Michael D. McKee
Emil H. Schemitsch *Editors*

Injuries to the Chest Wall

Diagnosis and Management

Springer

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This book is dedicated to my parents David and Nancy for their teaching, my partner Niloofar for her support, and my children Sacha, Tyler, Robbin, and Everett for enriching my life every day.

Michael D. McKee

This book is dedicated to my parents, Emil and Emma Schemitsch, who showed me the importance of books and learning, and to my wife Maureen Schemitsch and our four wonderful children, Laura, Geoffrey, Christine, and Thomas, who support and inspire me.

Emil H. Schemitsch

Foreword

Injuries to the thorax are common and are responsible for up to 25 % of all trauma deaths in North America. However, chest wall injuries are often neglected when considering thoracic injuries. Homer's *Iliad* is one of the classic works in Western literature and tells the story of the events related to the siege and battle of Troy. In his lurid description of hand-to-hand combat between the Achaeans and the Trojans, Homer documents 54 thoracic injuries in 53 separate warriors. However, rib fractures and chest wall injuries were not listed amongst the plethora of thoracic injuries sustained.

Chest wall injuries remain a significant cause of pain, long-term morbidity and mortality after injury. This type of injury can vary in severity from isolated rib fractures to severe, bilateral crush injuries leading to respiratory failure. The history of the medical treatment for these injuries mimics the movement of a pendulum. The Edwin Smith Papyrus is an Ancient Egyptian medical text written almost 4,000 years ago and is the oldest known trauma and surgical textbook. This document describes 48 cases of injuries and tumours. One case describes a patient with rib fractures, where the fragments were displaced enough to rupture the overlying skin. The treating physician initiated the trend of non-operative management of rib fractures by stating that this type of injury is generally not treated.

This paradigm has changed several times during the twentieth century. In a classic paper published in 1949, Cameron and colleagues wrote that:

> paradoxical respiration due to flail chest demands rib immobilization …. We use a single-pointed cervical tenaculum. This instrument has proven most satisfactory in the common type in which the sternum is the mobile fragment. The instrument can be easily introduced into intercostal spaces and a good grip on the sternum obtained … the excursions are [then] materially lessened.

However, since the advent of "internal pneumatic stabilization" in the mid 1950s, the pendulum has swung back to the non-operative management of chest wall trauma. Nevertheless, this treatment modality remains associated with significant morbidity and mortality. Approximately 30 % of patients with rib fractures develop pneumonia. Furthermore, trauma patients with more than four rib fractures have a mortality rate of approximately 10 %, and this increases to over 30 % in patients with eight or more fractures.

These facts and figures give great emphasis to the need for a textbook of this kind. There is renewed interest in chest wall fixation that has been fuelled both by the availability of new, specialized fixation equipment and by the publication of numerous promising clinical results. Thoracic trauma textbooks focus on treating cardiac and pulmonary injuries. For all surgeons, indeed, for all physicians who treat trauma patients, this definitive textbook provides an excellent learning manual as well as a reference source for current knowledge in the management of chest wall trauma.

Toronto, ON Homer Tien, MD

Preface

The treatment of severe injuries to the chest wall has traditionally been nonoperative, with a focus on ventilatory support, pain control, and complication management. However, it is clear from the literature that, despite optimal nonoperative care, patients who sustain unstable chest wall injuries continue to experience significant morbidity and mortality. This fact, in addition to the development of superior surgical implants and techniques and the positive early clinical experience of select centers with surgical intervention for chest wall stabilization, has led to a renewed interest in this topic. While the literature is still suboptimal in this area, dominated by retrospective reviews and relatively small prospective studies, it is becoming apparent that there is probably a subset of trauma patients who benefit from early surgical stabilization of a mechanically unstable chest wall.

However, there is a paucity of information regarding appropriate imaging, patient selection, surgical approach, implant choice, and complication rates/management regarding surgical fixation. Additionally, the clinical scene is complicated by the fact that this area is of interest to a number of different surgical specialties including orthopedic surgeons who have extensive experience in fixation but who rarely operate around the thorax and thoracic/trauma surgeons who have extensive operative experience in the thorax but may not be facile with the principles and techniques of fixation. Add into this mix the integral role of the attending intensivist, and it is easy to understand the complexity of this issue.

This book is designed to help optimize the treatment of the patient with a severe chest wall injury. With chapters written by intensivists, basic scientists, thoracic/trauma surgeons, and orthopedic surgeons from multiple leading academic institutions, it emphasizes the multidisciplinary approach necessary in this area. Readers of this book will also benefit from the concise, focused chapters and the multiple well-illustrated practical case examples. Whether it is to confirm established knowledge or to understand principles from clinical areas outside their typical realm of practice, we hope this book, to our knowledge the first of its kind dedicated to chest wall injuries, will be an invaluable resource for practicing clinicians.

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1

Introduction, Epidemiology, and Definition of Chest Wall Injuries

Michael D. McKee

Definition

As with any other traumatic condition involving the human body, there is a wide spectrum of injury that can afflict the chest wall. There can be injuries as minor as an isolated, undisplaced rib fracture to as severe as a complete destabilization of the chest wall with multiple displaced fractures of the ribs and sternum [1–3]. It is this latter type of injury that is the focus of this book, and it is important for the reader to apply the recommendations and information provided on this topic to the patient group that it is intended for. This chapter deals specifically with patients who have had severe trauma delivered to the ribs, sternum, or both, such that the chest wall is mechanically unstable and pathological deformity occurs and interferes with the physiologic process of respiratory function and gas exchange. The magnitude of injury required to produce this degree of injury is demonstrated in Fig. 1.1, a photograph taken by a first responder to an accident scene. The patient involved was crushed in the wheel well of a large transport truck and sustained multiple traumatic injuries, including a flail chest. In a study by Dehghan et al. that examined data from the National Trauma Databank (described in detail in Chap. 4), patients identified as having a flail chest injury had a mean Injury Severity Score (ISS) of 31, and all had associated injuries [4]. This ISS value is almost twice the generally defined value of a polytrauma patient (ISS of 16), which demonstrates the severity of injury sustained by these patients. It is to this severely injured population that the information contained in this book applies.

The term “flail chest” has typically been used to describe a biomechanically unstable chest wall following a traumatic injury. This results in a pathological degree of instability such that normal respiratory mechanics are interfered with: paradoxical respiration is often the result. This occurs during normal inspiratory effort, when, as a negative intrathoracic pressure is produced, the unstable chest wall collapses or caves in, rather than expands (Fig. 1.2). This compromises respiratory function and gas exchange. There is no generally accepted standard definition of a flail chest: it ranges from a minimum of two segmental fractures of adjacent ribs to as many as four segmental fractures of adjacent ribs [5–7]. For the purposes of defining this injury for research, clinical trials, and other studies, we have used the following definition of flail chest:

- ≥3 unilateral segmental rib fractures
- ≥3 bilateral rib fractures
- ≥3 unilateral fractures combined with sternum fracture/dissociation

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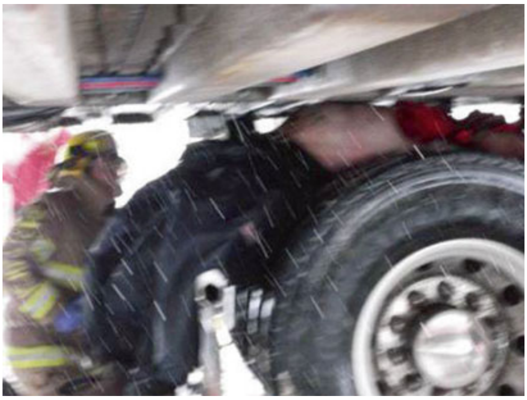

Fig. 1.1 Chest wall injuries with multiple rib fractures and a flail segment are typically the result of severe, crushing-type injuries. This worker was crushed in the wheel well of a large transport truck and sustained multiple injuries including a flail chest, multiple extremity fractures, and a severe, degloving arm injury that resulted in below-elbow amputation (Photograph provided by, and used with permission of, the patient)

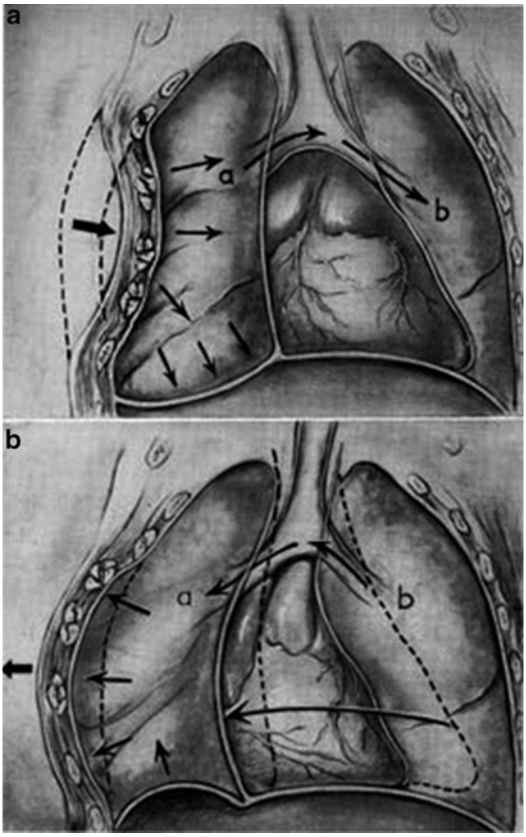

Fig. 1.2 An illustration of paradoxical respiration, which can occur as a result of chest wall instability: this is a common complication of a flail chest injury

Note: At least three of the rib fractures involved in the flail segment must demonstrate displacement.

