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Surgical Management of Flail Chest: State of Art and Future Perspectives

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Abstract

Purpose of Review Rib fractures are common among trauma patients with both blunt chest wall and thoraco-abdominal trauma, seen in up to 39% of patients following blunt chest trauma and present in 10% of all trauma admissions and, in these individuals, mortality rates can reach 9–16%. Notwithstanding, the objective of surgical stabilization is to recover thoracic wall rigidity and restore normal ventilation and functions, thus decreasing mortality and morbidity.

Recent Findings Currently, all possible indications for surgical rib fixation are far away from a consensus statement backed up with strong evidence.

Summary The aim of this review article is to highlight both the usefulness and the pitfalls of operative rib fixation techniques.

Keywords Chest injuries · Flail chest · Conservative treatment · Surgical stabilization · Quality of life · Surgery costs

Introduction

Rib fractures are common among trauma patients with both blunt chest wall and thoraco-abdominal trauma, seen in up to 39% of patients following blunt chest trauma and present in 10% of all trauma admissions [1••]. Notwithstanding most cases are conservatively treated, parietal chest trauma is associated with considerable mortality, with occurrences ranging from 4 to 20% [2]. Furthermore, chest injury is still directly responsible for about 25% of trauma-related deaths and indirectly for another 25% of overall trauma-related deaths [3]. Patients with a flail chest pattern of injury, defined as two fractures per rib in three or more consecutive ribs, often struggle with hypoxemic and hypercapnic respiratory failure secondary to inefficient ventilation due to a ventilatory-perfusion ratio mismatch, underlying pulmonary contusions, oedema, pneumonia, and pain [4]. In these individuals, mortality rates can reach 9–16% [5, 6•, 7]. However, also for patients who survive, difficulties with chronic chest pain, deformity, longstanding disability, poor quality of life, and inability to maintain employment are common [8, 9•, 10]. Again chest injury peaks in the productive age groups with severe economic implications [11]. Despite these well documented outcomes, treatment options for these patients remain poorly defined. A recent study utilizing the National Trauma Data Bank reported that less than 1% of patients with significant rib fractures underwent surgical stabilization and that only 8% were treated with offered adequate analgesic schedule [7]. Rib fractures have traditionally been managed conservatively by aggressive pulmonary toilet, mechanical ventilator support (i.e. pneumatic stabilization with endotracheal intubation) and conventional pain control methods, including oral analgesics, intercostal nerve blocks, serratus block, and epidural analgesia [12, 13••, 14].

Surgical versus Non-surgical Management

Compared with surgical stabilization, non-surgical management has been associated with increased risks of pneumonia, empyema, prolonged mechanical ventilation, decreased respiratory function, and chronic sequelae such as pain and non-

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union or malunion fractures causing deformity [12, 15, 16]. The objective of surgical stabilization is to recover thoracic wall rigidity and restore normal ventilation and functions [17, 18], thus decreasing mortality and morbidity due to causes such as pneumonia, adult respiratory distress syndrome, sepsis, length of mechanical ventilatory support, and length of stay in the intensive care unit (ICU). The surgical stabilization consists of immobilization of the fractured structures (ribs, costal cartilages, and sternum). Different devices of metal such as wires, bars, and plaques are used to accomplish the stabilization [19], via a thoracotomy and the structure is placed intramedullary or external to the rib. In a recent Cochrane Review [20], including three studies and involving 123 patients with flail chest in order to evaluate the effects and safety of surgery compared with conservative management referring both to primary and secondary outcomes. According to mortality, no statistically significant difference in deaths between the treatment groups was found (RR 0.56, 95% CI 0.13–2.42, $I^2 = 0\%$, p value $= 0.70$), while secondary outcomes included long-term sequelae such as deformity and chronic chest wall pain. Concerning with deformity of the thoracic cage, a statistically significant difference favoring the surgical group, while the internal pneumatic stabilization group continued to experience thoracic cage pain and chest tightness in the chest. The internal pneumatic stabilization group continued to experience thoracic cage pain and chest tightness more frequently than those in the surgical stabilization group (persistent pain: 89% with no surgery versus 39% with surgery, $p < 0.05$; persistent chest tightness: 84% with no surgery versus 33% with surgery, $p < 0.05$). Authors concluded there was some evidence that surgical intervention was superior to non-surgical intervention in the treatment of flail chest in reducing pneumonia, chest deformity, tracheostomy, duration of mechanical ventilation, and length of intensive care unit stay; however, they claimed for an urgent need for larger high-quality randomized controlled trials, but surgical fixation is an underutilized procedure. Mayberry et al. [21], in a survey including 406 among Trauma, Orthopedic, and Thoracic Surgeons, reported only twenty-six percent of surgeons had performed or assisted on a chest wall fracture repair, whereas 22% of them were only unfamiliar with published trials, highlighting generalized skepticism regarding the merits of surgical chest wall fracture repair form a lack of persuasion by randomized trials themselves. Moreover, rejection was common among those who were unfamiliar with the published literature about long-term outcomes.

