ARTICLE IN PRESS

Injury xxx (xxxx) xxx

Contents lists available at ScienceDirect

Injury

journal homepage: www.elsevier.com/locate/injury

Radiographic rib fracture nonunion and association with fracture classification in adults with multiple rib fractures without flail segment: A multicenter prospective cohort study

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A R T I C L E I N F O

Keywords:
Fracture healing
Nonunion
Chest wall injury
Chronic pain
Thoracic trauma

A B S T R A C T

Background: Rib fracture nonunion is a probable cause of chronic pain following chest trauma, although its prevalence remains unknown. The aims of this study were to determine rib fracture nonunion prevalence following nonoperative management and to determine if presence of nonunion was associated with the number of rib fractures, or the rib fracture classification of anatomical location, type, and displacement.

Methods: This multicenter prospective cohort study included trauma patients with three or more fractured ribs but without a flail segment, who participated in the nonoperative management group of the FixCon trial between January 2019 and June 2022. The number and classification of rib fractures were assessed on trauma chest CT. Chest CTs conducted six months post-trauma were evaluated for the presence of nonunion. Radiological characteristics of nonunions were compared with normally healed rib fractures using the Mann-Whitney U, χ^2 test, and Fisher's exact test as appropriate. A generalized linear model adjusted for multiple observations per patient when assessing the associations between nonunion and fracture characteristics.

Results: A total of 68 patients were included with 561 post-traumatic fractures in 429 ribs. Chest CT after six months revealed nonunions in 67 (12 %) rib fractures in 29 (43 %) patients with a median of 2 (P_{25}-P_{75} 1–3) nonunions per patient. Nonunion was most commonly observed in ribs seven to 10 (20–23 %, $p < 0.001$, adjusted $p = 0.006$). Nonunion occurred in 14 (5 %) undisplaced, 22 (19 %) offset, and 20 (23 %) displaced rib fractures ($p < 0.001$). No statistically significant association between rib fracture type and nonunion was found.

Conclusions: Forty-three percent of patients with multiple rib fractures had radiographic nonunion six months after trauma. Fractures in ribs seven to 10 and dislocated fractures had an increased risk of rib fracture nonunion.

Introduction

Rib fractures occur in approximately 10 % of patients following chest trauma [1,2]. They are associated with increased mortality and an increased risk particularly for pulmonary complications [3,4]. Over the long term, rib fractures can lead to chronic pain, disability, and a marked reduction in the quality of life for a significant portion of patients, even following isolated thoracic injuries [5–8]. An explanation for these persistent complaints may lie in abnormal healing of fractured ribs.

Normal fracture healing requires a delicate balance between biological factors and mechanical forces [9,10]. Respiration, ambulation, and coughing exert substantial mechanical stress on the chest wall, while noninvasive methods to restore anatomical alignment and stabilize rib fractures are rarely feasible [11]. Despite a growing popularity, surgical stabilization of rib fractures (SSRF) is only performed on a small proportion of patients [12,13]. Hence, it would not be unexpected to find a relatively high prevalence of bone healing complications for rib fractures, even though the exact prevalence of these fracture healing problems is currently unknown.

Symptomatic rib fracture nonunion can be profoundly debilitating. A commonly accepted definition of symptomatic rib fracture nonunion involves localized complaints combined with the absence of bony union,

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https://doi.org/10.1016/j.injury.2024.111335