It is very difficult to break a bony ring (such as the pelvic ring or the rib cage) at only one spot; therefore, most fractures of a circular bony structure tend to occur at two sites. This is also the case for rib fractures. Although a number of different fracture patterns can be seen, typically, one fracture site is displaced and the rib "hinges" or deforms without translational displacement at the other site. This is important clinically, as often only the displaced fracture site needs to be reduced and stabilized: this corrects the angular deformity at the "hinge" site, which is intrinsically stable. This is discussed further in Chaps. 6 and 9 and is a principle by which unnecessary dissection can be avoided. Of course, if both fractures are displaced and unstable, they must both be stabilized [8]. The sternum may represent a separate site of injury and produces the same biomechanical effect as a displaced rib fracture. Fortunately, there is abundant experience with sternal fixation in the cardiac surgery realm, and specialized plates and instruments are available. Additionally, a number of other patterns can have a similar negative clinical effect as a standard flail chest and may represent operative indications, including:

- Severe (100 %) displacement of three or more ribs
- Marked loss thoracic volume/caved in chest (>25 % volume loss in involved lobe(s))
- Overriding of three or more rib fractures (by minimum 15 mm each)
- Three or more rib fractures associated with intraparenchymal injury—i.e., fractured rib embedded in the lung parenchyma

The traumatic force delivered to the chest wall in an injury of this nature typically produces instability and deformity, which has both short-term and long-term consequences for the patient [9–11]. This deformity can be static or fixed, as demonstrated in the computerized tomography (CT) scan depicted in Fig. 1.3, with severe, fixed loss of chest wall contour, loss of thoracic cage volume, and subsequent interference with respiratory function.

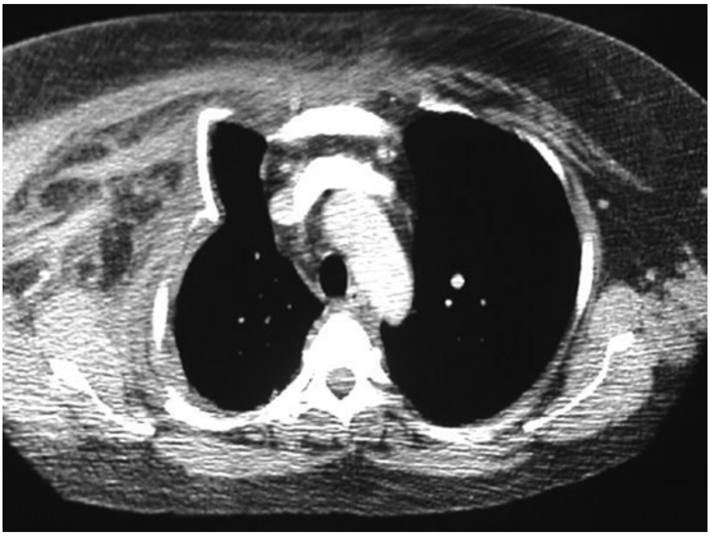

Fig. 1.3 A CT scan of a polytrauma patient with a severe right-sided chest injury, a flail segment, significant intrusion of the chest wall, and subsequent severe compromise of the thoracic cavity and respiratory function. This patient represents, with the current level of knowledge regarding these injuries, an ideal opportunity for surgical intervention. Reduction of deformity and stabilization in the reduced position has a number of theoretical and practical advantages

It must be remembered that the chest wall and rib cage are in constant motion during the ventilatory process, and associated deformity or instability can be dynamic in nature. In some cases, when static deformity may not be severe, the primary manifestation of chest wall instability can be incapacitating pain for the patient. In this situation, it may be difficult or impossible to wean a patient from mechanical ventilation. Mechanical instability of the chest wall can result in severe pain, the requirement for heavy sedation and analgesia, resultant respiratory depression, poor respiratory toilet, and a progressive downward spiral of prolonged mechanical ventilation and the potential complications therein. An example is demonstrated in Fig. 1.4, depicting a young patient with severe chest wall pain following a left-sided chest wall injury. Reduction and fixation of the patient's rib fractures resulted in an immediate decrease in narcotic medication requirement and rapid weaning and extubation. There is increasing evidence that this type of early primary fixation of multiple rib fractures may be superior to nonoperative treatment [12–15].

Associated Injuries

Most patients with a traumatic flail chest will have associated injuries, and these can be life threatening. While these injuries are discussed in detail in Chap. 10 (associated intrathoracic injuries) and Chap. 15 (associated fractures), it is important to emphasize that the presence of a flail chest should immediately prompt the initiation of the Advanced Trauma Life Support (ATLS) guidelines in the care of the patient. Associated injuries in this setting can be immediately fatal if not promptly treated. The flail chest patient depicted in Fig. 1.5 had sustained severe right-sided thoracic trauma with multiple segmental fractures of ribs 4 through 9, a tension pneumothorax, and rapid clinical deterioration. Rapid insertion of a chest tube resulted in decompression of the chest cavity and immediate clinical improvement: this case demonstrates the importance of detecting and treating other severe injuries prior to focusing on rib or sternal fractures. Additionally, injuries to the lung parenchyma or

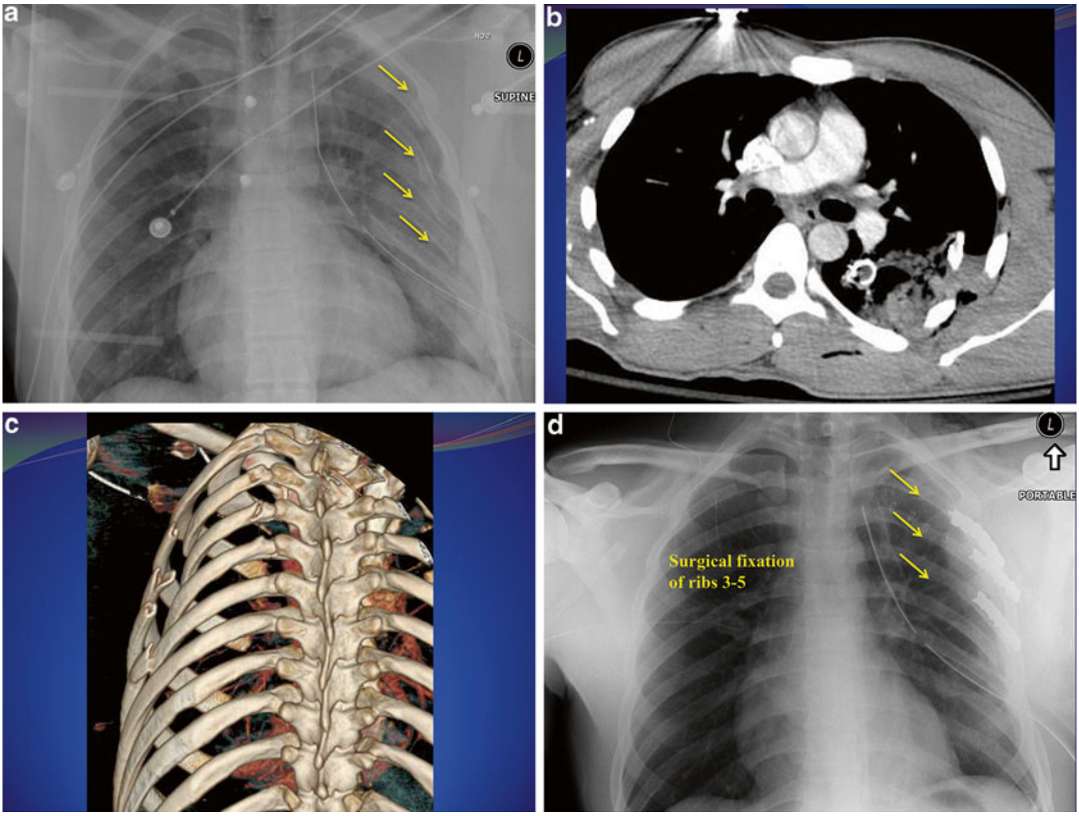

Fig. 1.4 (**a**) A 27-year-old man was accidentally crushed in a garbage compactor. This resulted in multiple, segmental left-sided rib fractures (ribs 3, 4, 5, 6) as seen on the initial trauma-room chest radiograph (*yellow arrows*). The patient had intractable pain, subsequently developed respiratory failure, and required prolonged intubation. (**b**) A CT scan demonstrated significant displacement of the rib fractures with intraparenchymal penetration of the fractured rib into the ipsilateral lung. (**c**) Three-dimensional reconstruction of the CT scan provides excellent representations of the nature and location of the fractures that can aid significantly in preoperative planning regarding surgical approach and tactics. This has become an integral part of the preoperative imaging of flail chest injuries. (**d**) A left thoracotomy, extrication of the ribs from the lung, rib fracture reduction, and fixation with 3.5 mm (unlocked) pelvic reconstruction plates were performed (*yellow arrows*). It is not always necessary to repair every rib fracture in a flail chest: the surgical goal is to stabilize the flail segment sufficiently to restore chest respiratory function without pathological deformation. The patient had immediate clinical improvement, a dramatic decrease in analgesic requirements, and was rapidly extubated

other intrathoracic structures are common and may dictate treatment initially (see Chap. 10).

Patients with severe thoracic trauma also have a high incidence of vascular injuries to the great vessels. While undoubtedly many of these patients will exsanguinate prior to their presentation from uncontrolled hemorrhage, those who do survive are often in critical condition with vascular damage that is held tenuously by adventitial tissue. The treating surgeon must have a high index of suspicion for vascular injuries of this nature, as the findings from standard imaging studies may be quite subtle. A proper diagnosis will aid in primary treatment of the vascular injury and will also influence the timing and nature of the associated chest wall injury. Associated fractures of the sternum (which can contribute to a flail chest pattern of injury) are often seen with aortic injuries (Fig. 1.6).

