SURGICAL FIXATION OF RIB FRACTURES

SUMMARY

Rib fractures are a common injury in patients sustaining blunt trauma to the chest. While most rib fractures heal uneventfully with conservative methods, some patients require more invasive treatment to prevent future pulmonary complications. Surgical fixation of rib fractures has long been a controversial mode of treatment that has recently gained support in certain clinical circumstances. While most research on the operative treatment of rib fractures takes place in the context of flail chest, various case reports and retrospective studies document its success for other select indications.

RECOMMENDATIONS

- **Level 1**
  - **None**
- **Level 2**
  - **Surgical fixation of rib fractures should be considered as the primary treatment in the following patients without severe head or other major organ system injury**
    - **Flail chest segment**
    - **Severe chest wall deformity with or without pulmonary herniation**
    - **Symptomatic fractures of 3 or more consecutive ribs**
- **Level 3**
  - **Intramedullary hardware should be employed for fixation of posterior rib fractures to avoid extensive dissection**
  - **Surgical fixation of rib fractures should be considered for patients with symptomatic malunion or nonunion of rib segments (chronic therapy)**
  - **Absorbable plates are not recommended for fixation of posterior rib fractures**

INTRODUCTION

In 2006, the Healthcare Cost and Utilization Project National Inpatient Sample recorded 78,856 patients admitted with multiple rib fractures (1). Patients who suffer rib fractures are at particular risk to develop pulmonary complications such as atelectasis, pneumonia and respiratory failure because of poor chest wall mechanics, decreased ventilatory capacity and diminished ability to cough and clear secretions. Most simple rib fractures are treated non-operatively using pain control and pulmonary hygiene (2). The vast majority of these injuries heal spontaneously without major complications. Severe rib fractures may require the use of mechanical ventilation. Recently, there has been a resurgence of interest in the surgical management of rib fractures. Indications for surgical fixation of rib fractures include flail chest, severe chest wall deformity, failure to wean from mechanical ventilation, chronic pain or disability, pulmonary herniation, non-union, and "on the way out" after thoracotomy (3). Initial research suggests that in select patients, operative management of chest wall injuries is a promising treatment option.

EVIDENCE DEFINITIONS

- **Class I:** Prospective randomized controlled trial.
- **Class II:** Prospective clinical study or retrospective analysis of reliable data. Includes observational, cohort, prevalence, or case control studies.
- **Class III:** Retrospective study. Includes database or registry reviews, large series of case reports, expert opinion.
- **Technology assessment:** A technology study which does not lend itself to classification in the above-mentioned format. Devices are evaluated in terms of their accuracy, reliability, therapeutic potential, or cost effectiveness.

LEVEL OF RECOMMENDATION DEFINITIONS

- **Level 1:** Convincingly justifiable based on available scientific information alone. Usually based on Class I data or strong Class II evidence if randomized testing is inappropriate. Conversely, low quality or contradictory Class I data may be insufficient to support a Level I recommendation.
- **Level 2:** Reasonably justifiable based on available scientific evidence and strongly supported by expert opinion. Usually supported by Class II data or a preponderance of Class III evidence.
- **Level 3:** Supported by available data, but scientific evidence is lacking. Generally supported by Class III data. Useful for educational purposes and in guiding future clinical research.

LITERATURE REVIEW

Flail Chest

Flail chest is typically defined as fracture of four or more consecutive ribs in two or more places resulting in paradoxical movement of the chest wall during respiration. There have been two prospective randomized controlled trials comparing the outcomes of surgical and nonsurgical stabilization of flail chest injuries.

