM 1631     |           |                    |                    | 58 ± 18                   | 1176 (72) |                         |           |
| Ali-Osman et al. (2018) [42] | RC           | USA       | RF 64              | NR                 | 68.5 [63–74]              | 41 (64)  | 7 [5.25–9]               | 17.5 [9–25]|
|                | NOM 135      |           |                    |                    | 72 [66–81]                | 73 (54)  | 5 [3.7–25]               | 14 [8–24] |
| Wijffels et al. (2018) [41] | CC           |           | RF 20              | NR                 | 60 [41–69]                | 15 (75)  | 9 [8–11]                 | 31 [21–48]|
|                | NOM 20       |           |                    |                    | 57 [44–69]                | 15 (75)  | 10 [9–14]                | 32 [21–41]|
| Kane et al. (2018) [44] | RC           |           | RF 116             | NR                 | 58.3 ± 14.4               | NR       | NR                       | 21.6 (9.1) |
|                | NOM 1000     |           |                    |                    | 46.9 ± 29.3               | NR       |                         | 16.1 (11.4)|
| Fitzgerald et al. (2017) [33] | CC           | USA       | RF 23              | NR                 | 68 (63–89)                | NR       | NR                       | 21 (16–26) |
|                | NOM 50       |           |                    |                    | 75 (65–97)                | NR       |                         | 19 (14–23) |
| Farquhar et al. (2016) [39] | CC           | Canada    | RF 19              | 21.9 ± 13.2        | 53 ± 14                   | 15 (79)  | NR                       | 31.4 ± 9.6 |
|                | NOM 36       |           |                    |                    | 16.0 ± 12.1               | 57 ± 16  | 25 (69)                  | 29.3 ± 8.1 |
| Pieracci et al. (2016) [37] | PC           | USA       | RF 35              | 28.3 (9–69)        | 51 (19–80)                | 32 (78)  | 11.2 (6–19)              | 27.5 (16–48)|
| Defreest et al. (2016) [38] | RC           | USA       | RF 41              | 13.0 (3–43)        | 56 (23–89)                | 39 (87)  | 10.6 (6–23)              | 29.3 (16–66)|
| Uchida et al. (2016) [30] | CC           | Japan     | RF 10              | NR                 | 63 [51, 72]               | 7 (70)   | 5 [4, 8]                 | NR        |
|                | NOM 10       |           |                    |                    | 57 [53, 75]               | 7 (70)   | 5 [2, 7]                 |           |
| Velasquez et al. (2016) [47] | CC           | USA       | RF 20              | 21.9 ± 13.2        | 53 ± 14                   | 15 (79)  | NR                       | 9 [9, 16] |
|                | NOM 20       |           |                    |                    | 16 [11, 22]               | 45 [36, 55]|                         | 13 [9, 17]|
| Qiu et al. (2016a) [18]  | RC           | China     | RF 21              | NR                 | 35 ± 13                   | 15 (48)  | 6.0 ± 1.3                | NR        |
|                | NOM 17       |           |                    |                    | 36 ± 14                   | 12 (71)  | 5.9 ± 1.3                |           |
| Qiu [18]       | RC           | China     | RF 65              | NR                 | 38 ± 12                   | 46 (71)  | 3.2 ± 1.2                | NR        |
|                | NOM 59       |           |                    |                    | 36 ± 12                   | 42 (71)  | 3.5 ± 1.2                |           |
| Jayle et al. (2015) [51] | CC           | France    | RF 10              | 21.7 ± 7.8         | 48 ± 11                   | 8 (80)   | 7.7 ± 2.4                | 21.7 ± 7.8 |
|                | NOM 10       |           |                    |                    | 32.3 ± 19.3               | 51 ± 13  | 8.0 (80)                 | 6.6 ± 2.9  |
| Zhang Y (2015) [25]  | RC           | China     | RF 24              | 38.3 [33, 54.25]   | 43 [34, 50]               | 19 (79)  | 11.5 [8, 15.3]           | 38 [34, 43]|
|                | NOM 15       |           |                    |                    | 60 [38, 90.75]            | 47 [35, 55]|                         | 38 [35, 43]|
| Zhang X (2015) [46]  | CC           | China     | RF 23              | 419.4 ± 107.1      | 58 ± 12                   | 21 (72)  | 7.8 ± 1.5                | NR        |
|                | NOM 29       |           |                    |                    | 419.4 ± 107.1             | 60 ± 10  | 7.4 ± 1.7                |           |
| Wada et al. (2015) [34] | CC           | Japan     | RF 84              | 53 (24–45)         | NR                       | 59 (70)  | NR                       | NR        |
|                | NOM 336      |           |                    |                    | 42 (23–38)                | 225 (76) |                         |           |
| Wu et al. (2015) [32]  | PC           | China     | RF 75              | 15.3 ± 6.4         | 52 ± 5                   | 75 (100) | 8.1 (6–12)               | NR        |
|                | NOM 89       |           |                    |                    | 26.5 ± 6.9                | 51 ± 3   | 79 (6–11)                |           |
| Majercik et al. (2015) [16] | CC         | USA       | RF 137             | 11.4 ± 5.7         | 56 ± 16                   | 110 (80) | 6.5 ± 2.0                | 21 ± 10.7 |
|                | NOM 274      |           |                    |                    | 12.3 ± 9.1                | 55 ± 20  | 4.6 ± 2.3                | 22 ± 11.8 |
| Xu et al. (2015) [28]  | RC           | China     | RF 17              | NR                 | 36 ± 14                   | 12 (71)  | 6.8 ± 2.1                | 21.8 ± 7.8 |
|                | NOM 15       |           |                    |                    | 39 ± 12                   | 12 (80)  | 7.4 ± 1.6                | 24.0 ± 8.0 |
Table 1 (continued)