Indications for Surgical Stabilization

Currently, all possible indications for surgical rib fracture fixation are considered to be relative without any consensus statement with strong evidence, but it is clear there is a need to subdivide them due to the onset and the extent of the trauma (rib fractures, flail chest).

Concerning with flail chest, most commonly the presence of a flail segment is considered to be a strong relative indication for surgery [4, 22, 23], particularly in the presence of associated visceral lesions. Often, these patients require mechanical ventilator support for respiratory compromise; therefore, patients who fail to wean from the ventilator should be considered for surgery [23]. Patients with paradoxical movement and wide chest wall instability are considered to be at risk for non-surgical treatment related complications, such as prolonged ventilatory times, longer stays in the intensive care unit (ICU), and higher rates of pneumonia. Moreover, the onset of acute respiratory failure or pain secondary to fractures and refractory to medical therapy should be mandatory for surgery [24]. Another factor to consider is the anatomical one. Direct crush injuries to the thorax can produce deformity impeding lung expansion and displaced ribs can lacerate lungs, causing pneumothorax, hemothorax, and pulmonary hernias [25] or injure other vital organs. Regarding to chronic sequelae, the mainstream for delayed surgical stabilization is the presence of a symptomatic non-union or malunion in order to restore the normal contour and volume of the thoracic cavity [26]. Moreover, in face of multiple non-unions, chest wall dynamic would result in impaired ventilation leading to debilitating pain or dyspnea. With regards to contraindications, the presence of a pulmonary contusion injury in a flail chest patients should be a contraindication to rib fracture fixation [24], though published experience are conflicting. Althausen et al. [16], comparing 22 patients with flail chest treated with locked plate fixation with a matched cohort of 28 nonoperatively managed ones, demonstrated surgical stabilization in patients with pulmonary contusions improved outcomes when compared with non-surgically managed patients. Tanaka et al. [12], reporting thirty-seven consecutive severe flail chest patients requiring mechanical ventilation, demonstrated no difference in pulmonary contusions between their randomized groups of patients. Finally, another contraindication for surgical fixation is the presence of a severe traumatic brain injury (TBI) [24] (Table 1). Another aspect to consider is the appropriate timing of fixation, with many investigators favoring for an earlier fixation within a few days of the primary injury [27••, 28, 29]. Rib fixation early in the patient's hospital course avoids factors such as inflammation, severe hematoma, and early callous formation which can complicate operative reduction of the fractures. Of course, the timing of surgery must be made in the context of the patients overall clinical condition, and occasionally must be delayed while other injuries and conditions are stabilized.