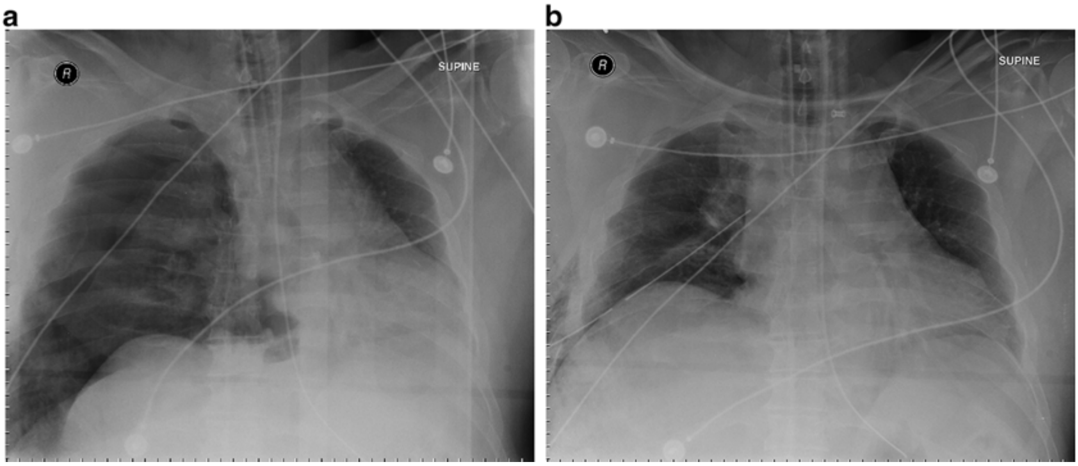

Fig. 1.5 (**a**) Initial chest radiograph of a polytrauma patient who was "T-boned" in a motor vehicle collision and sustained severe right chest wall trauma with multiple segmental fractures of ribs 4 through 9. The patient was intubated in the prehospital setting for respiratory compromise and, upon arrival to the trauma bay, rapidly deteriorated from a cardiovascular standpoint. The chest radiograph taken immediately upon arrival as part of the trauma protocol demonstrated a tension pneumothorax with severe deviation of the mediastinal structures and trachea. It could be argued that a chest radiograph of this nature should never be seen: the dire clinical situation combined with the physical examination of the chest would warrant immediate chest decompression with needle insertion or right-sided tube thoracostomy. (**b**) Following needle decompression, a large-bore chest tube was inserted with immediate improvement in cardiovascular parameters. This case demonstrates the importance of careful assessment of a flail chest patient for associated (potentially life-threatening) injuries

Associated Fractures

Fractures of the clavicle, scapula, and humerus are commonly seen in patients with flail chest injury, and their specific treatment is discussed in Chap. 15. While the fixation of displaced clavicle fractures has become more common as a result of multiple randomized clinical trials that demonstrate earlier return to function, improved shoulder scores, and decreased rates of complications such as nonunion or symptomatic malunion, similar studies on fractures of the scapula and ribs are not available at present [15, 16]. However, it is important to remember that these fractures should not be treated in isolation, but rather as an overall pattern of injury, as they will have some influence on each other (Fig. 1.7). It may be that while a particular fracture of the clavicle may not, in of itself, be of sufficient severity or displacement to warrant fixation, the associated rib/scapular fractures may represent instability or deformity that shifts the risk/benefit ratio of surgical decision making toward surgery. Additionally, given the difficulty in the secondary reconstruction of rib fractures (i.e., for nonunion or symptomatic malunion), primary repair may be a more attractive option (Fig. 1.8).

Epidemiology

The National Trauma Databank collects data from approximately 200 trauma centers in North America. A recent study utilizing this database identified 3,500 patients who met predetermined criteria for a flail chest injury, over a 3-year period [4]. Recognizing that, for a variety of reasons, a number of patients who sustain this injury are not "captured," this suggests that there are over 1,200 patients per year in North America who sustain this injury. Most (59 %) will require mechanical ventilation, and those who do are ventilated for a mean of 12 days.

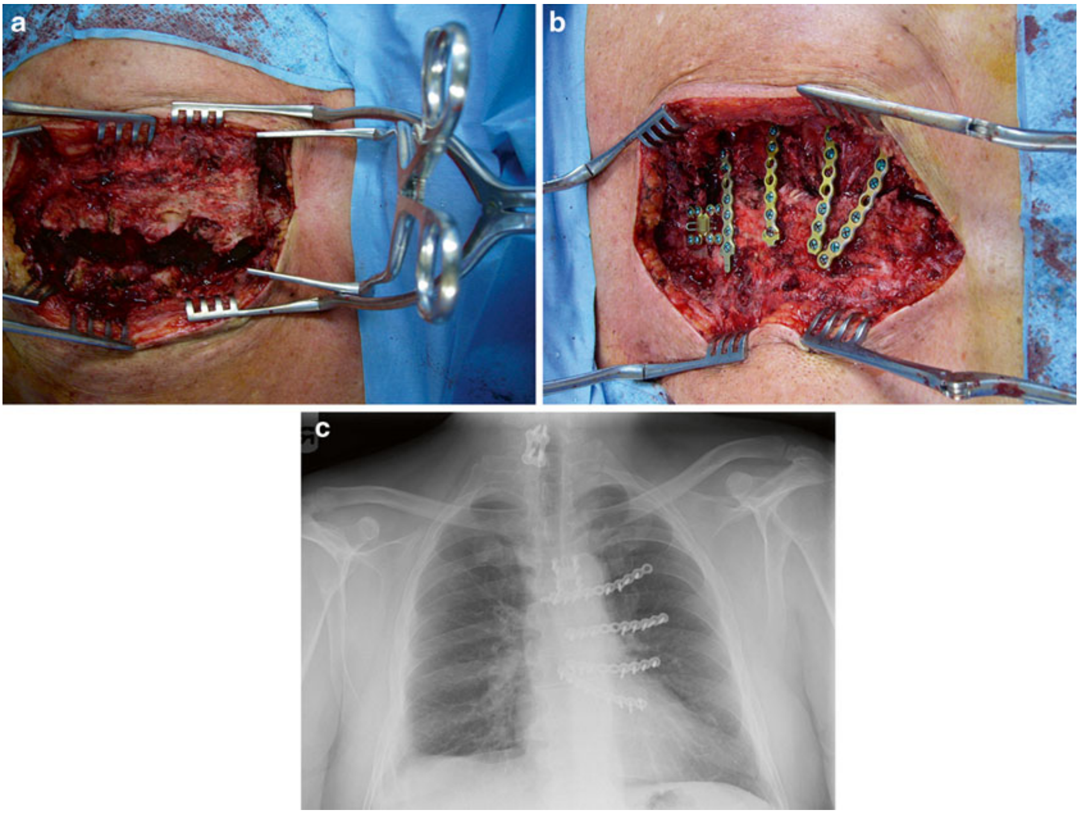

Fig. 1.6 (**a**) Intraoperative photograph of a 56-year-old male driver who was involved in a high-speed motor vehicle collision in which his car rapidly decelerated and the steering column impacted into his chest. This resulted in a completely displaced and unstable injury between the ribs and the sternum (costosternal dissociation), shown in the photograph with severe pain and respiratory compromise. (**b**) Fixation was performed with a plate set specifically designed for sternal repair in cardiac surgery. (**c**) The surgery was successful, the patient rapidly extubated, and the clinical recovery uneventful (the patient also had an unstable cervical spine injury that required fixation)

Surprisingly, despite the severity of these injuries (ICU stay was required in 82 %) and the increasing interest in surgical stabilization, proactive surgical intervention was rare and less than 1 % of patients had primary fixation of their chest wall fractures. Thus, at the present time in North America, nonoperative, supportive treatment must be considered the standard of care against which other treatment methods (i.e., primary open reduction and internal fixation (ORIF)) must be compared. Additionally, although epidural catheters have been demonstrated to be an effective mode of pain management for these injuries, only 8 % of patients had a catheter placed. These figures, combined with the significant residual disability experienced by these patients, would suggest that there is room for improvement in the management of these critically injured patients [17].

Conclusion

It is clear that the operative treatment of mechanically unstable injuries to the thorax and flail chest injuries has probably been underutilized in the past. These injuries are commonly seen in Level One trauma centers both worldwide and in North America and represent a significant source of correctable residual morbidity and mortality, since, with the latest available data, the vast majority are treated nonoperatively, and

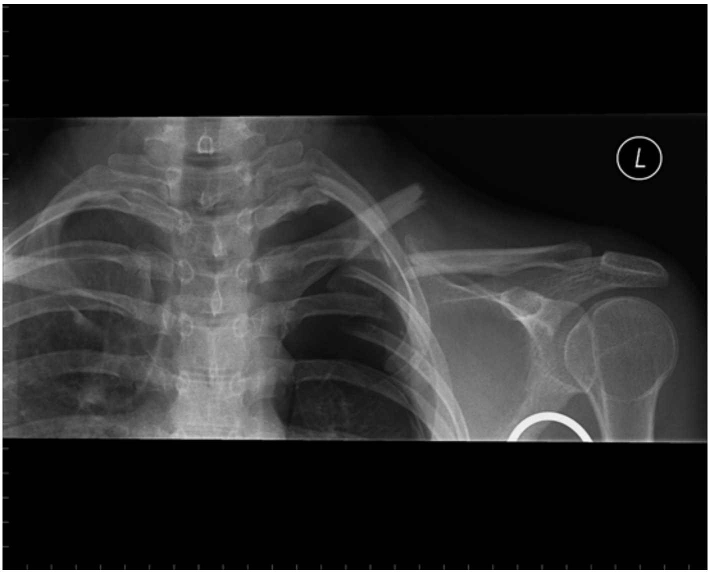

Fig. 1.7 Radiograph of a young trauma patient with a displaced mid-shaft fracture of the clavicle and multiple displaced ipsilateral upper rib fractures. An associated pneumothorax emphasizes the severity of the injury: this pattern represents a severe destabilization of the entire forequarter and represents, at present, a relative indication to surgically repair the clavicle fracture. As our experience increases and more clinical information becomes available, it is probable that indications for fixation in this situation will extend to the associated rib fractures