| Study                        | Study design | Country     | Number of patients | Follow-up (months) | Age (years, range or ±SD) | Male (%) | Number of fractured ribs | ISS score |
|------------------------------|--------------|-------------|--------------------|--------------------|---------------------------|----------|--------------------------|-----------|
| Granhed and Pazooki (2014)   | CC           | Sweden      | RF 60              | NR                 | NR                        | 53 (77)  | 7.5 (2–14)               | 21.7±10.7 |
|                              |              |             | NOM 153           | NR                 | NR                        | NR       | NR                       | 30.9±13.3 |
| Doben et al. (2014)          | CC           | USA         | RF 10              | 21.6 (8–59)        | 47 ± 15                   | 9 (90)   | 8.3 (4–20)               | 26.3±9.5  |
|                              |              |             | NOM 11            | 28.5 (6–50)        | 57 ± 17                   | 7 (64)   | 9.2 (6–16)               | 35.7±12.7 |
| Marasco et al. (2013)        | RCT          | Australia   | RF 23              | 90                  | 58 ± 17                   | 20 (87)  | 11.0 ± 3.1               | 35.0±11.4 |
|                              |              |             | NOM 23            | 90                  | 59 ± 10                   | 20 (87)  | 11.3 ± 4.7               | 30.0±6.3  |
| Khandelwal et al. (2011)     | PC           | India       | RF 31              | 47                  | 40 (66)                   | 3.1      | NR                       | 25.7      |
|                              |              |             | NOM 29            | 45                  | NR                        | 3.3      | NR                       | 27.5      |
| Moya et al. (2011)           | CC           | USA         | RF 16              | 18 ± 12             | 45 ± 16                   | 14 (88)  | 8 ± 4                    | 24±7      |
|                              |              |             | NOM 32            | 16 ± 11             | 47 ± 14                   | 26 (81)  | 8 ± 3                    | 25±9      |
| Alfhausen et al. (2011)      | CC           | USA         | RF 22              | 17.84 ± 4.51       | 48                        | 17 (74)  | 5.9                      | 25.1      |
|                              |              |             | NOM 28            | NR                  | 51                        | 23 (79)  | 7.3                      | 24.3      |
| Solberg et al. (2009)        | RC           | USA         | RF 9               | 16.1 ± 6.7          | 39 ± 17                   | 6 (67)   | NR                       | 24.9±6.5  |
|                              |              |             | NOM 7             | 12.0 ± 2.3          | 41 ± 13                   | 5 (71)   | 30 ± 7                   | 24.8±6.2  |
| Nirula et al. (2006)         | CC           | USA         | RF 30              | NR                  | NR                        | 52       | NR                       | 25.7      |
|                              |              |             | NOM 30            | 50                  | NR                        | 3.3      | NR                       | 27.5      |
| Granetzny [23]               | RCT          | Germany     | RF 20              | 2                   | 41 ± 8                    | 17 (85)  | 4.4                      | 16.8±3.5  |
|                              |              |             | NOM 20            | 2                   | 36 ± 15                   | 16 (80)  | 4.0                      | 18.0±5.1  |
| Baki et al. (2004)           | RC           | Turkey      | RF 27              | NR                  | NR                        | 35 ± 8   | 20 (74)                  | 4.0±3.7   |
|                              |              |             | NOM 37            | NR                  | NR                        | 31 ± 10  | 28 (76)                  | 18.4±8.1  |
| Tanaka et al. (2002)         | RCT          | Japan       | RF 18              | 360                 | 43 ± 12                   | 12 (67)  | 8 ± 3                    | 33±11     |
|                              |              |             | NOM 19            | 360                 | 46 ± 9                    | 14 (74)  | 8 ± 3                    | 30±8      |
| Voggenreiter (1996a)         | RC           | Germany     | RF 10              | NR                  | NR                        | 55 ± 8   | NR                       | 31.0±7.0  |
|                              |              |             | NOM 18            | NR                  | 44 ± 19                   | NR       | NR                       | 36.6±12.3 |
| Voggenreiter (1996a)         | RC           | Germany     | RF 10              | NR                  | NR                        | 50 ± 16  | NR                       | 37.0±7.9  |
|                              |              |             | NOM 4             | NR                  | 48 ± 27                   | NR       | NR                       | 37.8±19.5 |
| Ahmed and Mohyuddin (1995)   | RC           | United Arab | RF 26              | (3–9)               | 20–60 (range)             | 23 (88)  | NR                       | NR        |
|                              |              | Emirates    | NOM 38            | (3–9)               | 10–60 (range)             | 36 (95)  | NR                       | NR        |
| Kim et al. (1981)            | RC           | France      | RF 18              | NR                  | NR                        | NR       | NR                       | NR        |
|                              |              |             | NOM 142           | NR                  | NR                        | NR       | NR                       | NR        |
| Aubert et al. (1981)         | RC           | France      | RF 224             | NR                  | NR                        | NR       | NR                       | NR        |