Granetzy et al. in 2005 randomized 40 patients who experienced fractures of 3 or more ribs with paradoxical movement to receive either conservative or surgical treatment (4). Conservative treatment consisted of strapping and packing with elastoplast for 7-10 days. Surgical treatment consisted of stabilization of the rib fractures using Kirschner and stainless steel wires (14 patients) or stainless steel wire only (6 patients) within 24-36 hours after admission to the Intensive Care Unit (ICU). Patients were excluded if they presented with head trauma affecting level of consciousness, injuries unsafe for general anesthesia, severe injury to other systems, and fractures of the upper three ribs only. Both groups demonstrated significant improvement in measurements of PaO_2 and $PaCO_2$ after the interventions suggesting that both methods were effective. However, the results indicated that patients in the surgical group experienced significantly fewer days on mechanical ventilation (2 vs. 12; $p<0.001$), fewer days in the ICU (9.6 vs. 14.6; $p<0.001$) and fewer total days in the hospital (11.7 vs. 23.1; $p<0.001$). Furthermore, the surgical group exhibited a significantly less restrictive pattern on pulmonary function tests two months after treatment ($p<0.001$). The respective results for the surgical vs. conservative group for FVC was 75.0% vs. 66.5%, for TLC was 90.7% vs. 85.8% and for FEF_{75} was 65.6% and 60.4%. Stability of the chest wall was best for patients treated with Kirschner wires and stainless steel wires (100%) compared to conservative treatment or stainless steel wires only (50%). With regards to morbidity, surgically treated patients demonstrated significantly fewer post-operative chest infections (10% vs. 50%), less chest wall deformity (5% vs. 45%) and fewer patients with consequential scoliosis (0% vs. 25%). The authors concluded that certain patients with flail chest who meet individualized criteria regarding age, injury severity, and cardiopulmonary status should be considered candidates for surgical repair rather than mechanical ventilation.

In 2002 Tanaka et al. randomized 37 patients with flail chest who required mechanical ventilation to receive surgical stabilization or internal pneumatic stabilization (5). All patients required mechanical ventilation, fractured at least 6 ribs, and developed acute respiratory failure. Patients with a severe closed head and/or spinal cord injury or preexisting disease of major organ systems were excluded. Surgical fixation was accomplished using Judet struts within 2 weeks after injury (mean of 8.2 days) and was limited to ribs between T4 and T10. Patients in both groups were maintained on mechanical ventilation until extubation criteria were achieved. The surgically treated patients demonstrated significantly lower incidence of pneumonia at 21 days after injury (22% vs. 90%; $p<0.05$), shorter total duration on mechanical ventilation (10.8 days vs. 18.3 days; $p<0.05$), shorter duration in the trauma ICU (16.5 days vs. 26.8 days $p<0.05$), and less medical expense ($13,455 vs. $23,423 $p<0.05$). Patients who were surgically treated also demonstrated significantly better FVC compared to mechanically ventilated patients at 1, 2, 3, 6, and 12 months after injury ($p<0.05$). They also reported less chest tightness, thoracic cage pain and dyspnea compared to the conservatively treated group at 12 months after injury. Furthermore, 11 of 18 patients with surgical stabilization had returned to full-time employment at 6 months after injury compared to 1 of 19 in the internal pneumatic stabilization group. The findings are similar to Granetzy et al. The authors of the current study suggest that patients with multiple rib fractures who may require prolonged mechanical ventilation could benefit from surgical stabilization of the chest wall.

A retrospective study by Ahmed et al. in 1995 compared the outcomes of 64 patients with flail chest (6). Patients with a dominant injury to another body system were excluded. All patients in this study were initially managed with intubation and mechanical ventilation. There were 26 patients who had surgical stabilization of the flail segment using Kirschner wires within 12-48 hours after admission. The fixation occurred on only one side of the flail segment thereby converting the injury to multiple single rib fractures. 38 patients were treated conservatively with mechanical ventilation alone. The results indicated that patients in the surgical group experienced fewer days on mechanical ventilation (3.9 vs. 15) and fewer days in the ICU (9 vs. 21). With regards to morbidity, patients in the surgical group experienced fewer instances of chest infection (15% vs 50%), fewer instances of septicemia (4% vs. 24%), and fewer instances of tracheostomy (11% vs. 37%). The mortality of the surgical group was 8% compared to 29% in the mechanically ventilated group. The researchers also note that the Kirschner wire migrated in one patient requiring removal under local anesthesia. Nonetheless, the authors conclude that surgical stabilization of flail chest decreases the need for mechanical ventilation thereby improving the immediate and future outcomes of the patient.