Devices and Techniques

Locking Plates

Locking plates present several advantages to traditional plates (such as stainless non-locking steels or wires) in anatomical reconstruction. Precontoured titanium ones are elastic and allow the normal rib motion during breathing cycle; while, locking systems increase stability with a very minimal muscle dissection is needed to place them on the outer surface of the rib [30]. Currently, most favored prostheses are the MatrixRIB Fixation and the STRATOS™ systems [31]. The former is secured to the rib ends using clips that resemble claws at the two ends of the titanium bar whereas the latter system is secured by fastening the plate to the rib with locking screws through predrilled holes. Several case series have reported the successful use of locking plates with very favorable results. The main advantage of these anatomically precountured plates results from their decreased surgical time, which is certainly not negligible in the context of a traumatized patient. Doben et al. [32•], in a retrospective double-arm review including twenty-one patients (10 SRF patients vs 11 non-operative controls), reported surgical cohort presented a reduction in overall ICU stay (12.5 vs. 15.3 days, $p = 0.370$), a significant reduction in ventilator days (8.2 vs. 18.0 days, $p = 0.004$) and the median time of postoperative extubation in SRF group was 1.5 days. Althausen et al. [16], comparing 22 surgical locked plate patients with a matched cohort of 28 nonoperatively managed patients, reported shorter intensive care unit stays for the former group (7.59 vs. 9.68 days, $p = 0.018$), decreased ventilator requirements (4.14 vs. 9.68 days, $p = 0.007$), shorter hospital LOS (11.9 vs. 19.0 days, $p = 0.006$), fewer tracheostomies (4.55 vs. 39.29%, $p = 0.042$), less pneumonia (4.55 vs. 25%, $p = 0.047$), less need for reintubation (4.55 vs. 17.86%, $p = 0.34$), and decreased home oxygen requirements (4.55 vs. 17.86%, $p = 0.034$). Furthermore, no case of hardware failure, hardware prominence, wound infection, or non-union was reported. Rare postsurgical complications are generally of first or second degree according to Clavien and Dindo, as noted by Schulz-Drost et al. [33], who in a series of fifteen SRF patients reported a morbidity rate of 26.66%, in particular two cases of pneumothorax and two of seroma. Surgical locked fixation assures excellent outcomes with important social implications. As reported by Majercik et al. [34], in a survey including fifty SRF patients, pain was gone at 5.4 ± 1.1 weeks post discharge with a mean satisfaction grade of 9.2 ± 0.2 on a scale of 1–10 and ninety percent of employed patients returned to the same work at 8.5 ± 1.2 weeks. Encouraging results were also found by Billè et al. [35] in terms of postoperative Quality of Life (QoL) and analyzing ten consecutive trauma patients who underwent surgical fixation. Of these 10 patients, 9 were satisfied with the results of the operation, only one did not find any improvement after the operation. The median QOL and general health score according to the QLQ-C30 in the Stratos group were 4.5 (range 2–7) and 4 (2–7, respectively), and 7 (range 6–7) and 7 (range 6–7) in the Synthes group. There is a statistical difference in the two groups in terms of QOL and general health ($p = 0.04$). Finally, regarding to complications such as infection or rupture is rarely reported in such devices [36]. Recently, there have been reports of STATOS system bar fractures following parietal reconstruction probably secondary to the metal composition itself, which has less strength when compared with titanium alloys [37]. By contrast, fracture failure in the MatrixRIB System has been reported only in one case, suggesting the initiation of microfractures in the plates, which can eventually lead to a full fracture failure [31].