Available online 19 January 2024

observed at least three months after the initial injury, although some sources extend this timeframe to six months [14–16]. Frequently reported symptoms of rib fracture nonunion include chronic pain around and in the dermatome of the nonunion, exertional dyspnea, and rib instability, often accompanied by a clicking sensation. Despite several case series reporting improvement after surgical stabilization of rib fracture nonunion, comparative data on the management of this condition are scarce [14,15,17–22]. Nevertheless, a significant proportion of patients with rib fracture nonunion continues to experience symptoms, underscoring the need for better treatment and, preferably, prevention [15,17,18,22,23]. Achieving these goals necessitates a deeper understanding of the clinical entity encompassing rib fracture nonunion. Supposedly, not all rib fracture nonunions are equally symptomatic and probably only a small group of patients with nonunion-related symptoms will seek medical attention. Therefore, the currently available data on rib fracture nonunion likely underestimate the proportion of patients with rib fracture healing issues. Consequently, the primary aim of this study was to determine the prevalence of radiographic rib fracture nonunion in patients with nonoperatively managed multiple rib fractures without a flail segment, irrespective of clinical symptoms. The secondary aim was to investigate whether radiographic nonunion prevalence was associated with the number of rib fractures, the specific rib involved, or the acute rib fracture classification regarding anatomical location, type, and displacement. The local Medical Research Ethics Committee exempted the study.

Patients and methods

Setting and study population

This multicenter prospective cohort study included patients from the nonoperative arm of the 'Early fixation versus conservative therapy of multiple, simple rib fractures (FixCon)' randomized clinical trial. These patients were treated nonoperatively for multiple rib fractures without a radiologically confirmed flail segment between January 1, 2019, and June 30, 2022 [24]. Included were patients aged 18 years or older with three or more CT-confirmed fractured ribs within 72 h following blunt chest trauma. Rib fractures were required to exhibit a shaft-width displacement of at least one rib fracture, or the patient continued to suffer from uncontrollable pain with a Numeric Rating Scale (NRS) higher than six after the initiation of maximal feasible analgesia. In addition, all patients needed to have undergone a follow-up chest CT at six months (24–28 weeks) in accordance with the FixCon protocol. Exclusion criteria were the same as previously described in the FixCon protocol, with the added exclusion of patients who underwent SSRF prior to the follow-up chest CT, as this study exclusively focused on nonoperative controls [24]. Patients who underwent SSRF for nonunion within six months but after the follow-up CT were not excluded.

The institutional Ethics Committee exempted this study. Informed consent was obtained from all participants. The STROBE guideline was adhered to for reporting the methods, results, and discussion (SDC 1).

Variables

Demographic data, including age, sex, and smoking status, were retrieved from the FixCon trial database. Radiology reports and chest CT scans were reviewed, both at the time of trauma and during the follow-up, by at least two members of the research team. Discrepancies in evaluation were resolved by consensus. The initial trauma chest CT for each patient was evaluated for the number of rib fractures, the number of fractured ribs, rib fracture location (rib number, side, anatomical

Table 1
Baseline and injury characteristics of patients with rib fracture nonunion compared with patients whose rib fractures were healed at chest CT six months after trauma.

	All patients (*N* = 68)	Nonunion present (*N* = 29)	All rib fractures healed (*N* = 39)	*p*-value
Age	66 (56–76)	67 (59–75)	65 (53–77)	0.660
Male	44 (65 %)	19 (66 %)	25 (64 %)	1.000
Smoking				
Currently	8 (12 %)	3 (10 %)	5 (13 %)	0.787
Previously	35 (51 %)	14 (48 %)	21 (54 %)	
Never	25 (37 %)	12 (41 %)	13 (33 %)	
Time between trauma and follow-up CT (weeks)	27 (26–28)	27 (26–28)	27 (26–28)	0.602
Fractured ribs (N)	6 (5–7)	7 (5–8)	6 (5–7)	0.710
Rib fractures (N)	8 (6–11)	7 (5–11)	8 (6–11)	0.690
Bilateral rib fractures	8 (12 %)	4 (14 %)	4 (10 %)	0.936
Fractures in $\geq$2 anatomical regions	49 (72 %)	18 (62 %)	31 (79 %)	0.190

Data are shown as median (P_{25}–P_{75}) or as n (%). There were no missing data. CT, computed tomography.

sector), and rib fracture type and displacement, following the Chest Wall Injury Society taxonomy [25,26]. If multiple fracture lines were observed in a single rib, the fracture was categorized as a single complex fracture if the distance between the fracture lines was less than two centimeters; otherwise, the fracture lines were considered separate fractures. The follow-up chest CT scans were assessed to determine the healing status of the rib fractures.