A retrospective case-control study in 2006 by Nirula et. al compared the outcomes patients sustaining blunt chest injury, 30 of whom received surgical fixation of rib fractures and 30 patient who did not (7). Surgical stabilization was accomplished in most patients via a formal thoracotomy with Adkins struts (14mm). Surgical stabilization occurred at a mean of 2.7 days after admission. The indication for most patients to receive surgical stabilization included flail chest (21 patients), pain (5 patients), bleeding (2 patients) and failure to wean (2 patients). The patients were matched in terms of age, Injury Severity Score, and chest Abbreviated Injury Score (AIS). Of note, patients were not matched according to head AIS and there was a significantly higher head AIS score among control patients. Comparing both the surgical and conservatively treated group, the results demonstrate a similar length of ICU stay (12.1 vs. 14.1) and similar length of hospital stay (18.8 and 21.1). Total ventilator days were less for the surgical group (6.5 vs. 11.2), but this statistic did not reach significance (P=0.12). However, when using the day of surgery as day zero for both the surgically treated patients and their case counterpart, the surgically treated groups demonstrated significantly fewer days on the ventilator (2.9 vs. 9.4, P=0.02). The authors remark that the approach via thoracotomy leads to considerable morbidity which may account for extended post-operative mechanical ventilation requirement. Nonetheless, the researchers find the results to be promising in favor of surgical fixation of rib fractures and suggest that future efforts are justified to perform a randomized trial of early operative rib fracture treatment in patients with flail chest.

To determine the significance of underlying pulmonary contusion in surgical fixation of flail chest, Voggenretier et al. in 1998 performed a retrospective comparison of 20 patients with surgical stabilization of flail chest, in which 10 patients had an underlying pulmonary contusion and 10 patients did not as determined by acute infiltrates on chest radiograph and bronchoscopy (8). The results showed that patients without an underlying pulmonary contusion had significantly fewer days on mechanical ventilation (6.5 vs. 30.8; $p<0.02$) and less post-operative pneumonia (10% vs. 40%). Furthermore, the study included 18 matched patients without pulmonary contusion who were treated conservatively without surgical fixation. These patients required ventilatory support for a mean of 27.6 days and 5 patients (28%) had pneumonia during their stay in the hospital. The researchers concluded that an underlying pulmonary contusion in patients with flail chest is a relative contraindication to surgical rib fixation as these patients did not appear to benefit from the procedure when compared to patients with an underlying pulmonary contusion who were treated conservatively. Fibrosis and scarring of the lung is a known complication of pulmonary contusion which can lead to long-term deficits of pulmonary function tests (9). This helps explain how surgical fixation of a flail chest improves respiratory function related to poor chest wall dynamics but is ineffective when the lung parenchyma is intrinsically compromised.

Favorable long-term outcomes of patient undergoing chest wall stabilization have also been documented in the literature. A prospective study by Lardinois et al. determined the outcomes of 66 patients who received surgical fixation of chest wall injuries from 1990-1999 (10). The indications for surgical fixation included respiratory failure (28), flail chest (15), failure to wean from mechanical ventilation (21), and “on the way out” after thoracotomy (2). Repair was completed using a lateral approach with 3.5mm reconstruction plates at a mean of 2.8 days after admission. The results demonstrated that patients remained on mechanical ventilation for an average of 2.1 days. Patients had a mean total ICU stay of 6.8 days and a mean hospital of an average of 17.4 days. With regards to morbidity and mortality, five patients developed pneumonia and two patients developed superficial wound infections requiring debridement, but not removal of hardware. Four patients died from pneumonia and multi-organ failure. These patients received delayed operative fixation after an extended trial of mechanical ventilation. At 6 months post-operatively, 57 patients were assessed for follow-up. Six patients complained of chest wall pain which was relieved in three patients following removal of the hardware. Patients returned to work at an average of 8 weeks post-operatively. Pulmonary function testing of 50 patients at 6 months demonstrated normal findings in 52%, an obstructive pattern in 22% and a mixed obstruction and restriction pattern in 16%. A restrictive pattern, defined as a TLC <85% of the expected value, was found in 10% of patients. Based on these findings, the authors concluded that surgical fixation of the chest wall injuries does not significantly affect post-operative pulmonary function tests and that surgical fixation can reduce costs and complications associated with severe chest wall injuries among select patients.