CC case control, PC prospective cohort, RC retrospective cohort, RCT randomized controlled trial, RF rib fixation, NOM nonoperative treatment, NR not reported
reduction of tracheostomies compared to nonoperative treatment with a risk ratio of 0.59 (95% CI 0.36, 0.90, \( p = 0.01 \), \( I^2 = 72\% \)) (Online Appendix 10). When stratified by study design both subgroups showed similar results (Table 3).

**Other outcome measures**

Nine studies \( (n = 1174) \) reported on implant removal; five studies reported zero events and four studies reported implant removal ranging from 1.5 to 4.9% (Online Appendix 4) \[17, 26, 28, 36–38, 40, 45, 48\]. Eleven studies reported on wound infection; five studies reported zero events and six studies reported a wound infection rate ranging from 1.7 to 25% \[18, 23, 24, 26–30, 46\]. Other short and/or long-term complications were poorly reported and described mainly respiratory complications.

**Sensitivity analyses**

In sensitivity analysis for study quality, results did not change significantly except for HLOS which increased in favor of rib fixation in studies with higher quality with a mean difference of –3.53 (95% CI –7.27, –0.21, \( p = 0.06 \)) (Table 3). Results from studies published after 2012 did not show a reduced HLOS, ILOS, incidence of pneumonia or need for tracheostomy after rib fixation (Table 3).