Rib fracture classification

Rib fractures were evaluated on the trauma chest CT by examining each fracture in both axial and coronal views [25]. The anatomical sector was categorized as costal cartilage, anterior, lateral, posterior, or paravertebral. Although no consensus exists on the method for distinguishing anterior, lateral, and posterior fractures, the anterior and posterior axillary lines were used as reference points, as this is the most commonly used method [26]. Rib fracture type was classified as simple, wedge, and complex fractures. Simple rib fractures consist of one fracture line and wedge fractures of one complete fracture line involving both cortices and an incomplete fracture line affecting only one cortex of the rib, creating a 'butterfly' segment. Complex fractures consist of multiple closely related complete fracture lines. Rib fracture displacement was categorized as undisplaced, offset, or displaced. Undisplaced fractures have 90 % or more cortical contact between both ends of the fracture. Offset fractures have some cortical contact, but less than 90 %. Displaced rib fractures have no contact between both ends of the fracture site. Rib fracture healing was assessed through a follow-up chest CT conducted six months (range 24–28 weeks) after trauma. The primary outcome was radiographic rib fracture nonunion, defined as the presence of a visible fracture line spanning both cortices without signs of ongoing fracture healing between both ends of a rib fracture on the follow-up CT scan.

Statistical analysis

Data were analyzed using the Statistical Package for the Social Sciences (SPSS) version 28 (SPSS, Chicago, IL, USA). P-values for two-sided tests were considered significant if below 0.05. The distribution of

A

	Left side						Right side					
∑	PV	P	L	A	CC	Rib	CC	A	L	P	PV	∑
2	0	1	0	1	0	**1**	0	3	0	1	1	5
13	2	3	5	3	0	**2**	0	6	1	4	1	12
30	3	6	11	9	1	**3**	0	5	8	8	0	21
39	3	12	18	6	0	**4**	0	7	12	8	2	29
49	2	18	24	4	1	**5**	0	8	14	9	3	34
55	6	17	23	7	2	**6**	1	4	14	10	2	31
50	7	20	17	3	3	**7**	1	4	17	9	3	34
36	3	18	10	4	1	**8**	0	2	17	9	1	29
24	1	13	9	1	0	**9**	0	2	7	11	1	21
14	1	10	3	0		**10**		0	5	10	1	16
6	1	3	2			**11**			0	6	0	6
1	0	1				**12**				4	0	4
∑ 319	29	122	122	38	8		2	41	95	89	15	242

B

	Left side						Right side					
∑	PV	P	L	A	CC	Rib	CC	A	L	P	PV	∑
1	0	0	0	1	0	**1**	0	1	0	0	0	1
0	0	0	0	0	0	**2**	0	0	0	0	0	0
1	0	0	1	0	0	**3**	0	0	0	0	0	0
3	0	1	1	1	0	**4**	0	0	0	0	0	0
4	0	2	2	0	0	**5**	0	0	0	0	0	0
7	0	5	1	0	1	**6**	1	0	0	0	0	1
13	0	7	3	0	3	**7**	1	0	3	1	0	5
13	0	7	5	0	1	**8**	0	0	1	1	0	2
8	0	3	5	0	0	**9**	0	0	1	1	0	2
6	0	4	2	0		**10**		0	0	0	0	0
0	0	0	0			**11**			0	0	0	0
0	0	0				**12**				0	0	0
∑ 56	0	29	20	2	5		2	1	5	3	0	11

Fig. 1. Heatmaps of the location of acute rib fractures (A) and rib fracture nonunions (B) six months after trauma in patients with nonoperatively managed multiple rib fractures A, anterior; CC, costochondral; L, lateral; P, posterior; PV, paravertebral; ∑, sum. The absolute number of fractures (A) or nonunions (B) is mentioned for each rib and each anatomic location. Yellow indicates lower and red indicates higher numbers of fractures (A) or nonunions (B).