Long-term morbidity was assessed by Mayberry et al. through a postal survey of fifteen patients who had received operative fixation for chest wall injuries (11). The survey consists of 36 items to assess physical function, limitation in role due to physical problems, bodily pain, general health perceptions, mental health, limitation in role due to emotional problems, social function and vitality (12-14). Three reference cohorts were used for comparison of RAND-36 Health Survey data. The first cohort consisted of 2471 patients with one of more of four chronic medical conditions (heart disease, hypertension, diabetes or depression) who were chosen because several of the surgical patients were known to have chronic medical conditions. The second cohort consisted of orthopedic trauma patients. The third cohort consisted of the friends and family of the orthopedic trauma patients who were chosen to represent the general population. The authors found that when compared to a cohort of patients with chronic medical conditions, the surveyed patients were similar in all categories of the RAND-36 questionnaire except for mental health in which they reported significantly better scores. When compared to the orthopedic trauma cohort, the survey patients reported better scores in all categories except for similar scores of general health. When compared to the reference cohort for the general population, the surveyed patients scored similarly in all categories except for significantly lower scores of limitation in role due to physical problems. Although this research includes a limited number of participants, the authors conclude that surgical repair of chest wall injuries improves long-term pain and reduces disability.

Chronic Pain / Disability and Nonunion

Chronic pain from rib fractures is often associated with malunion or nonunion of rib segments. The intercostal nerve runs within the intercostal groove immediately inferior to the ribs and is susceptible to irritation by non-united rib fractures. A rib segment may also cause a jabbing sensation of the lung with deep inspiration. The pain can be severe and disabling, preventing an individual from participating in exertional activities or physical labor. A thorough review of the non-operative options for acute pain management in patients with multiple rib fractures has been described by Karmarkar and Ho (2). However, only a handful of case reports can be found in the literature addressing patients with chronic pain from malunited or nonunited rib fractures who are treated with surgical fixation.

Ng et al. described a 57-year-old male with 11-months of pain from spontaneous fractures of his right 5th, 6th, and 7th ribs due to forceful coughing (15). The fibrous pseudoarthrosis was removed and the ribs were united with 3.5mm reconstruction plates. The postoperative course was complicated by a hematoma and subsequent wound infection treated successfully with IV antibiotics. The patient later returned to his daily activities without any further complications or complaints. Cacchione et al. reported on a 47 year old male with a symptomatic chest wall deformity due to a motor vehicle collision 2 years prior that had been unsuccessfully treated with various pain remedies (16). The patient experienced chronic pain and dyspnea on exertion. Fixation of the 4th, 5th, and 6th ribs was accomplished with titanium reconstruction ribbon plates and 4.0mm screws. The patient was discharged on his fifth post-operative day and subsequently demonstrated complete relief of symptoms with complete union of the ribs 6 months later. Slater et al. reported on a 57 year old man who had sustained a flail chest injury 6 years prior due to an all-terrain vehicle crash (17). The patient complained of dyspnea on exertion and pain when lifting or rotating his body. Operative fixation was accomplished with resection of the pseudoarthroses and segments of the deformed ribs followed by reduction and stabilization using 3.5mm and 4.5mm reconstruction plates and steel wire. The patient was discharged on post-operative day 5. At 18 months, the patient reported working full-time with significant improvement of his dyspnea and pain. Finally, Anavian et al. described a 50 year old man who had suffered multiple rib fractures after falling from a ladder (18). He complained of pain with movement and tenderness of his right ribs. Surgical fixation of the 7th and 8th right ribs was accomplished with 2.7mm locking reconstruction plates. The patient returned to full-time work as a painter and his typical physical hobbies with no complaints of pain or limitations.