Judet Struts

As introduced in the seventies by Judet [38], these struts are simple linear steel plates, variable in length and width, with superior and inferior finger-like projections that are crimped over the fractured rib in order to stabilize it. The application requires a subperiosteal exposure as well as a

Table 1 Indications and contraindications for operative rib fixation

	Indications	Contraindications
Urgent osteosyntesis	Flail segment associated with respiratory failure	Extended pulmonary contusions
	Flail segment with major instability of chest wall	Extended acute lung injury (ALI)
	Flail segment with failure to wean from ventilator	Traumatic brain injury (TBI)
	Indication for urgent thoracotomy due to visceral lesions	
Delayed osteosyntesis	Deformity	
	Non-union	
	Chronic pain	

pre-fixation reduction of fractures. Disadvantages of these implants are the possibility for intercostal neurovascular injury (especially on the caudal surface of the rib), periosteal injury with devascularisation with subsequent necrosis. Pseudarthrosis of the stumps and spontaneous rupture of the device have been described [39]. The use of the Sanchez-Lloret struts is preferable in case of multiple rib fractures [40] by differing from the previous ones for the possibility of modeling and orientation of them.

Bioabsorbable Plates

Bioabsorbable poly-lactide plates present the theoretical advantage of avoiding long-term stress shielding at the fracture site and techniques consist of the use of absorbable poly-lactide plates supplemented by cerclage rib sutures. Mayberry et al. [41], in a case series involving ten patients who underwent surgical rib fixation with poly-lactide plates, showed good clinical results both in the immediate period (weaning from the ventilator) and at a distance (return to work or daily activities). At the same time, the authors emphasized two-point fixation (screw fixation plus suture cerclage) were required. In this regard, Oyamatsu et al. [42] proposed a revision of the fixing technique by the adoption of a U-shaped bioabsorbable plate (SuperFIXSORB MX40; Johnson and Johnson) and fixation by passing nonabsorbable 0/0 Ethibond suture through holes in the mesh of the plate and holes that were drilled in the edge of the fractured rib. Authors concluded a bioabsorbable plate was ideal for fixing fracture bone due to its durability after injury and long-term absorption, despite potential post-fixation infection risk, swelling, or pain. However, failure in the stability of the surgical reduction has been described as the result of vector forces (internal pressure, intercostal and rotational forces) acting during the respiratory cycle and especially in the exhalation phase, resulting in an instability of the absorbable plating system on the posterior part of the fractured rib and leading to dislodgement [43].

Intramedullary Stabilization

Several different forms of intramedullary implants, such as Kirschner wires (k-wires), Adkins struts, steel wires and Rehbein plate, have been used for rib fracture fixation [44, 45]. Compared to extracortical plate fixation, intramedullary stabilization has several benefits, such as less surgical dissection required for insertion. Kirschner wires (k-wire) have been reported in multiple studies with generally good results [18, 46]; however, authors reported rotational instability of the fractures due to the small cross section of the devices [47] and the potential for loss of fracture reduction with migration of the wire resulting in additional injury to the surrounding tissue [48, 49]. A particular extracortical fixation technique by means K-wires has been described [50]. The Authors, in a retrospective study involving seventeen flail chest patients, reported no cases of wound infection, dislodgment of the wires or osteosynthesis failure with an early postoperative improvement in pulmonary ventilation (Δpa_{O_2} and Δp_{CO_2}). Another device is the Rehbein plate, an intramedullary plate with a rectangular cross section designed to provide improved rotational stability by a direct suture of the strut to the rib. More recently, the intramedullary MatrixRIB fixation system has been introduced and seems to overpass some of the inherent issues of intramedullary devices in that they assure rotational control with a locked proximal screw to prevent migration. Bottlang et al. [51], evaluating twenty-two paired human ribs according to durability, strength, and failure modes of rib fracture fixation with Kirschner wires and rib splints, reported rib splint constructs remained 48% stronger than Kirschner wire constructs after dynamic loading ($p = 0.001$). Moreover, five of 11 Kirschner wire constructs failed catastrophically by cutting through the medial cortex, leading to complete loss of stability, and wire migration through the lateral cortex. Finally, an emerging concept for treatment of rib fractures is the use of intramedullary bioabsorbable materials [52]; with Liović et al. [53] who have reported a new experimental technique using an intramedullary telescoping splint anchored by bone cement.