Table 2
Characteristics of rib fractures that demonstrated abnormal healing compared with normally healed rib fractures.

	All fractures (*N* = 561)	Rib fracture nonunion (*N* = 67)	Healed rib fractures (*N* = 494)	*p*-value χ^2	*p*-value GLM
Anatomical region					
Costal cartilage	10 (100 %)	7 (70 %)	3 (30 %)	**<0.001**	0.679
Anterior	79 (100 %)	3 (4 %)	76 (96 %)		
Lateral	217 (100 %)	25 (12 %)	192 (88 %)		
Posterior	211 (100 %)	32 (15 %)	179 (85 %)		
Paravertebral	44 (100 %)	0 (0 %)	44 (100 %)		
Type					
Simple	403 (100 %)	42 (10 %)	361 (90 %)	0.163	0.517
Wedge	112 (100 %)	19 (17 %)	93 (83 %)		
Complex	46 (100 %)	6 (13 %)	40 (87 %)		
Displacement					
Undisplaced	303 (100 %)	14 (5 %)	289 (95 %)	**<0.001**	**<0.001**
Offset	171 (100 %)	33 (19 %)	138 (81 %)		
Displaced	87 (100 %)	20 (23 %)	67 (77 %)		
Another fracture in a different anatomical region in the same rib	118 (28 %)	9 (16 %)	109 (29 %)	**0.047**	0.971

Data are shown as n (%) fractures. Statistically significant *p*-values are printed in bold. χ^2, unadjusted result of the Chi squared test. GLM, result adjusted for repeated measures by a generalized linear model.
There were no missing data.

continuous data was assessed by visually inspecting histograms and normality plots for each continuous variable. A non-normal distribution of data was confirmed by presence of positive or negative skewness in the histograms and normality plots (also verified by the Shapiro-Wilk test). Non-normally distributed data are presented as median with percentiles (P_{25}-P_{75}). Categorical variables are presented as number with percentage. There were no missing values. Patients were stratified into those with rib fracture nonunion and those with all rib fractures healed. Univariate comparisons were conducted using the Mann-Whitney U, χ^2 test, and Fisher's exact test as appropriate. The nonunion rate per rib was assessed using the Kruskal Wallis test.

Associations with rib fracture nonunion after six months were analyzed with a generalized linear model to account for multiple fractures per patient. Nonunion was entered into the model as the binary, dependent variable and patient was entered as factor. The variables of interest were separately added to the model either also as factor if categorical (e.g., rib fracture location), or as covariate if continuous (e.g., number of rib fractures).

Results

The study period included 72 nonoperatively managed patients with multiple rib fractures without a flail chest. After six months, one patient had passed away, and three patients were lost to follow-up due to the inability to establish contact. A total of 68 patients were included in the analysis. Their median age was 66 (P_{25}-P_{75} 56–76) years and 44 (65 %) patients were male (Table 1). The majority of patients were former smokers (n = 35, 51 %), while 25 (37 %) had never smoked. The total number of acute rib fractures was 561 in 429 ribs. The median number of acute rib fractures per patient was eight (P_{25}-P_{75} 6–11) in a median of six fractured ribs (P_{25}-P_{75} 5–7). The chest CTs conducted at median 27 weeks (P_{25}-P_{75} 26–28, range 22–33) following trauma demonstrated rib fracture nonunion in 29 (43 %) patients. The total number of rib fracture nonunions in all patients was 67 (12 % of the acute fractures Each patient with nonunion had median two rib fracture nonunions (P_{25}-P_{75} 1–3). The maximum number of rib fracture nonunions in a single patient was six. Baseline characteristics and smoking status did not differ between patients with and without rib fracture nonunion. Similarly, the number of rib fractures or fractured ribs did not significantly differ between patients with nonunion and those without nonunion (median 7 (P_{25}-P_{75} 5–8) versus 6 (P_{25}-P_{75} 5–7) ribs, $p = 0.710$; median 7 (P_{25}-P_{75} 5–11) versus 8 (P_{25}-P_{75} 6–11) fractures, $p = 0.690$). The presence of bilateral rib fractures or rib fractures in two or more anatomical regions did not differ between patients with and without nonunion (14 % versus 10 % for bilateral fractures, $p =$ 0. 936; 62 % versus 79 % for multiple anatomical regions, $p =$ 0. 190).