Severe Chest Wall Deformity

Severe chest wall deformity is a rare injury that may occur from blunt trauma to the thoracic cage. A retrospective study by Solberg et al. describes 16 patients who experienced an implosion deformity of the chest wall from a high-energy side impact mechanism (19). Patients with anterior flail chest injuries and severe head trauma were excluded from this research. Nine patients were treated with surgical fixation while 7 patients were managed non-operatively. Surgical stabilization occurred within 48 hours after injury (mean of 18 hours) and was accomplished with 2.4mm titanium plates via a para-midline posterior approach. Patients undergoing surgical stabilization demonstrated significant benefits in terms of less total intubation time (1.9 vs. 13.3 days), less ICU length of stay (5.4 vs. 21 days), less chest tube duration (5.6 vs. 16.8 days). Of note, 5 patients (71%) in the non-operative group and 3 patients in the operative group (33%) had pulmonary contusions.

On Retreat After Thoracotomy

There are few cases of "on the way out" rib fracture repair to be found in the literature. The identified indications for the thoracotomy include retained hemothorax, intercostal artery hemorrhage, pulmonary laceration with persistent air leak and hemorrhage, pulmonary hematocele with hemoptysis, open pneumothorax, and diaphragm laceration (11,20). The Practice Management Guidelines established by the Eastern Association for the Surgery of Trauma supports surgical fixation "in severe unilateral flail chest or in patients requiring mechanical ventilation when thoracotomy is otherwise required" as a Level III recommendation (21). In a survey of trauma, orthopedic and thoracic surgeons, 18% of the participants agreed that "after thoracotomy for other trauma indications" would be an acceptable indication for rib fracture repair in selected patients (22).

Pulmonary Herniation

Pulmonary herniation is an uncommon occurrence in which the lung parenchyma and pleura membranes protrude through a weakness of the thoracic cage. They have been reported to occur secondary to a variety of causes such as blunt chest wall trauma, seatbelt use, CPR, chronic coughing, or post-operatively. However, due to their infrequency, their treatment with surgical fixation has yet to be assessed in a prospective randomized controlled trial. Nonetheless, it was selected by 58% of trauma, orthopedic and thoracic surgeons as an acceptable indication for rib fracture repair, thereby making it the most popular indication among the cohort of practitioners (22). Numerous techniques have been reported to surgically treat pulmonary herniations and include use of wire or absorbable suture to provide pericostal fixation of adjacent ribs and synthetic mesh or biologic tissue patches (23-25).

TECHNIQUES AND TECHNICAL CHALLENGES

The surgical fixation of fractured ribs poses unique challenges that require special consideration during operative treatment. In terms of unique physical characteristics, the rib has thin cortex spanning 1-2mm surrounding a core of soft marrow. As a result, it has limited potential to provide adequate purchase for cortical screws (26). As mentioned earlier, the intercostal neurovascular bundle runs along the inferior border of the rib posing a threat for impingement and chronic pain with the application of certain hardware. Nirula and Mayberry reviewed the complications of 704 surgically repaired rib fractures that have been reported in the literature since 1975. They reported 14 superficial wound infections (2%), four draining wounds, two pleural empyemas, one persistent pleural effusion, one wound hematoma, and one case of osteomyelitis secondary to a contaminated chest tube. Fixation failure due to hardware was noted in nine patients (1.3%) and removal of hardware due to patient discomfort was found in nine patients.

In a survey of 238 trauma surgeons, 97 orthopedic trauma surgeons and 70 thoracic surgeons roughly one-quarter (26%) reported that they had either assisted or were the primary surgeon on a rib fracture repair (22). Because there is a paucity of surgeons who are experienced with the surgical rib fracture repair, researchers have recommended a team approach consisting of trauma surgeons, orthopedic surgeons and thoracic surgeons when approaching this procedure (20,27). The use of three-dimensional computed tomography has also been suggested to further aid the pre-operative and intra-operative experience (18,20,27).