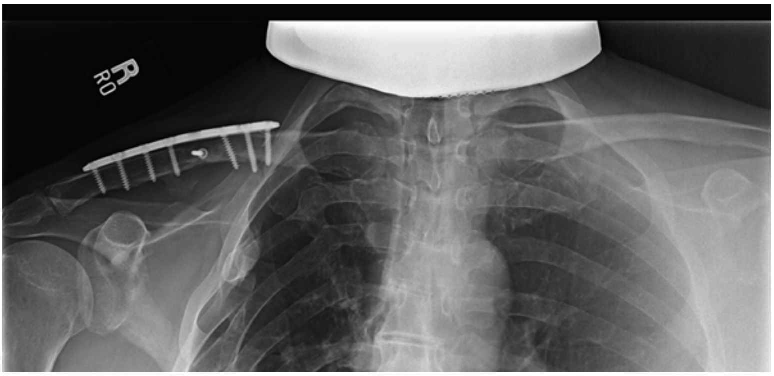

Fig. 1.8 Chest radiograph of a 58-year-old male who sustained multiple injuries to the right chest wall in a hunting accident. The clavicle and multiple rib fractures were treated nonoperatively, and recovery was prolonged with an extended ICU stay. Two years post-injury, clinical function was significantly compromised by malunion of both the clavicle fracture and the multiple rib fractures resulting in significant residual deformity, weakness, and pain. Osteotomy, reduction of deformity, and fixation of the clavicular malunion improved shoulder function, but the patient still had significant chest wall pain, deformity, and respiratory compromise. Established rib malunion or nonunion represents a challenging problem with little published data or clinical experience to guide surgical treatment: prevention (through primary fixation of displaced rib fractures) may be preferable in certain situations

results are far from ideal. There is some evidence that primary operative repair of flail chest injuries may have significant benefits in terms of decreased time of mechanical ventilation, decreased ICU stay, decreased rate of tracheostomy, and better long-term function. The following chapters will, using expert opinion from leaders in the field and the most up-to-date literature available, consist of an in-depth evaluation of every aspect in the identification and management of trauma patients with flail chest injuries.

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The devices that are the subject of this manuscript are FDA approved.

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2

A Review of the Modern Literature

Gerard P. Slobogean and David J. Stockton

Introduction

The treatment algorithm for severe chest wall injury is evolving. The high rates of short-term mortality and long-term morbidity have compelled a recent resurgence of interest in operative fixation of the multiple-rib-fractured patient. Operative intervention appears to be beneficial for patients with flail chest injuries, but many other indications for surgical fixation remain untested or hampered by limited evidence (Table 2.1).

For the purposes of this review, "modern" literature refers to academic work published after 1995, as prior to that point the literature consists only of uncontrolled case series [1]. Since then, operative fixation of severe chest wall injuries has been tested for various indications including flail chest, intractable rib fracture pain, chest wall deformity, symptomatic nonunion, thoracotomy for other indications, and open fractures. The most robust evidence exists for flail chest injuries and will be the focus of this chapter.

Historical Perspective

Interest in fixation or bracing of an unstable chest wall existed long before the advent of mechanical ventilation. Jones and Richardson described a percutaneous technique where traction was applied to the fractured ribs [2]. Cohen described traction of the flail segment using percutaneous towel clips [3]. An even more enterprising device, the "Cape Town Limpet," a sink plunger type of device was reported by Schrire in 1962 [4]. Significant complications from these external traction devices resulted from the prolonged bed rest required [5].

Several reports describing internal fixation of rib fractures were published in the 1950s and 1960s. Wire sutures and rush rod fixation were suggested [6, 7], but neither gained traction in clinical practice.

In the late 1950s, clinical practice was greatly affected following the introduction of positive-pressure ventilation to internally splint the unstable chest wall [8]. Mortality from flail chest was initially lowered, leading to widespread adoption of this intervention for the next two decades; however, ventilator-associated complications arose such as

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Table 2.1 Comparative and randomized studies examining the effect of operative fixation for patients with flail chest injury

Author	Year of publication	Location	Implant	Study design	N: op; nonop patients	Timing of operation	Outcome	Findings (op vs. nonop)
Ahmed and Mohyuddin	1995	United Arab Emirates	K-wire	Retrospective cohort	26; 38	12–24 h after ICU admission	• Mortality • Ventilator days • ICU days • Pneumonia • Septicemia • Tracheostomy	8 % vs. 29 % 3.9d vs. 15d 9d vs. 21d 15 % vs. 50 % 4 % vs. 24 % 11 % vs. 37 %
Granetzny et al.	2005	Egypt	K-wire, stainless steel wire, or both	RCT	20; 20	24–36 h after ICU admission	• Mortality • Ventilator days • ICU days • Hospital days • Pneumonia • Chest wall deformity	10 % vs. 15 % 2d vs. 12d* 9.6d vs. 14.6d* 11.7d vs. 23.1d* 10 % vs. 50 %* 5 % vs. 45 %*
Karev	1997	Ukraine	Unspecified	Retrospective cohort	40; 93	Within 24 h of admission	• Mortality • Ventilator days • Pneumonia	23 % vs. 46 % 2d vs. 6d 15 % vs. 34 %
Voggenreiter et al.	1998	Germany	Isoelastic rib clamps	Retrospective cohort	20; 22	Not specified	• Mortality • Ventilator days • Pneumonia	15 % vs. 36 % 6.5 ± 7.0d (without PC) and 30.8 ± 33.7d (with PC) vs. 26.7 ± 29.0d (without PC) and 29.3 ± 22.5d (with PC) 25 % vs. 32 %
Tanaka et al.	2002	Japan	Judet struts	RCT	18; 19	8.2 ± 4.1d after admission	• Ventilator days • ICU days • Pneumonia • Tracheostomy	10.8 ± 3.4d vs. 18.3 ± 7.4d* 16.5 ± 7.4d vs. 26.8 ± 13.2d* 22 % vs. 90 %* 17 % vs. 79 %
Balci et al.	2004	Turkey	Silk sutures and traction	Retrospective cohort	27; 37	Within 48 h of admission (all except 2)	• Mortality • Ventilator days • Hospital days	11.1 % vs. 27.0 % 3.1d vs. 7.2d 18.3d vs. 19.6d

Nirula et al.	2006	USA	Adkin struts	Case control	30; 30	Mean 3d after admission	• Ventilator days • ICU days • Hospital days	6.5 ± 1.3d vs. 11.2 ± 2.6d 12.1 ± 1.2d vs. 14.1 ± 2.7d 18.8 ± 1.8d vs. 21.1 ± 3.9
Teng et al.	2008	China	Absorbable nail, suture, or titanium plate	Retrospective cohort	32; 28	Not specified	• Ventilator days • ICU days • Hospital days • Pneumonia • Chest wall deformity	14d vs. 20d* 8.7d vs. 15.2d* 17.1d vs. 22.4d* 12 % vs. 42 %* 0 % vs. 64 %*
Althausen et al.	2011	USA	2.7 mm locking plate	Retrospective cohort	22; 28	Mean 2.3d after admission	• Ventilator days • ICU days • Hospital days • Pneumonia • Tracheostomy	4.1d vs. 9.7d* 7.6d vs. 9.7d* 11.9d vs. 19.0d* 5 % vs. 25 %* 5 % vs. 39 %*
de Moya et al.	2011	USA	Small or mini-fragment titanium or steel plates	Case control	16; 32	Mean 5d after injury	• Ventilator days • ICU days • Hospital days • Pneumonia • Morphine dose	7 ± 8d vs. 6 ± 10d 9 ± 8d vs. 7 ± 10d 18 ± 12d vs. 16 ± 11d 31 % vs. 38 % 79 ± 63 mg vs. 76 ± 55 mg
Marasco et al.	2013	Australia	Inion resorbable 6- or 8-hole plates	RCT	23; 23	Mean 4.6d after ICU admission	• Mortality • ICU days • Hospital days • Pneumonia • Tracheostomy	0 % vs. 5 % 13.5d vs. 18.7d* 20d vs. 25d 48 % vs. 74 % 39 % vs. 70 %*

*Statistically significant $p < 0.05$

ICU intensive care unit, *PC* pulmonary contusion, *RCT* randomized controlled trial barotrauma, ventilator-associated pneumonia, and tracheal injury were often encountered [9].

As the understanding of the pathophysiology of severe chest wall injury matured, researchers proposed that concomitant pulmonary contusion, not the paradoxical motion of the flail segment, was primarily responsible for the morbidity and mortality associated with such injuries [10]. Two prospective randomized studies guided clinicians to use selective mechanical ventilation techniques based on failure to maintain oxygenation, ventilation, and pulmonary hygiene [11, 12]. Research focus shifted to focus on the underlying pulmonary contusion.

Few investigators continued to study operative rib fixation in severe chest injury, and none used prospective or randomized methodology. However, severe chest wall injuries continued to carry relatively high morbidity and mortality, despite the improvements conferred by selective mechanical ventilation. In the last 20 years, several comparative studies and a few randomized trials have suggested that significant further improvements can be made in the care of these patients with operative rib fixation. This has become a much more viable treatment option given newly available, rib-specific fixation products such as DePuy/Synthes'® MatrixRIB™ System.

Comparative Studies

Three studies were conducted prior to 1995 and will be mentioned briefly as they were included in recent meta-analyses. In 1972, Ohresser et al. [13] retrospectively reported significant improvements in dyspnea at 1 year after severe closed chest injury for patients treated with operative osteosynthesis (implant not described) when compared to the nonoperative group. In 1981, Kim et al. [14] retrospectively compared 18 patients with flail chest treated with Judet clasps to 45 patients with flail chest treated with mechanical ventilation alone. The operative group had fewer deaths and fewer ventilator days. In 1985, Borrelly et al. [15] retrospectively compared 79 patients treated with osteosynthesis using Judet clasps or sliding staples to 97 patients treated with ventilation alone for chest instability. The operative group had a significantly lower incidence of sepsis and spent fewer hospital days. All three studies used variable definitions of "flail chest," "severe chest injury," and "chest instability," and all were conducted in France.