**Discussion**

In this systematic review and meta-analysis of RCTs and observational studies, rib fixation for patients with flail chest resulted in lower mortality, shorter ILOS and DMV, lower pneumonia rate, and lower need for tracheostomy. Pooled results from RCTs and observational studies were similar for all studied outcome measures although results from RCTs showed a larger treatment effect for HLOS, ILOS, and DMV. Results from recent studies showed lower mortality and shorter DMV after rib fixation, but there were no significant differences for the other outcome measures. The implant removal rate ranged from 1.5 to 4.9%. There were not enough studies of only patients with multiple rib fractures to perform meta-analyses on rib fixation for this patient population.

This meta-analysis included a large number of studies demonstrating the potential short-term benefit of rib fixation over nonoperative treatment for flail chest. Most often the indication for rib fixation was the presence of flail chest and to a lesser extent respiratory failure or intractable pain. Even though almost all studies included patients with flail chest, in many cases it was unclear whether it was a radiological or clinical flail chest making results harder to interpret. It is important to distinguish between these subgroups as respiratory compromise as well as injury severity is thought to mark important differences and influence outcome. The heterogeneous indication and patient populations reported on in the literature mask the exact indication and patient subgroup that would benefit most from rib fixation and consequently the adaptation of rib fixation in current practice.

Very few studies are available investigating patients with multiple rib fractures without flail chest. In a retrospective study, Qiu et al. performed separate analysis on patients with multiple rib fractures without flail segment and showed good short-term results and an earlier return to ‘normal activity’ after rib fixation \[18\]. Another notable study on multiple rib fractures was from Khandelwal et al. who described a prospective cohort of patients with multiple rib fractures where most patients had two or three rib fractures and only two (5.3%) had a flail chest \[29\]. They reported a significant reduction of pain and earlier return to work after rib fixation. No other studies have reported on rib fixation compared to nonoperative treatment focused on multiple rib fractures even though this is the largest subgroup of patients seen in daily practice.

In this review, we have included both RCTs and observational studies and show similar results for all outcome measures between both designs. Concato et al., Benson et al., and Ioannides et al. have provided an empirical basis for the comparison of RCTs and observational studies and showed results from these different designs can be remarkably similar, but can be rather different as well \[52–54\]. Although, treatment effects can be similar across studies regardless of design, genuine differences in treatment effects between different patient populations may be masked by biases in observational studies. Pooling results across different design could then lead to incorrect inferences. The judgement about validity of pooling results from different designs should be made on a case-by-case basis, since for instance the potential for confounding bias is context- and research-specific. Still, within the field of (orthopedic) trauma surgery there is growing evidence showing the potential of observational studies in meta-analyses leading to more robust conclusions without decreasing quality of the results \[7–9\].

Interestingly, RCTs in this study showed a larger treatment effect for some of the outcome measures as compared to observational studies. It is thought that observational studies tend to overestimate treatment effect which is possibly the result of the surgeon introducing a selection bias by choosing the optimal patient or publication bias \[55, 56\]. The three RCTs available on this subject all had very strict inclusion and exclusion criteria resulting in specific patient groups where treatment effects could be demonstrated yet with limited generalizability \[22, 23, 50\]. In
Table 2  Treatment characteristics of the included studies comparing operative versus nonoperative management of traumatic rib fractures