Furthermore, presence of more than one fracture in the same rib was not related to higher nonunion rates. Of 374 fractured ribs without nonunion after six months, 104 (28 %) ribs had two fractures and nine (2 %) ribs had three fractures. In contrast, of the 55 fractured ribs in which a nonunion developed after six months, nine ribs (15 %) had sustained two fractures, and no ribs had sustained three or more fractures ($p = 0.082$). No association was found between nonunion development and the total number of rib fractures per patient (adjusted $p =$ 0.900)

Rib fracture nonunion occurred predominantly in the costal cartilage sector of the ribs (Fig. 1 and Table 2). Seven (70 %) of the 10 fractures in this cartilaginous sector demonstrated no signs of healing six months after trauma. Nonunion rates were lower for fractures located in other anatomical sectors of the ribs, ranging from between 0 % (0 of 44 rib fractures) in the paravertebral and 15 % (32 nonunions in 211 rib fractures) in the posterior sector ($p < 0.001$). When adjusted for repeated measures per patient, no statistically significant association between rib fracture nonunion and rib fracture location was found (adjusted $p = 0.679$).

The nonunion rate did not differ statistically significantly between the three rib fracture types: 11 % (42 nonunions in 403 rib fractures) for simple rib fractures, 17 % (19 in 112 rib fractures) for wedge fractures, and 13 % (six in 46 rib fractures) for complex rib fractures ($p = 0.163$, adjusted $p = 0.517$; Fig. 2 and Table 2). However, more severe rib fracture displacement was associated with higher nonunion rates in the rib fractures (Fig. 3 and Table 2). In undisplaced rib fractures, 5 % (14 in 303 rib fractures) became nonunions half a year following the trauma. In contrast, nonunion occurred in 19 % (33 in 171 rib fractures) of the offset fractures and in 23 % (20 in 87 rib fractures) of the completely displaced rib fractures, which were significantly higher nonunion rates than in the undisplaced rib fractures (unadjusted and adjusted $p <$ 0.001). Rib fracture nonunion also demonstrated statistically significant variations by rib number ($p < 0.001$, adjusted $p = 0.006$) and was most prevalent in ribs one (29 %, 2 of 7 fractures), seven (21 %, 18 of 84 fractures), eight (23 %, 15 of 65 fractures), and nine (22 %, 10 of 45 fractures; Fig. 4).

A

		Left side				Right side			
	∑	C	W	S	Rib	S	W	C	∑
	2	0	2	0	1	5	0	0	5
	13	2	2	9	2	10	2	0	12
	30	3	4	23	3	15	4	2	21
	39	5	9	25	4	20	6	3	29
	49	3	14	32	5	24	8	2	34
	55	4	14	37	6	26	5	0	31
	50	4	12	34	7	26	6	2	34
	36	4	3	29	8	19	7	3	29
	24	0	3	21	9	14	4	3	21
	14	2	1	11	10	10	2	4	16
	6	0	0	6	11	4	2	0	6
	1	0	0	1	12	2	2	0	4
∑	319	27	64	228		175	48	19	242

B

		Left side				Right side			
	∑	C	W	S	Rib	S	W	C	∑
	1	0	1	0	1	1	0	0	1
	0	0	0	0	2	0	0	0	0
	1	0	0	1	3	0	0	0	0
	3	1	1	1	4	0	0	0	0
	4	0	3	1	5	0	0	0	0
	7	1	4	2	6	1	0	0	1
	13	0	5	8	7	5	0	0	5
	13	2	2	9	8	1	1	0	2
	8	0	2	6	9	1	0	1	2
	6	1	0	5	10	0	0	0	0
	0	0	0	0	11	0	0	0	0
	0	0	0	0	12	0	0	0	0
∑	56	5	18	33		9	1	1	11