In the modern literature, two studies have investigated wire fixation for flail chest injury. In 1995, Ahmed and Mohyuddin [16] compared 26 flail chest patients treated with K-wire internal fixation to 38 patients treated with endotracheal intubation and intermittent positive-pressure ventilation alone. Significant improvements noted in the operative group included fewer days on mechanical ventilation, fewer ICU days, fewer cases of chest infection and sepsis, fewer tracheostomies, and lower overall mortality rate. The second trial investigating wire fixation was randomized and controlled and will be discussed later in this chapter.

In 1997, a Ukrainian study by Karev [17] compared 40 patients with flail chest treated operatively to 93 patients treated nonoperatively. A variety of unspecified extramedullary osteosynthesis implants were used, typically at the end of other emergency surgical procedures. This indication is otherwise referred to as "thoracotomy for other indications" and essentially means that rib fixation was performed "on the way out." Operatively managed patients had fewer days on mechanical ventilation, a lower incidence of pneumonia, and a decreased incidence of mortality.

Voggenreiter et al. [18] tested isoelastic rib clamps and pelvic reconstruction plates in one of the more comprehensive retrospective studies of the 1990s. Forty-two patients were analyzed in a two-by-two matrix based on the presence or absence of pulmonary contusion and whether they received operative chest wall fixation or nonoperative management. Specific indications included flail chest with thoracotomy for other indications, flail chest without pulmonary contusion, paradoxical chest wall motion on weaning from ventilator, and severe chest wall deformity. While the pulmonary contusion distinction is important, their analysis resulted in small groups for comparison and was therefore biased toward the null hypothesis of no treatment effect. Independent pooled post-hoc analysis revealed significant improvements in ventilator days, pneumonia, and septicemia for the operative group compared to the nonoperative group [19].

Silk suture was the fixation method used in a study by Balci et al. published in 2004 [20]. Surgery was indicated when clinical dyspnea and blood gas measurements of $PaO_2 < 60$ mmHg and $PaCO_2 > 40$ mmHg were present in flail-chest patients. The authors concluded that operative intervention conferred benefit to patients through reduction in mortality, pneumonia, and days on mechanical ventilation.

In one of the few existing North American studies, Nirula et al. [21] tested the Adkins strut implant on flail-chest patients. This case-historical control study selected patients for operative treatment based on ventilator compromise, thoracic deformity, hypoxemia, and refractory pain. Nonsignificant trends were observed toward decreased ICU days, hospital days, and ventilator days.

The first Chinese study was published in 2008 by Teng et al. [22]. A range of implants were used including absorbable nails, sutures, and titanium plates for the surgical indications of bilateral flail chest, persistent respiratory dysfunction, persistent pain, or thoracotomy for other indications. Significant decreases were observed in the operative group for ventilator days, ICU days, hospital days, incidence of pneumonia, and chest wall deformity.

In the most relevant comparative study using modern fixation implants, Althausen et al. [23] compared 22 flail-chest patients that received locked plate fixation with a matched cohort of 28 nonoperatively managed patients. Operatively treated patients had shorter ICU stays, less ventilator days, less hospital days, fewer tracheostomies, less pneumonia, less reintubation, and decreased home oxygen requirements. Importantly, no cases of hardware failure, hardware prominence, wound infection, or nonunion were reported. In the same year, 2011, de Moya et al. [24] published a study with conflicting results, also using metallic-plate implants. They compared 16 flail-chest patients that received operative intervention to 32 matched controls. They found no significant differences in mean morphine dose, hospital days, ICU days, ventilator days, or pneumonia rates.

Although there are several published reports that use comparative study designs to suggest the superiority of surgical fixation over nonoperative management, one must be cautious when interpreting the existing literature. Uniformly, the retrospective study designs and small sample sizes severely hamper the ability to make definitive treatment conclusions. Furthermore, there is significant heterogeneity in the types of implants used, their indications, and in the definition of flail chest used in the studies themselves. Only Balci et al. [20] and Althausen et al. [23] use the universally accepted definition of "at least three or more sequential ribs fractured in at least two places resulting in paradoxical motion of the chest wall with respiration." The remainder of studies either do not define flail chest or refer to it with variable definitions such as rib fractures resulting in "failure to wean from ventilator" [25] or "severe chest deformity" [18], for example. The comparative studies cited offer some potentially promising benefits for patients, but overall are unable to provide compelling data to support the widespread adoption of internal fixation as the standard of care for flail chest injuries.

Randomized Controlled Trials

Three studies have employed more robust methodology in their investigations. Inclusion and exclusion criteria were strictly defined and applied; however, many of the same methodology limitations remain, particularly the small sample sizes.

Tanaka et al. [26] randomized 37 patients with flail chest injuries requiring mechanical ventilation to either operative intervention using Judet struts or to nonoperative management consisting of standard respiratory management. Despite the small sample size, the two groups were similar in age, sex, Injury Severity Score (ISS), site of flail segment, and number of fractures. Surgical stabilization using Judet struts had beneficial effects on the number of pneumonia cases, duration of ventilation, ICU days, and tracheostomies, all measured at 21 days post injury.

Granetzny et al. randomized 40 patients with flail chest injury to receive either nonoperative management in the form of Elastoplast adhesive chest taping or operative management using Kirschner wires or stainless steel wires or both.

Mechanical ventilation was utilized in both groups when indicated. Despite randomization, the nonoperative group was younger (36 ± 14.9 years vs. 40.5 ± 8.2 years) and slightly sicker (Injury Severity Score 18.0 ± 5.1 vs. 16.8 ± 3.5) than the operative group. The operative group had significantly less ventilator days, ICU days, hospital days, cases of pneumonia, and chest wall deformity than the nonoperative group.

The most recent randomized trial was reported by Marasco et al. [27] in 2013. The operative and nonoperative groups were demographically similar, and the implant tested was the resorbable 6- or 8-hole plate with bicortical screws. The plate is a polylactide copolymer prosthesis and is completely resorbed by the body over 1–3 years. There was no difference between groups in the duration of invasive mechanical ventilation, but the operative group underwent less noninvasive ventilation, had fewer ICU days, and fewer tracheostomies. There was a trend toward less cases of pneumonia in the operative group.

Currently, we are aware of two actively recruiting clinical trials (ClinicalTrials.gov #NCT01367951 and #NCT02132416) and three completed trials (ClinicalTrials.gov #NCT00298259, #NCT01308697, and #NCT00556543) investigating operative fixation of unstable chest wall trauma. These include multicenter randomized trials headed by Niloofar Dehghan and colleagues from St. Michael's Hospital in Toronto and another by Peter O'Brien and colleagues in Vancouver, Canada. These trials should provide additional clinical information and aid in providing definitive answers for guiding the care of flail-chest patients.

Systematic Reviews and Meta-Analyses

The conclusions drawn from many of the comparative studies and some of the underpowered randomized studies have been strengthened by the application of pooled analyses. These meta-analyses lay the foundation for more definitive high-level trials (Table 2.2).

Our group conducted a meta-analysis of 11 manuscripts with 753 patients. Using pooled analysis, surgical fixation resulted in substantial decreases in ventilator and ICU days and lower odds of developing pneumonia, tracheostomy, septicemia, chest deformity, and mortality. All results were stable to basic sensitivity analysis. These benefits stood despite a heterogeneous group of surgical implants, suggesting that operative stabilization of the flail segment is more important than the specific implant used. Importantly, the upper limit of the number needed to treat (NNT) for most outcomes remained below ten patients. For the sake of perspective, the NNT supporting the use of acetylsalicylic acid (ASA) in the secondary prevention of ischemic stroke is 22 patients [28]. Despite the encouraging results, we cautioned that changing one's clinical practice solely on the available data was premature, as the literature is dominated by small retrospective studies.

More recently, Leinicke et al. [29] pooled nine studies for a total of 538 patients that met their inclusion criteria. They similarly noted fewer ventilator days, fewer ICU days, fewer hospital days, and decreased mortality, pneumonia, and tracheostomy. They highlighted the exploratory and hypothesis-generating purpose of their meta-analysis and suggested that future studies should examine patient selection, timing, and techniques and utilize standardized ventilator and sedation protocols. They suggested that such an approach could possibly confirm operative fixation for flail chest as definitive management and further define the boundaries for its use.

Summary

Several issues remain to be resolved before operative fixation of unstable chest wall injuries is accepted as standard practice with appropriate guidelines for its implementation.

Very little evidence exists regarding the long-term outcomes of operatively fixing rib fractures. A minority of studies discussed complications encountered with operative intervention. As with any surgical procedure, rib fixation is associated

Table 2.2 Pooled analyses of operative vs, nonoperative management of flail chest

Author	Year of publication	Journal	Databases searched	N: included manuscripts	N: patients	Outcome	Findings (operative intervention associations)
Slobogean et al.	2013	J Am Coll Surg	Medline Embase Cochrane	11	753	• Mortality • Ventilator days • ICU days • Pneumonia • Septicemia • Tracheostomy • Chest deformity	OR: 0.31 (95 % CI: 0.20–0.48) ES: −7.5d (95 % CI: −9.9 to −5.0) ES: −5d (95 % CI: −8 to −2) OR: 0.18 (95 % CI: 0.11–0.32) OR: 0.36 (95 % CI: 0.19–0.71) OR: 0.06 (95 % CI: 0.02–0.20) OR: 0.11 (95 % CI: 0.02–0.60)
Leinicke et al.	2013	Ann Surg	Medline Embase Scopus Cochrane ClinicalTrials.gov	9	538	• Mortality • Ventilator days • ICU days • Hospital days • Pneumonia • Tracheostomy	RR: 0.44 (95 % CI: 0.28–0.69) ES: −4.52d (95 % CI: −5.54 to −3.50) ES: −3.40d (95 % CI: −6.01 to −0.79) ES: −3.82d (95 % CI: −7.12 to −0.54) RR: 0.45 (95 % CI: 0.30–0.69) RR: 0.25 (95 % CI: 0.13–0.47)

ICU intensive care unit, *OR* odds ratio, *RR* relative risk, *ES* pooled effect size with the risk of complications like wound infection, hardware failure, malunion or nonunion, and symptomatic hardware requiring subsequent operations. Considering the thin layer of soft tissue covering any proposed implant, these complications must be further elucidated prior to widespread implementation.