| Study                  | Treatment groups | Included fractures | Flail chest in surgery group n (%) | Indication for surgery                                                                 |
|------------------------|------------------|--------------------|-----------------------------------|---------------------------------------------------------------------------------------|
| Dehghan et al. (2018)  | NR               | FC                 | 77 (100%)                         | NR                                                                                    |
| Ali-Osman et al. (2018)| RF: plates + screws | FC + MRF          | NR                               | Displaced rib fractures, uncontrolled pain, rib crepitus with breathing               |
| Wijffels et al. (2018) | RF: plates + intramedullary nails | FC               | 20 (100%)                         | Flail chest                                                                           |
| Kane et al. (2018)    | RF: NR           | FC + MRF           | 75 (65%)                          | 3 consecutively displaced rib fractures plus FEV1 and FVC less than 50% predicted       |
| Fitzgerald et al. (2017)| RF: plates + screws | FC + MRF          | NR                               | NR                                                                                    |
| Farquhar et al. (2016) | RF: plates + screws | FC               | 19 (100%)                         | FC (≥ 3 fractures), displaced, segmental rib fractures with respiratory insufficiency  |
| Pieracci et al. (2016) | RF: titanium plates + screws | FC + MRF          | 28 (80%)                         | FC (≥ 3 fractures), ≥ 3 displaced fractures; ≥ 30% thorax volume loss, failure treatment within first 72 h |
| Defreest et al. (2016) | RF: titanium locking plates + screws | FC               | 41 (100%)                         | Failure to wean, intractable pain, or respiratory failure                              |
| Uchida et al. (2016)  | RF: titanium plates + locking screws | FC + MRF          | NR                               | Flail segment, massive dislocation, > 15 mm fracture overlapping, or pain               |
| Velasquez et al. (2016) | RF: Thoracic Osteosynthesis System (STRATOS) | FC + MRF          | NR                               | FC (≥ 3), ≥ 3 ribs fractured + respiratory failure, intractable pain, thorax deformity, or displacement |
| Qiu et al. (2016a)    | RF: AO standard plates + cancellous screws | FC               | 21 (100%)                         | NR                                                                                    |
| Qiu (2016)            | RF: AO standard plates + cancellous screws | MRF              | 0 (0%)                            | NR                                                                                    |
| Jayle et al. (2015)   | RF: titanium plates + screws | FC               | 10 (100%)                         | FC (≥ 3 fractures)                                                                   |
| Zhang Y (2015)        | RF: ORIF         | FC with PC         | 24 (100%)                         | NR                                                                                    |
| Zhang X (2015)        | RF: claw-type titanium plates | FC               | 23 (100%)                         | FC (≥ 3 fractures)                                                                   |
| Wada et al. (2015)    | RF: ORIF         | FC + MRF           | 84 (100%)                         | NR                                                                                    |
| Wu et al. (2015)      | RF: nickel–titanium alloy devices | FC + MRF          | 31 (41%)                          | FC (≥ 3 fractures), ≥ 3 rib fractures, dislocation, thorax deformity, or chest cavity active bleeding |
| Majercik et al. (2015)| RF: plates + locking screws | FC + MRF          | 101 (75%)                         | FC, severely displaced fractures, intractable pain, failure to wean, or combination of these |
### Table 2 (continued)