Fig. 2. Heatmaps of the type of acute rib fractures (A) and rib fracture nonunions (B) six months after trauma in patients with nonoperatively managed multiple rib fractures C, complex; S, simple; W, wedge; ∑, sum. The absolute number of fractures (A) or nonunions (B) is mentioned for each rib and each fracture type. Yellow indicates lower and red indicates higher numbers of fractures (A) or nonunions (B).

A

		Left side				Right side			
	∑	D	O	U	Rib	U	O	D	∑
	2	0	0	2	1	3	2	0	5
	13	0	5	8	2	11	0	1	12
	30	2	11	17	3	11	7	3	21
	39	8	10	21	4	15	6	8	29
	49	9	14	26	5	22	9	3	34
	55	4	25	26	6	23	6	2	31
	50	8	18	24	7	21	7	6	34
	36	7	12	17	8	11	9	9	29
	24	6	7	11	9	11	5	5	21
	14	2	7	5	10	7	6	3	16
	6	1	0	5	11	2	4	0	6
	1	0	1	0	12	4	0	0	4
∑	319	47	110	162		141	61	40	242

B

		Left side				Right side			
	∑	D	O	U	Rib	U	O	D	∑
	1	0	0	1	1	1	0	0	1
	0	0	0	0	2	0	0	0	0
	1	0	0	1	3	0	0	0	0
	3	1	2	0	4	0	0	0	0
	4	2	1	1	5	0	0	0	0
	7	3	3	1	6	0	1	0	1
	13	3	8	2	7	1	2	2	5
	13	5	6	2	8	0	2	0	2
	8	2	3	3	9	0	2	0	2
	6	2	3	1	10	0	0	0	0
	0	0	0	0	11	0	0	0	0
	0	0	0	0	12	0	0	0	0
∑	56	18	26	12		2	7	2	11

Fig. 3. Heatmaps of the displacement of acute rib fractures (A) and rib fracture nonunions (B) six months after trauma in patients with nonoperatively managed multiple rib fractures D, displaced; O, offset; U, undisplaced; ∑, sum. The absolute number of fractures (A) or nonunions (B) is mentioned for each rib and each displacement category. Yellow indicates lower and red indicates higher numbers of fractures (A) or nonunions (B).

Discussion and conclusions

The primary aim of this study was to determine the prevalence of rib fracture nonunion in patients with multiple rib fractures without a flail segment, treated nonoperatively, six months after their trauma. The prevalence of nonunion was 12 % of all traumatic rib fractures, affecting 43 % of patients. Notably, costal cartilage fractures showed the highest nonunion rate (70 %). Furthermore, nonunion predominantly occurred in the first rib and ribs seven to 10. Fracture displacement was associated with a statistically significant increase in nonunion rates (5 % in undisplaced, 19 % in offset, and 23 % in displaced rib fractures). An association between nonunion occurrence and rib fracture type was not found.

Commonly assumed is that 5–10 % of all fractures in human bodies

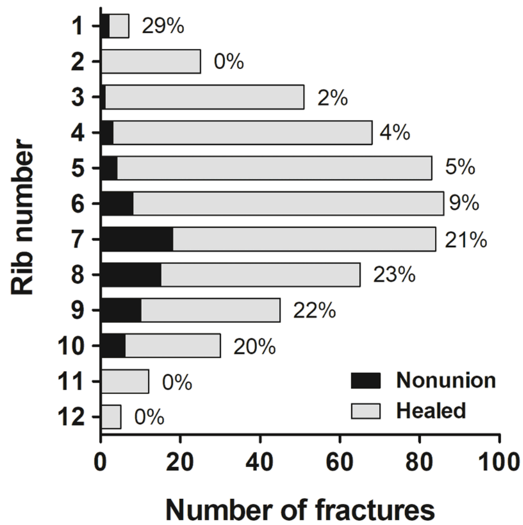

Fig. 4. Total number of healed rib fractures and nonunions with percentage of nonunions for each rib number after six months in patients with nonoperatively managed multiple rib fractures The nonunion rate differs for rib number, Kruskal Wallis $p < 0.001$. Adjusted for repeated measures with generalized linear model analysis $p = 0.006$.