Operative Rib Fixation: a Cost Analysis

Recently, a cost-effectiveness analysis was conducted in order to assess both the economic and medical benefits of rib fractures early fixation in severe chest trauma according to the guidelines by the Panel on Cost-Effectiveness in Health and Medicine [54•]. Authors included 20 references by estimating solely payer perspective costs as there are no riable data about long-term indirect costs (e.g. return to work) and basing on quality-adjusted life year (QALY) and incremental cost-effectiveness ratio (ICER). An average procedure cost of 21,100$, ranging from $17,500 to $26,000, was reported. On sensitive analysis, ORIF remained the most cost-effective strategy, with ICER never exceeding $16,000/QALY and, even with complication/revision rates as high as 50%, the procedure still presented an ICER of $18,000/QALY due to an important decrease in complications and length of stay overcoming some of the increased cost of surgery. Bhatnagar et al. [55] reported, in a Markov transition state analysis through a literature review, a cost effectiveness of $15,269 for surgical repair compared with $16,810 for conservative management.

Authors concluded, surgery remained the most cost-effective strategy by $8400 when the incidence of ventilator-associated pneumonia after ORIF was as high as 22%.

Future Perspective

Currently, the trend is moving away from the use of metal materials toward a preference for biodegradable products thanks to an increased sophistication of their structure and an increased use of 3D printers making them to overcome some limitations such as low break points. As known, the main advantage of a biodegradable device is its harmless degradation over time, which means that there is no need for additional removal. Biodegradable materials have applications as pins for the fixation of chondral or osteochondral small defects of articular surfaces, as well as for thin plates and areas used for fracture treatment in the maxillofacial area. These areas include the orbit and skull, especially in children [56]. Favorable results have occasionally been reported using 3D precontoured biodegradable compounds in cases of chest wall fracture [41, 57]. One biodegradable material is a biocomposite based on poly (e-caprolactone) (PCL) and reinforced by natural fibers, such as silk fibroin. Biocomposites consisting of PCL and SF fibers seem to have promising potential in biomedical fields because of their favorable mechanical characteristics and biocompatibility for rib fixation; however, limited experimental data have been published. Huang et al. [58], reporting their experience on 18 animal models, noted an high bending stress value ($3.44 \pm 2.36 \times 107$ Pa) with an optimal biotransformation with fibrous tissue surrounding the plates at 24 weeks' postoperatively. Moreover, these plates can be used both for linear and oblique fractures or comminuted ones by minimizing the chance of non-union or deformities resulting from postoperative bone deficits; indeed, in our study there were no instances of non-union. During operative fracture stabilization, the plate is bent in a convex curvature to approximate the surface of the rib. The SF/PCL plates become soft enough after immersion in hot water to be shaped easily. This saves operative time and avoids any potential weakening of plates, which may be caused by repeated bending to achieve an appropriate contour. SF/PCL is biodegradable by direct macrophage infiltration into the periosteal surface of the plates was possible because of the blood supply to the plates. Potential disadvantages associated with the use of SF/PCL plates include the long degradation time, as it can take more than two years to degrade the plates completely, but this will allow adequate time for fracture healing. The material is unsuitable for load bearing bone fractures as there is the possibility of dislocations due to the lack of screws. The SF/PCL plates used in this study were of a standard size, but by using a different mold to construct different sizes of SF/PCL plates, fractures of different lengths could easily be stabilized.

Conclusions

Reconstructive surgical management of thoracic trauma, although innovative materials and devices are available, is still an open challenge both in technique and, above all, in terms of distance results. The choice of devices should be based on the typology and extent of parietal defect, patient's comorbidity (age, life expectancy, work experience) and on the surgeon's experience. The latter appears to be the main cause of reticence by many to surgical stabilization, though it could be improved through theoretical and practical courses as well as through the establishment of a multidisciplinary and transversal panel of experts.

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Compliance with Ethics Guidelines

Conflict of interest The authors declare no conflicts of interest relevant to this manuscript.

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