Metal Plates

Various types of hardware exist for the fixation of rib fractures. One technique is to secure metal plates to the anterior surface of the rib with wire cerclage (11). This method has been reported to be unsatisfactory due to wire breakage and the potential for nerve impingement (26). One described technique to avoid nerve impingement is to run the wire through holes drilled in the middle of the rib (7).

The Judet strut is metal plate with crimps along it edges designed to fasten to the superior and inferior borders of the rib. While it has reported success in the literature, it does not avoid the complication of impinging the intercostal nerve along the inferior border. The U-plate is designed to avoid damage to the neurovascular bundle by clamping onto the superior aspect of the rib only and secured with locking screws. A study by Sales et al. compared the stability of U-plates to anterior locking plates through a model using cadaveric ribs (26). They attempted to simulate the long-term mechanics of breathing in which surgically reconstructed ribs underwent two Newtons of force 50,000 times. The anterior locking plate lost a significant amount of stiffness (9.9%) whereas the U-plate did not demonstrate a loss of significant stiffness (1.9%) suggesting that U-plate fixation is more durable than anterior plate fixation.

The 3.5mm reconstruction plates have been commonly employed due to their frequent use in other orthopedic procedures. However, these plates require intra-operative contouring resulting in increased intra-operative time and technical skill. Additionally there are several reports in the literature of their mechanical failure resulting in screw pullout and loosening (8,28). Anatomic rib plates were introduced by Bottlang et al. based on the research of Mohr et. al who described the geometry of human ribs (29,30). By using pre-contoured rib plates, a surgeon can avoid the time and skill required to reshape standard plates which can be particularly valuable when reconstructing multiple ribs.

Absorbable Plates

The use of biodegradable polymer materials for the fixation of rib fractures has been shown to be safe and effective in preliminary trials (31-33). They are an attractive option for fracture fixation because they preclude the need for future removal and are compatible with magnetic resonance imaging. Furthermore they may result in faster and stronger bone healing by avoiding the stress-shielding occurring from metallic plates (34). Mayberry et al. reported ten cases of rib fixation for flail chest using absorbable plates with indications of failure to wean from a ventilator (5), acute pain with instability (4) and chest wall defect (1) (31). All flail chest patients were weaned at an average of nine days postoperatively. All patients with acute pain reported decreased pain and increased stability postoperatively. The one patient with the chest wall defect healed without complications and has returned to his preoperative level of physical activity. Two of the cases in which the absorbable plates were fixated using only absorbable screws resulted in partial loss of rib alignment that was noticeable only on chest radiograph. The researchers then used screw fixation combined with absorbable suture cerclage thereafter without any future complications. In a retrospective chart review, Mayberry et al. reported 3 out of 46 patients with fixation failure following rib fracture repair, all of whom had absorbable plates used as primary fixation posteriorly (11). Thereafter, the authors recommended using metal plates in conjunction with absorbable plates for posterior chest wall stabilization. High rates of fixation failure have been reported in preliminary studies when stabilizing posterior rib fractures with absorbable plates (31,32). Furthermore, adverse tissue reactions and sinus formations are reported complications in the use of bio absorbable materials for fracture fixation (35).

Intramedullary Fixation

Rib fixation with intra-medullary hardware generally requires less dissection compared to reconstruction with extra-medullary plates. Furthermore the intra-medullary nature of the appliance limits the potential for chronic iatrogenic injury or irritation of surrounding structures. Intra-medullary hardware is particularly useful for posterior rib fractures where adequate exposure for plate-fixation requires extensive dissection. The Kirschner wire is a type of intra-medullary implants that has fallen out of favor due to reports of its poor rotational stability and potential to migrate. The Rehbein plate was developed in 1972 which attempted to improve the rotational stability of the Kirschner wire design. This plate is rectangular rather than cylindrical and exposes one end extra-medullary to be sutured to the surface of the rib thereby preventing migration. Similar to the Rehbein plate, an intra-medullary pre-contoured rib splint has been recently introduced that uses a locking screw for fixation to the rib (36). Bottlang et al. evaluated the biomechanics of the pre-contoured intra medullary rib splint and determined that after 360,000 cycles of simulated heavy breathing, cadaveric ribs repaired with the Rehbein plate was 48% stronger (p=0.001) than K-wires (29).