| Study                          | Treatment groups                                      | Included fractures | Flail chest in surgery group \(n\) (%) | Indication for surgery                                                                 |
|-------------------------------|-------------------------------------------------------|--------------------|----------------------------------------|----------------------------------------------------------------------------------------|
| Xu et al. (2015) [28]         | RF: titanium locking plates NOM: standard conservative management | FC                 | 17 (100%)                             | NR                                                                                     |
| Granhed and Pazooki (2014) [43]| RF: titanium plates + intramedullary splints NOM: NR | FC+MRF             | 56 (93%)                              | Impaired saturation in spite of oxygen administration; intractable pain                |
| Doben et al. (2014) [40]      | RF: plates + intramedullary nails NOM: standard conservative management | FC                 | 10 (100%)                             | Failure of nonoperative management                                                    |
| Marasco et al. (2013) [50]    | RF: union resorbable plates + bicortical screws NOM: mechanical ventilator management | FC                 | 23 (100%)                             | FC (≥ 3 fractures) and ventilator dependent without prospect of weaning within 48 h  |
| Khandelwal et al. (2011) [29] | RF: titanium plates + screws NOM: NR                   | FC+MRF             | 2 (5.3%)                              | NRS score > 7 on 10 days after trauma                                                  |
| Moya et al. (2011) [31]       | RF: titanium or steel plates NOM: NR                   | FC+MRF             | 9 (56%)                               | Intractable pain, ≥ 2 severely displaced rib fractures with pain, and respiratory failure |
| Althausen et al. (2011) [26]  | RF: locking plates + locking screws NOM: NR            | FC                 | 22 (100%)                             | FC with displacement, failure to wean, respiratory failure, or need of thoracotomy     |
| Solberg et al. (2009) [24]    | RF: titanium plates NOM: ventilatory pneumatic stabilization | FC                 | 9 (100%)                              | Superolateral chest wall deformity                                                    |
| Nirula et al. (2006) [35]     | RF: Adkin struts NOM: NR                               | FC+MRF             | 15 (50%)                              | FC, intractable pain, bleeding, and inability to wean                                 |
| Granetzny (2006) [23]         | RF: K-wires and/or stainless steel wire NOM: strapping and packing | FC                 | 20 (100%)                             | FC (≥ 3 rib fractures) with paradoxical chest wall movement                           |
| Balci et al. (2004) [45]      | RF: suture and traction NOM: endotracheal intubation   | FC                 | 27 (100%)                             | FC with paradoxical chest wall movement, respiratory failure, dyspnea, and insufficient blood gas |
| Tanaka et al. (2002) [22]     | RF: Judet struts NOM: internal pneumatic stabilization | FC                 | 18 (100%)                             | FC (≥ 6 fractures) with respiratory failure requiring mechanical ventilation and failure to wean |
| Voggenreiter (1996a) [19]     | RF: ASIF reconstruction plates NOM: standard conservative management | FC without PC     | 10 (100%)                             | FC and thoracotomy for other injury, respiratory failure, paradoxical chest wall movement, or deformity |
| Voggenreiter (1996a) [19]     | RF: ASIF reconstruction plates NOM: standard conservative management | FC with PC        | 10 (100%)                             | FC and thoracotomy for other injury, respiratory failure, paradoxical chest wall movement, severe deformity |
| Ahmed and Mohyuddin (1995) [37]| RF: K-wires NOM: endotracheal intubation               | FC                 | 26 (100%)                             | NR                                                                                     |
| Kim et al. (1981) [49]        | RF: Judet struts NOM: internal pneumatic stabilization | FC                 | 18 (100%)                             | NR                                                                                     |
| Aubert et al. (1981) [48]     | RF: osteosynthesis NOM: ventilator assistance, physiotherapy | FC                 | 22 (100%)                             | NR                                                                                     |

RF rib fixation, NOM nonoperative management, NR not reported, FC flail chest, MRF multiple rib fractures, PC pulmonary contusion
observational studies, usually with less strict inclusion and exclusion criteria, an unclear indication together with other serious concomitant injuries can result in a selection of patients including patients who would benefit more from nonoperative treatment. A wrong patient selection can reduce measured treatment effects after rib fixation which could explain differences found between RCTs and observational studies in this specific topic. Additionally, differences in timing of the surgical procedure between studies might have introduced bias in comparability as early surgical stabilization is associated with favorable outcomes [57]. However, data regarding timing of surgery were not sufficiently reported in the included studies to further explore these effects. Finally, improvement of intensive care management over time could have attributed to differences in treatment effects as shown by our sensitivity analysis. In more recent studies only mortality and DMV improved after rib fixation, but there was no difference for the other outcome measures.

This study had some limitations. First, the results may be altered by missed studies in the literature search or by publication bias. However, we performed an extensive search using multiple databases with citation and reference checking of included studies. A funnel plot of the primary outcome measure did not suggest bias due to selective publication. Therefore, we are confident that we
have a representative overview of the current literature. Second, we did not distinguish between studies with both flail chest and multiple rib fractures and studies including only flail chest patients. Very few patients with multiple rib fractures were included in these studies. Therefore, we think results from these studies translate to flail chest patients and should not be excluded from analyses. Still, cautious interpretation of study results is necessary as the variety of definitions used in the included studies might have resulted in a high in-between study variability of patient samples.