As with much trauma literature, evidence so far has been hampered by small sample sizes and uncontrolled study designs. We are hopeful that cooperative multicenter research efforts will help guide definitive clinical practice.

Given the limitations of the literature and the lack of rib-specific fixation devices, rib fracture fixation was rarely performed in North America. In a recent review of outcomes and treatment practices from the American College of Surgeon's National Trauma Data Bank (NTDB), out of 3,467 patients with a flail chest injury, 0.7 % were treated with surgical fixation [30]. While the lack of evidence and availability of modern rib fixation implants may have been the principal determinant, the lack of training among surgical disciplines also likely contributed to the NTDB results. Fracture surgeons are not necessarily trained to operate on the chest wall, and thoracic surgeons are rarely introduced to modern fracture fixation principles [31]. A 2007 survey of 238 American orthopedic, trauma, and thoracic surgeons reported that 16 % of the orthopedic surgeons, 21 % of the trauma surgeons, and 52 % of the thoracic surgeons indicated that they had ever performed or assisted in open reduction and internal fixation of rib fractures [32].

The current state of the modern literature suggests potential benefits for operative treatment compared with nonoperative treatment of flail chest injuries. Recommendations regarding fixation of rib fractures for other indications such as intractable acute pain are primarily anecdotal at this time. Though initial results are encouraging, several important questions remain to be addressed. Cooperative efforts between centers and across surgical specialties will be instrumental in addressing the limitations of the literature and improving the care of these critically injured trauma patients.

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The Pathophysiology of Flail Chest Injury

3

Akhilesh Tiwari, Shalini Nair, and Andrew Baker

Introduction

Traumatic thoracic injury usually accounts for maximum trauma-related death second only to head injury [1, 2]. The exact epidemiology of thoracic trauma is largely unknown; however, various studies have been conducted at various trauma centers to find the answer. Thoracic trauma accounts for about 10–15 % of all trauma and results in approximately 400,000 hospitalizations per year [1–3]. Varying incidences of rib fractures have been reported ranging from nearly two thirds of patients with severe trauma [4–6] to about 10 % in similar cases presenting to a trauma center [3, 7]. Motor vehicle collisions were the most common underlying cause of rib fractures in those studies looking at incidence. The presence of over-the-shoulder seat belts has been considered life saving on numerous occasions but has also been linked to the occurrence of rib fractures.

The incidence, severity, and long-term morbidity and mortality of chest injuries are different at the extremes of ages. In the pediatric subgroup, the chest wall is more compliant due to lack of calcification and hence more pliable as a result of which the impact of trauma is easily transmitted to the underlying viscera. As a result of this, lung contusion may be seen predominantly without overlying rib fractures. Although both rib fractures and flail chest have been reported [8], the presence of rib fractures in the pediatric population should point toward a much higher absorption of energy. Elderly individuals (over age 65 years), on the other hand, are prone to suffer from rib fractures even from low-velocity trauma, due to the presence of osteoporosis, decreased muscle mass, and various comorbidities. More than 50 % of patients in this subgroup who have rib fractures on presentation had suffered a fall of less than 6 feet. This signifies the low-impact trauma needed in an elderly individual to produce rib fractures [7]. The number of rib fractures is a direct indicator of the severity of trauma and correlates indirectly with the morbidity and mortality. One of the studies performed in the elderly population found that mortality increases from about 4 % for one to two fractures to about 32–33 % for more than six fractures [7, 9]. The increased incidence of mortality in the elderly subgroup is largely due to their underlying comorbidities and limited cardiorespiratory reserve. The risk of pneumonia and mortality increases by 27 % and 19 %, respectively, for every additional

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rib fracture [10]. The presence of a rib fracture also points toward underlying visceral organ injury, and the incidence of splenic and hepatic injury increases by 1.4 and 1.7 times, respectively.

Anatomy

The chest wall is basically comprised of the bony thorax with muscles, cartilage and underlying heart, lungs, and esophagus along with the major vessels. The bony thorax is bounded anteriorly by the sternum and posteriorly by the vertebrae with the ribs extending between them and the diaphragm forming the inferior boundary of the thoracic cage.

The first seven ribs are attached to the sternum directly (sterna joints or interchondral joints) via costal cartilage and are called true ribs. Ribs 5–12th are known as "false ribs" as the costal cartilage is not attached directly to the sternum. The cartilage of the eighth to tenth ribs are attached to each other and then to the cartilage of the seventh rib and collectively forms the costal margins which in combination with the costal margin from the other side forms the costal arch. Coordinated movement of these ribs, facilitated by the muscles, results in the excursion of the chest wall (Fig. 3.1).

Anatomically, a flail segment is a part of the chest wall which has lost its continuity with the chest wall and usually results from multiple rib fractures. In simple terms, it can be defined as a fracture of three or more ribs at two or more places. The literature also supports the definition of flail chest as a fracture of two or more ribs at two or more places (Fig. 3.2). The common factor in both definitions is the presence of an unstable segment, which is not continuous with the chest wall and moves in a paradoxical fashion—inward during inspiration and outward during expiration. Splinting of muscles early in the course may conceal the rib motion, and hence, this paradoxical motion could be missed. Also, induction of mechanical ventilation may also conceal the flail segment as paradoxical motion is minimized. Paradoxical movement of the flail segment occurs mainly because of two factors: loss of anatomical continuity and the effect of the negative intrapleural pressure acting on the detached segment (Fig. 3.3). Similarly flail segments of the sternum and vertebrae have also been reported, with the underlying mechanism largely remaining the same.

The flail segment occurs after compressive forces are applied to the chest, with the thorax able to withstand about 20 % volume compression before a rib fracture can occur. In one of the studies conducted on cadavers, ribs were fractured by opening a median sternotomy with a retractor. The authors proposed that the ribs in the posterior region along with their vertebral articulations function like a lever and act as a single unit. Any force over the anterior chest wall hence results in the fracture of the ribs not only over the weaker lateral aspect but also over the posterior region near the costotransverse process articulation [11]. Anatomically, the presence of right-sided rib fractures (the eighth and below) is associated with a probability of 19–56 % of underlying liver injury, and the presence of left-sided rib fractures is associated with a 22–28 % probability of splenic injury [10]. Involvement of respiratory muscles is also a very important contributory factor in the pathophysiology of the flail chest. Hence, it is apt at this juncture to briefly discuss the muscles involved in respiration.

Inspiratory Muscles The diaphragm is the most important inspiratory muscle; it is dome shaped having a central cartilaginous and peripheral muscular portion and forms a thin but effective boundary between the thoracic and abdominal cavity. It is inserted on the lower ribs and receives its sensory nerve supply by the phrenic nerve (C3–C5) over the central region, whereas the peripheral portion of the diaphragm is supplied by the lower 6–7 intercostal nerves. Contraction of the diaphragm increases the dimensions of the chest wall in almost all directions and forces the abdominal contents forward and downward. The diaphragm may move anywhere between 1 and 10 cm depending upon the depth of respiration. Upward movement of the diaphragm during inspiration is known as paradoxical movement of the diaphragm and this condition is commonly

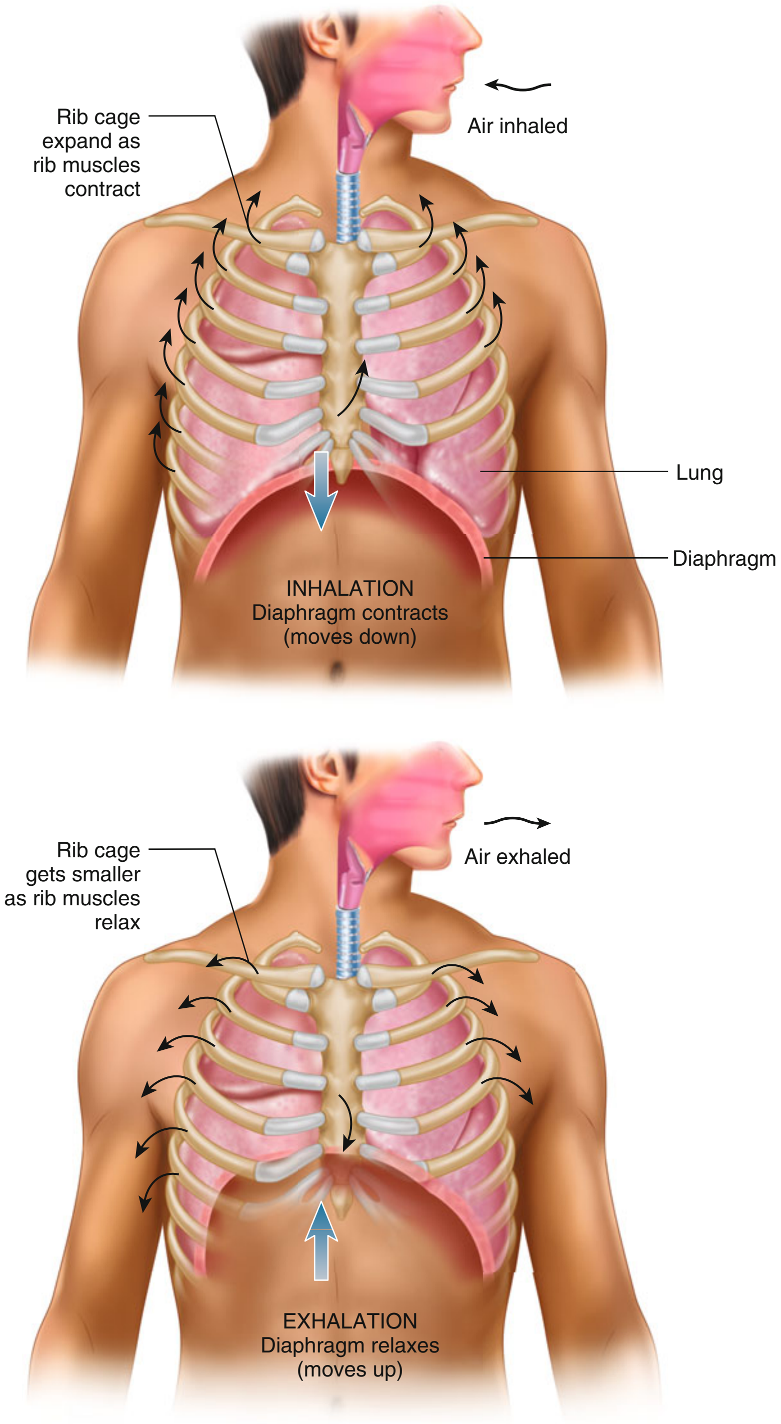

Fig. 3.1 The normal mechanics of respiration. As the (intact) chest wall expands outward under the influence of the respiratory muscles (including the intercostal muscles), the diaphragm contracts and lowers, creating a negative intrathoracic pressure, and in response air enters through the upper respiratory system. In expiration, the process is reversed