REFERENCES

1. National Center for Health Statistics, National Hospital Ambulatory Medical Care Survery. http://wwwcdcgov/nchs.
2. Karmakar MK, Ho AM. Acute pain management of patients with multiple fractured ribs. J Trauma 2003;54:615-25.
3. Nirula R, Diaz JJ, Jr., Trunkey DD, Mayberry JC. Rib fracture repair: indications, technical issues, and future directions. World J Surg 2009;33:14-22.
4. Granetzny A, Abd El-Aal M, Emam E, Shalaby A, Boseila A. Surgical versus conservative treatment of flail chest. Evaluation of the pulmonary status. Interact Cardiovasc Thorac Surg 2005;4:583-7.
5. Tanaka H, Yukioka T, Yamaguti Y, et al. Surgical stabilization of internal pneumatic stabilization? A prospective randomized study of management of severe flail chest patients. J Trauma 2002;52:727-32; discussion 32.
6. Ahmed Z, Mohyuddin Z. Management of flail chest injury: internal fixation versus endotracheal intubation and ventilation. J Thorac Cardiovasc Surg 1995;110:1676-80.
7. Nirula R, Allen B, Layman R, Falimirski ME, Somberg LB. Rib fracture stabilization in patients sustaining blunt chest injury. Am Surg 2006;72:307-9.
8. Voggenreiter G, Neudeck F, Aufmkolk M, Obertacke U, Schmit-Neuerburg KP. Operative chest wall stabilization in flail chest--outcomes of patients with or without pulmonary contusion. J Am Coll Surg 1998;187:130-8.
9. Kishikawa M, Yoshioka T, Shimazu T, Sugimoto H, Sugimoto T. Pulmonary contusion causes long-term respiratory dysfunction with decreased functional residual capacity. J Trauma 1991;31:1203-8; discussion 8-10.
10. Lardinois D, Krueger T, Dusmet M, Ghisletta N, Gugger M, Ris HB. Pulmonary function testing after operative stabilisation of the chest wall for flail chest. Eur J Cardiothorac Surg 2001;20:496-501.
11. Mayberry JC, Kroeker AD, Ham LB, Mullins RJ, Trunkey DD. Long-term morbidity, pain, and disability after repair of severe chest wall injuries. Am Surg 2009;75:389-94.
12. Ware JE, Jr., Sherbourne CD. The MOS 36-item short-form health survey (SF-36). I. Conceptual framework and item selection. Med Care 1992;30:473-83.
13. McHorney CA, Ware JE, Jr., Raczek AE. The MOS 36-Item Short-Form Health Survey (SF-36): II. Psychometric and clinical tests of validity in measuring physical and mental health constructs. Med Care 1993;31:247-63.
14. McHorney CA, Ware JE, Jr., Lu JF, Sherbourne CD. The MOS 36-item Short-Form Health Survey (SF-36): III. Tests of data quality, scaling assumptions, and reliability across diverse patient groups. Med Care 1994;32:40-66.
15. Ng AB, Giannoudis PV, Bismil Q, Hinsche AF, Smith RM. Operative stabilisation of painful non-united multiple rib fractures. Injury 2001;32:637-9.
16. Cacchione RN, Richardson JD, Seligson D. Painful nonunion of multiple rib fractures managed by operative stabilization. J Trauma 2000;48:319-21.
17. Slater MS, Mayberry JC, Trunkey DD. Operative stabilization of a flail chest six years after injury. Ann Thorac Surg 2001;72:600-1.
18. Anavian J, Guthrie ST, Cole PA. Surgical management of multiple painful rib nonunions in patient with a history of severe shoulder girdle trauma: a case report and literature review. J Orthop Trauma 2009;23:600-4.
19. Solberg BD, Moon CN, Nissim AA, Wilson MT, Margulies DR. Treatment of chest wall implosion injuries without thoracotomy: technique and clinical outcomes. J Trauma 2009;67:8-13; discussion
20. Nirula R, Mayberry JC. Rib fracture fixation: controversies and technical challenges. Am Surg;76:793-802.
21. Simon B EJ, Bokhari F, Capella J, Emhoff T, Hayward T, Rodriguez A, Smith L. Practice Management Guideline for "Pulmonary Contusion- Flail Chest". EAST Practice Management Workgroup for Pulmonary Contusion - Flail Chest 2006.