may develop nonunion [27]. This is lower than the rib nonunion rate found in the studied group of patients with multiple rib fractures, which is a specific subset of the population of patients with a fracture in general. Interestingly, the nonunion rates described in the current study align well with a prior study of patients with flail chest who underwent SSRF and had CT imaging performed three months post-trauma, indicating no healing in 13 % of non-stabilized rib fractures [28]. Another study, including nonoperatively treated patients with multiple rib fractures, reported that clear rib fracture lines were still visible on CT in 22 % of rib fractures after three months [29]. The discrepancy in reported nonunion rate between these studies and the current study could be partly attributed to the shorter three-month interval, compared with our six-month interval.

The nonunion rate of costal cartilage fractures was notably high with 70 %. However, although literature about costal cartilage fractures is scarce, several case reports have described nonunion in this fracture location [30–32]. The rate of costal cartilage nonunion could still be an underestimation, since visualizing the costal cartilage on CT can be challenging. Using magnetic resonance imaging (MRI) scans for evaluating fractures and nonunions in the costal cartilage of the chest wall may be more suitable. However, no MRIs were conducted in this study, as is often the case in clinical practice. Both clinical studies involving costal cartilage resections as part of pectus excavatum surgery and experimental research on costal cartilage fractures in mice have suggested that injuries to costal cartilage are particularly susceptible to healing failure [33,34]. The perichondrium of the costal cartilage probably mediates the initial biological response to injury similar to the response to injury of osseous tissue. However, costal cartilaginous tissue lacks vasculature from within, a factor that could contribute to the cartilaginous tissue's vulnerability to healing failure [33]. Another contributing factor could be the reduced mechanical stability of the callus formed around fractured cartilage compared with the progressively mineralized callus of bone. The absence of such a biological splint that stabilizes the fracture may increase the risk of healing failure in costal cartilage injuries [33]. The findings in the current study confirm the susceptibility of costal cartilage fractures to nonunion. Although no comparative studies have been performed to date, and SSRF was not investigated in this study, it is theoretically plausible that SSRF could be considered an option to prevent symptomatic nonunions in costal cartilage fractures [30,35].

Most rib fractures were concentrated in ribs four to eight. However, the nonunion rate was highest in the first rib, and ribs seven to 10. Nonunion in the first rib holds a different clinical significance, and SSRF is rarely performed on this rib. The higher prevalence in ribs seven to 10 could hypothetically be attributed to several factors. First, these ribs tend to be larger in size, resulting in greater leverage of mechanical forces during movement, which can exert more stress on the fractures compared with smaller ribs. Second, the costochondral part of these ribs is relatively large, making it more susceptible to healing failure, as described previously. Last, most patients had a row of multiple ribs with fractures in the same anatomical sector. Possibly, the distal end of the row of fractures is more prone to healing failure.

The findings in this study also suggest that displacement is a contributing factor to the development of rib fracture nonunion. This observation aligns with previous research indicating decreased fracture healing with increased fracture gap size [36]. Furthermore, increased rib fracture displacement is likely associated with more damage to the intercostal vessels in close proximity to the rib. Arterial injury in the lower leg increases the nonunion risk for open tibial fractures three times the rate of patients with a normal arteriogram [37]. Vascular damage could have a role in the development of rib fracture nonunion and warrants further investigation.