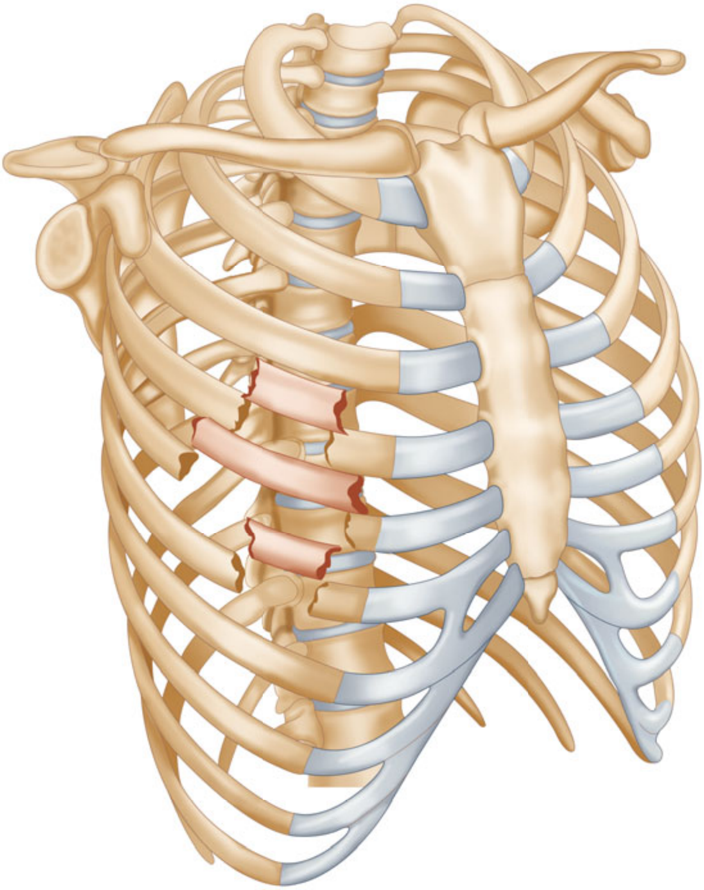

Fig. 3.2 Illustration of a flail chest injury—three or greater adjacent ribs with segmental fractures is a generally accepted definition (see also Chap. 1)

seen in diaphragmatic palsy. The paradoxical movement of the ribs and the diaphragm, however, unrelatedly seems to have a common underlying physiology of negative intrathoracic pressure.

The external intercostals, the other inspiratory muscles, run in a downward and forward direction, starting from the inferior edge of the rib above and inserting into the superior margin of the rib below. The contraction of these muscles pulls the ribs upward and forward increasing both the lateral and anteroposterior diameters. The "bucket handle movement" of the rib brought about by these muscles is responsible for increasing the lateral diameter of the chest. These muscles receive innervation by the intercostal nerves coming off the spinal cord at the same level. The movement of the diaphragm and other inspiratory muscles results in negative intrathoracic pressure by the virtue of increased thoracic volume, whereas the contraction of the intercostals stabilizes the thoracic cavity and brings about a twisting movement. This action of intercostals makes the diaphragmatic activity more efficient and avoids wastage of energy. As the lungs are attached to the thorax by means of pleural membranes, the lungs also expand, creating a negative intrapleural and intrapulmonary pressure, thereby creating a rush of air to the lungs through the upper airway. Accessory muscles of respiration which include the scalene muscle (elevates the first and second ribs) and the sternomastoid which raises the sternum may be deployed in certain conditions like exercise, asthma, etc.

Expiratory Muscles Expiration is almost always passive, mainly due to the natural elastic recoil of the lungs. Abdominal muscles like the rectus

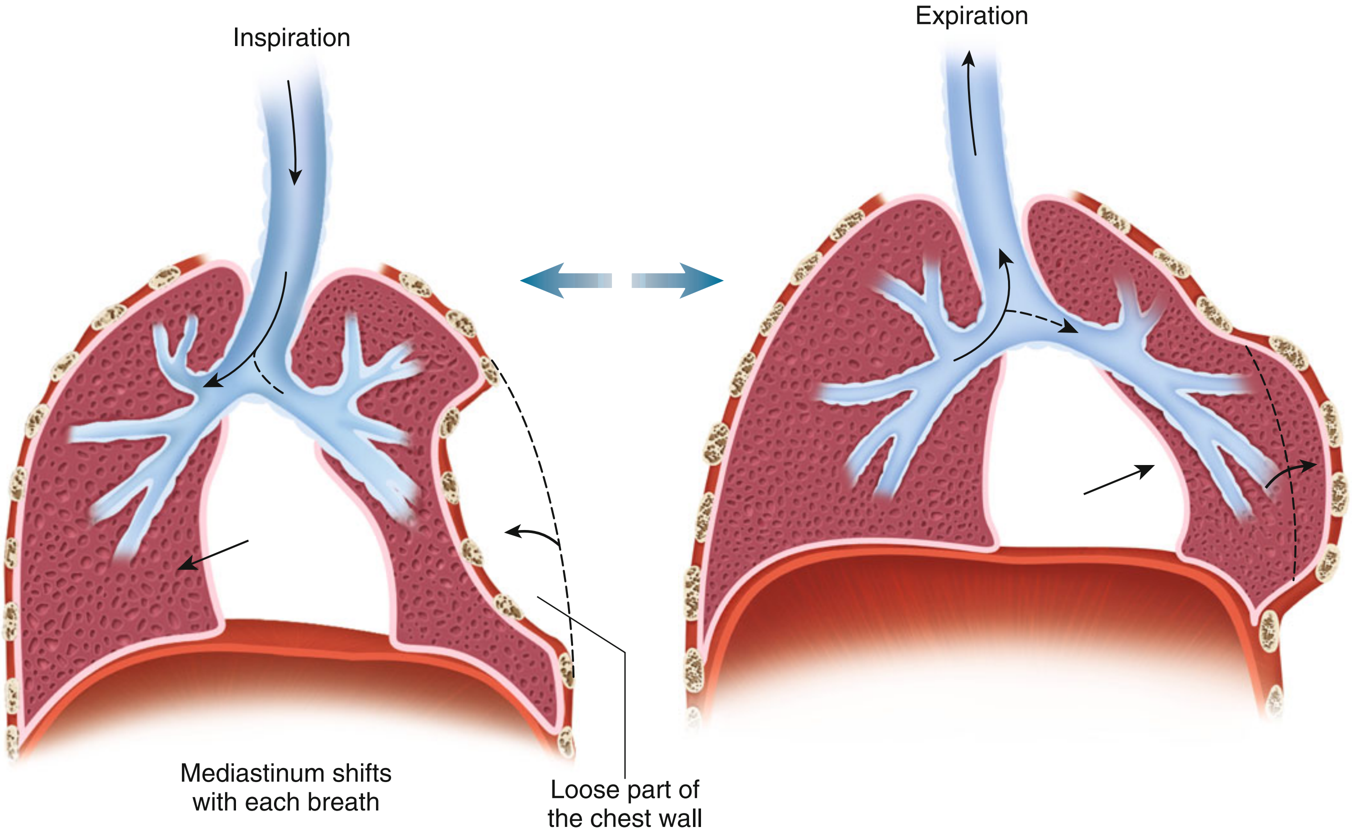

Fig. 3.3 Paradoxical breathing occurs when instability (i.e., from multiple rib fractures) causes inward motion of the chest wall in response to the generation of negative intrathoracic pressure (see Fig. 3.1). Expiration causes a similarly dysfunctional expansion of the unstable chest wall

abdominis, internal and external oblique, transverses abdominis, and internal intercostals are a few of the expiratory muscles involved depending upon the clinical scenario.

One of the studies looking into biomechanics and mathematical calculations have demonstrated that local bending and shearing forces are the most important modes during an impact leading to rib fractures [12]. The bony thoracic cavity gets compressed under an external force in both the anteroposterior and lateral directions with the degree of damage depending upon the direction, the severity, and the surface area of the impact of the force. As seen already, the required force to produce a rib fracture in the pediatric population may have to be considerably higher due to the pliable nature of the ribs. If this force produces fracture of the rib at two points, a flail segment may occur. Paradoxical movement of the ribs should not be considered as an absolute diagnostic criterion, as the flail segment underlying scapular cover may not demonstrate paradoxical movement. Authors have also proposed two different terminologies, namely, flail segment and flail chest. Flail segment refers to a part of the chest wall that has detached from the adjacent thorax, whereas flail chest refers to clinical evidence of paradoxical motion [13, 14].

Based on the anatomical location, flail segment can be broadly defined into the following subcategories:

(a) Anterolateral flail segment—the site of anterior fractures lies in the area of anterior rib angles.
(b) Posterolateral flail segment—refers to those fractures where the posterior fracture comprises the posterior rib angle (Fig. 3.4).