More research is needed to further identify the right indication and right patient for rib fixation. As previously mentioned, RCTs in this heterogenic population are very difficult to perform and for adequate subgroup analyses sufficiently large sample sizes are needed. In the rapidly developing area of surgery, RCTs can be expensive, time consuming, and often have limitations in terms of generalizability and small sample sizes due to strict inclusion and exclusion criteria [58, 59]. Observational studies show similar results as compared to RCTs and might be an achievable first step in gathering high-quality evidence. Currently a large prospective multicenter database is created in the Netherlands including both patients with flail chest and multiple rib fractures from multiple level-I trauma centers, aiming to answer the above questions with the use of large sample sizes and long-term follow-up [60].

**Conclusion**

Rib fixation significantly improves short-term outcome for patients with flail chest, although the indication and patient subgroup who would benefit most from

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**Table 3** Subgroup and sensitivity analyses of studies included in a meta-analysis of rib fractures comparing rib fixation versus nonoperative treatment for patients with a flail chest

| Analysis description | n  | Mortality | RR (95% CI) | P value | n  | HLOS | MD (95% CI) | P value | n  | ILOS | MD (95% CI) | P value |
|----------------------|----|-----------|-------------|---------|----|------|-------------|---------|----|------|-------------|---------|
| All studies          | 25 | 0.41 (0.27, 0.61) | *p* < 0.001 | 21 | −1.46 (−4.31, 1.39) | 0.32 | 26 | −2.00 (−3.61, −0.38) | 0.02 |
| Subgroup analysis    |    |           |             |        |    |      |             |         |    |      |             |         |
| RCT                  | 3  | 0.57 (0.13, 2.52) | 0.46 | 2   | −8.33 (−14.60, −2.07) | 0.009 | 3   | −6.37 (−9.72, −3.03) | *p* < 0.001 |
| Observational studies| 22 | 0.40 (0.26, 0.60) | *p* < 0.001 | 19 | −0.77 (−3.72, 2.18) | 0.61 | 23 | −1.53 (−3.21, 0.15) | 0.07 |
| Sensitivity analysis |    |           |             |        |    |      |             |         |    |      |             |         |
| High-quality studies | 13 | 0.71 (0.35, 1.44) | 0.34 | 15 | −3.53 (−7.27, 0.21) | 0.06 | 17 | −2.83 (−4.75, −0.91) | 0.004 |
| Studies after 2012   | 17 | 0.43 (0.25, 0.77) | 0.004 | 16 | −0.64 (−3.98, 2.69) | 0.71 | 19 | −1.51 (−3.40, 0.37) | 0.12 |

**Table 3** contains subgroup and sensitivity analyses of studies included in a meta-analysis of rib fractures comparing rib fixation versus nonoperative treatment for patients with a flail chest. The table includes the number of studies (n), the risk ratio (RR), the mean difference (MD), and the P value for mortality, hospital length of stay (HLOS), and intensive care length of stay (ILOS). The analysis is divided into All studies, Subgroup analysis, RCT, Observational studies, Sensitivity analysis, High-quality studies, and Studies after 2012. The results show a significant improvement in short-term outcomes for patients with flail chest. The table also includes a section on the analysis of DMV, pneumonia, and tracheostomy, with similar results. The table uses RCT randomized controlled trial, RR risk ratio, MD mean difference, CI confidence interval, n no. of studies, RR risk ratio, MD mean difference.
this treatment remain unclear. There is not enough data regarding patients with multiple rib fractures without flail segment. Observational studies show similar results as compared to RCTs and might be an achievable first step in gathering high-quality evidence. Larger prospective studies are required to investigate proper indications and relevant outcome after rib fixation.

Compliance with ethical standards

Conflict of interest  Reinier Beks, Jesse Peek, Mirjam de Jong, Karlijn Wessem, Cumhur Öner, Falco Hietbrink, Luke Leenen, Rolf Groenwold, and Roderick Houwert declare that they have no conflict of interest.

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