This prospective cohort study has several strengths. It included patients with nonoperatively managed rib fractures who underwent chest CT scan at six months after trauma as part of the study protocol, irrespective of symptoms potentially related to rib fracture nonunion. This design, combined with a low number of patients lost to follow-up, assesses the radiographic nonunion rate with a low risk of selection bias in patients with nonoperatively managed multiple rib fractures after six months. Using an interval of six months allowed sufficient time for callus formation and bone remodeling to manifest on imaging, aligning with the intervals frequently reported in rib fracture nonunion literature [15,16,23,38].

Nonetheless, this study has some limitations. Nonunion is a complex, multifactorial pathologic process, and this study solely considered radiological fracture characteristics. Comprehensive biological, patient, or management factors that may have influenced nonunion development were not accounted for [39]. Distinguishing between hypotrophic and hypertrophic nonunions could offer insight into whether poor biology or inadequate stability was the primary factor contributing to rib fracture nonunion [40]. A better understanding of biological and nonoperative treatment factors could improve the care of patients with rib fracture nonunion. Moreover, this study did not explore the association between nonunions and symptoms, leaving the clinical impact on patients and the recommended treatment strategy unresolved. Probably not all radiological rib fracture nonunions cause symptoms, so the rate of symptomatic rib fracture nonunion remains to be established. Lastly, this study contained the nonoperative control group of a randomized controlled trial designed and powered for a different research question than the one that was addressed in this study. Consequently, there is a risk of inherent bias and underpowering.

The finding that 43 % of patients demonstrated radiographic rib fracture nonunion six months after trauma suggests that the process of rib fracture healing likely extends beyond the commonly assumed six-weeks [41]. This finding has the potential to provide valuable information to patients with multiple rib fractures, aiding in managing their expectations regarding the recovery timeline. A future comparative study of SSRF versus nonoperative treatment will show if early SSRF can reduce the risk of rib fracture nonunion. A future comparative study of SSRF versus nonoperative treatment will have to determine if early SSRF decreases the risk of rib fracture nonunion and, more importantly, if SSRF decreases nonunion associated symptoms for patients with multiple rib fractures [24].

In conclusion, radiographic nonunion occurred in 43 % of patients with multiple rib fractures six months after trauma. Radiographic nonunion affected 12 % of all rib fractures in patients with at least three rib fractures and no flail segment. Rib fracture displacement and fracture location in the costal cartilage and the lower ribs seven to 10 increased the risk of radiographic rib fracture nonunion.

Source of funding

This study is supported by grants from The Netherlands Organization for Health Research and Development (ZonMw; Reference No. 852001921), the OTC Foundation (Reference No. 2017-JVMW), Stichting Coolsingel (Reference No. 573), and Johnson and Johnson DePuy Synthes. The funders of the study had no role in the study design, data collection, data analysis, data interpretation, or writing of this manuscript

Supplemental digital content

SDC 1 STROBE Checklist of items that should be included in reports of observational studies

CRediT authorship contribution statement

Suzanne F.M. Van Wijck: Conceptualization, Formal analysis, Investigation, Methodology, Project administration, Visualization, Writing – original draft. **Max R. Van Diepen:** Investigation, Validation, Writing – review & editing. **Jonne T.H. Prins:** Investigation, Writing – review & editing. **Michael H.J. Verhofstad:** Conceptualization, Resources, Supervision, Writing – review & editing. **Mathieu M.E. Wijffels:** Conceptualization, Project administration, Supervision, Writing – review & editing. **Esther M.M. Van Lieshout:** Conceptualization, Data curation, Formal analysis, Methodology, Project administration, Supervision, Writing – review & editing.

Declaration of competing interest

none.

Acknowledgements

This study is supported by grants from The Netherlands Organization for Health Research and Development (ZonMw; Reference No. 852001921), the OTC Foundation (Reference No. 2017-JVMW), Stichting Coolsingel (Reference No. 573), and Johnson and Johnson DePuy Synthes. The funders of the study had no role in the study design, data collection, data analysis, data interpretation, or writing of this manuscript.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.injury.2024.111335.

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