22. Mayberry JC, Ham LB, Schipper PH, Ellis TJ, Mullins RJ. Surveyed opinion of American trauma, orthopedic, and thoracic surgeons on rib and sternal fracture repair. J Trauma 2009;66:875-9.
23. Fackeldey V, Junge K, Hinck D, et al. Repair of intercostal pulmonary herniation. Hernia 2003;7:215-7.
24. Francois B, Desachy A, Cornu E, Ostyn E, Niquet L, Vignon P. Traumatic pulmonary hernia: surgical versus conservative management. J Trauma 1998;44:217-9.
25. Khalil MW, Masala N, Waller DA, Cardillo G. Surgical repair of post-traumatic lung hernia using a video-assisted open technique. Interact Cardiovasc Thorac Surg 2008;7:506-7.
26. Sales JR, Ellis TJ, Gillard J, et al. Biomechanical testing of a novel, minimally invasive rib fracture plating system. J Trauma 2008;64:1270-4.
27. Richardson JD, Franklin GA, Heffley S, Seligson D. Operative fixation of chest wall fractures: an underused procedure? Am Surg 2007;73:591-6; discussion 6-7.
28. Mouton W, Lardinois D, Furrer M, Regli B, Ris HB. Long-term follow-up of patients with operative stabilisation of a flail chest. Thorac Cardiovasc Surg 1997;45:242-4.
29. Bottlang M, Helzel I, Long WB, Madey S. Anatomically contoured plates for fixation of rib fractures. J Trauma;68:611-5.
30. Mohr M, Abrams E, Engel C, Long WB, Bottlang M. Geometry of human ribs pertinent to orthopedic chest-wall reconstruction. J Biomech 2007;40:1310-7.
31. Mayberry JC, Terhes JT, Ellis TJ, Wanek S, Mullins RJ. Absorbable plates for rib fracture repair: preliminary experience. J Trauma 2003;55:835-9.
32. Marasco SF, Sutalo ID, Bui AV. Mode of failure of rib fixation with absorbable plates: a clinical and numerical modeling study. J Trauma;68:1225-33.
33. Campbell N, Conaglen P, Martin K, Antippa P. Surgical stabilization of rib fractures using Inion OTPS wraps--techniques and quality of life follow-up. J Trauma 2009;67:596-601.
34. Viljanen J, Pihlajamaki H, Kinnunen J, Bondestam S, Rokkanen P. Comparison of absorbable poly-L-lactide and metallic intramedullary rods in the fixation of femoral shaft osteotomies: an experimental study in rabbits. J Orthop Sci 2001;6:160-6.
35. Bostman OM, Pihlajamaki HK. Adverse tissue reactions to bioabsorbable fixation devices. Clin Orthop Relat Res 2000:216-27.
36. Helzel I, Long W, Fitzpatrick D, Madey S, Bottlang M. Evaluation of intramedullary rib splints for less-invasive stabilisation of rib fractures. Injury 2009;40:1104-10.

Surgical Critical Care Evidence-Based Medicine Guidelines Committee

Primary Author: Matthew W. Lube, MD
Editor: Michael L. Cheatham, MD
Last revision date: February 6, 2013

Please direct any questions or concerns to: webmaster@surgicalcriticalcare.net