One important point to note, in both the above types of flail segment, is the involvement of the lateral segment, which is the site of insertion of serratus anterior muscles. Matteo in a series of studies in canine models [15–17] had demonstrated the role which respiratory muscles play following chest trauma in general and flail segment in particular. It would probably not be wrong to say that the term “floating segment” at times may not be observed clinically as these patients suffer from various other confounding variables like underlying pneumothorax, pulmonary contusion, and abdominal trauma. Normal mechanics of breathing are affected in the individuals suffering from flail chest due to various underlying conditions as stated above. Pain, which is one of the most common and most severe symptoms in this patient population, also alters the pattern of the respiratory muscle activation. In these canine model studies, they also note that the cranial movement of the fractured ribs was maintained during inspiration, with increased inspiratory activity recorded from the external intercostals by electromyography. They went on to prove that the respiratory displacement of the ribs is primarily determined by the balance between forces related to the fall in pleural pressure and that generated by the parasternal intercostal muscles. The extrapolation of the results from these animal studies to human subjects remains open to discussion, with further randomized trials on human subjects being warranted.

The altered role which the respiratory muscles play in this scenario is also very important. The serratus anterior with its digitations inserted on the ribs individually may act on each rib pulling it like an “arm on a drawer” leading to the dislocation of the ribs. This could also explain the tendency of the overriding ribs seen in flail segments following chest trauma.

Box 1 Anatomical Pearls [18]

Fracture of the First to Fourth Ribs

(a) Involvement of the first rib is usually rare.
(b) Fracture of the first three ribs usually indicates high-velocity trauma as they are well protected by the scapula from behind along with other associated musculatures.
(c) Involvement of these ribs, the clavicle, and the upper sternum may be associated with brachial plexus and vascular injury in about 3–15 % of patients [19, 20].
(d) The “surfer’s rib” is one typical example commonly seen in surfers performing layback maneuver where the first rib fracture may be noted [21].

(continued)

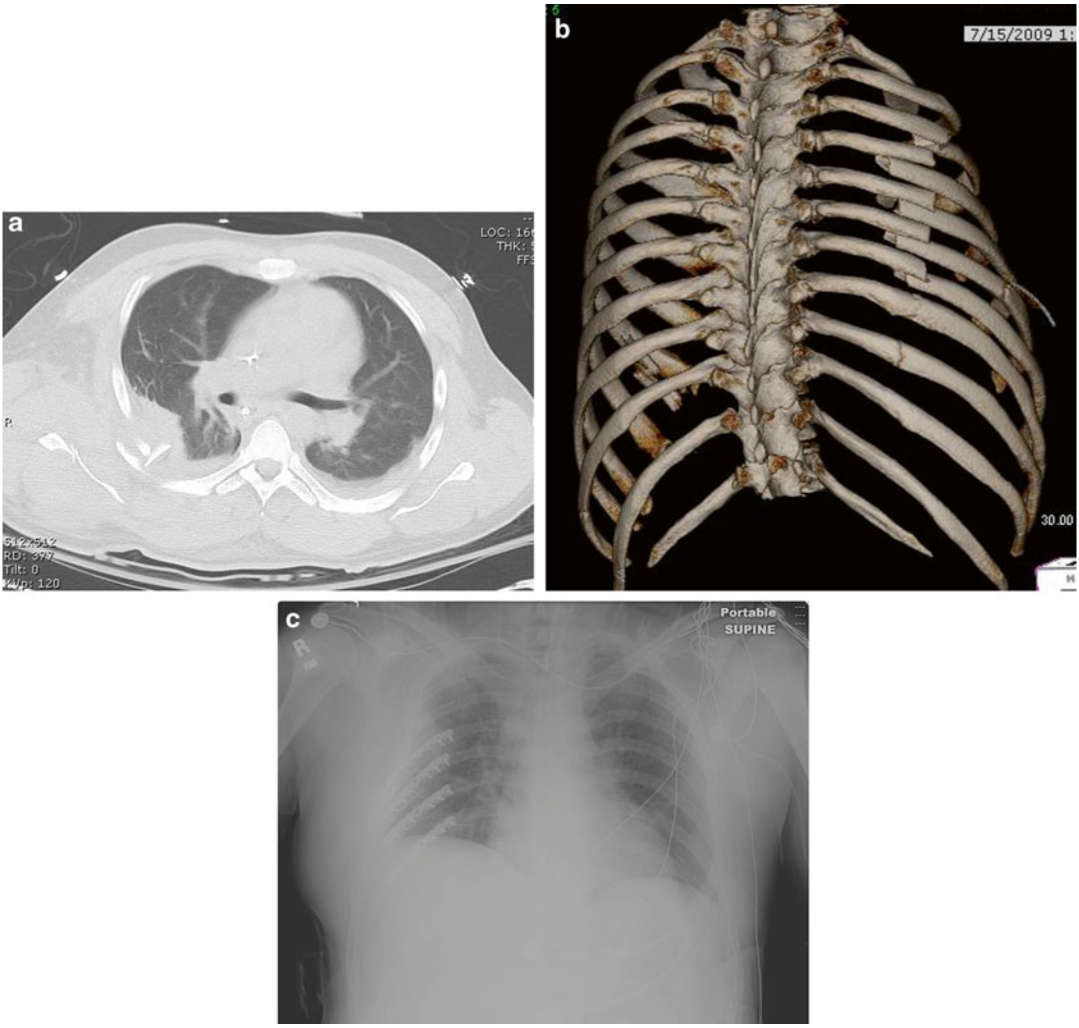

Fig. 3.4 A CT scan (**a**) of a severely displaced flail chest injury with multiple comminuted rib fractures and a localized hemothorax/pulmonary contusion. A 3D CT scan (**b**) provides excellent visualization of the injury, demonstrates the shortening and displacement of the posterior rib fractures, and aids in surgical planning. The patient was treated with early open reduction and plate fixation (**c**)

Box 1 (continued)

Fracture of the Fifth to Ninth Ribs

(a) They are usually more common and may be seen as an uncomplicated single rib fracture or may present with multiple fractures resulting in flail chest.

(b) Inward displacement of the fractured ribs is associated with injury to the lung and other visceral organs.

Fracture of the 10th to 12th Ribs

(a) Depending on the side affected, they may be associated with splenic or hepatic injury [20].

Sternal Flail A sternal flail chest is basically a form of anterior flail chest, where the flail segment is formed by the sternum, due to bilateral chondrosternal fracture. These fractures may be seen in the trauma resulting from frontal impact. Motor vehicle accident with steering wheel impact on the sternum is one of the most common causes leading to sternal fracture. Due to its anatomical location, the common associated injuries include pulmonary and cardiac contusion along with associated vascular injury. The presence of sternal fracture is however not indicative of cardiac contusion and does not warrant special investigation unless indicated otherwise [22].

Vertebral Flail Support to the thoracic cage is provided by the spine posteriorly and sternum anteriorly. The three-column model of spine stability proposed by Denis was modified to a "4th spinal column" explaining the role of the sternum in providing stability to the thorax [23, 24]. High-velocity trauma sustained to the thorax could well be associated with traumatic vertebral injury. Involvement of the thoracic spine accounts for about 25–30 % of all spine fractures and is often seen following hyperflexion or axial loading and less commonly due to other mechanisms of injury [25]. Anterior wedge compression fractures and burst fractures are the most common types [20]. Multiple rib fractures coupled with sternal and/or vertebral fractures could lead to a complete bony disruption; however, fractures producing a flail segment of the spine are extremely rare and are mostly of academic interest.

Pathophysiology of Flail Chest and Thoracic Trauma

Thoracic trauma is one of the most common causes of trauma-related mortality and morbidity in both civilian and military life. The underlying injury and subsequent pathophysiology contributing to the fatalities and morbidity depend on the severity and the direction of the impact [26]. Single fractures of the ribs, therefore, are benign and are most often missed and, if at all diagnosed, pose few clinical difficulties. Liman and colleagues reviewed 1,490 patients admitted with chest trauma over a 2-year period and reported that the presence of two or more rib fractures is a marker of severe injury [26]. Eighty-one percent of these patients had hemothorax and/or pneumothorax at presentation. The mortality was also different with 0.2 % observed in patients without rib fractures and 4.7 in patients with more than two rib fractures. The detailed understanding of the pathophysiology is extremely important to help understand the difference in mortality and also effectively manage such a patient. The effect basically depends on the size of flail chest; however, the most important cause of respiratory compromise following flail chest is pulmonary contusion which is commonly seen in patients with an injury severity score (ISS) of more than 15. Various factors like direct blow, shearing or bursting at the gas-liquid interface and high- and low-density interface, and transmission of shock waves play a role in the causation of pulmonary contusion either alone or in combination.

The main factors leading to serious morbidity in patients with rib fractures are respiratory insufficiency due to pain, underlying lung collapse, paradoxical movement, and underlying pulmonary contusion. Of all the above, pulmonary contusion is the most important, along with the fall in total lung capacity and functional residual capacity due to paradoxical motion, which contributes to hypoxia. Other factors which could also contribute to hypoxia in these patients could be injury primarily to the pleura and lung such as pneumothorax and aspiration or secondary to brain injury or cardiac injury. Table 3.1 enumerates a few important life-threatening events which could be encountered in patients presenting with thoracic trauma and multiple rib fractures that are flail.

In earlier days, the pulmonary contusion was not well recognized, and its clinical relevance was never emphasized until World War I, where a number of soldiers were noticed to have died

Table 3.1 Life-threatening complications following thoracic trauma

Immediate threats to life	Potential threats (not immediate)
1. Tension pneumothorax	1. Pulmonary and myocardial contusion
2. Cardiac tamponade	2. Vascular disruption
3. Airway obstruction	3. Flail chest
4. Major vascular tear	4. Diaphragmatic and esophageal rupture

without suffering obvious external trauma [27]. Paradoxical motion of the chest wall was also considered to be the main cause of respiratory embarrassment in this subset of patients. This "pendelluft" or out-of-phase movement of the chest wall refers to the to-and-fro movement of deoxygenated air between the lung of the normal and flail side during spontaneous breathing and was considered to be the main cause of respiratory insufficiency. However, certain canine-based studies later refuted this hypothesis. Now, it is widely believed and accepted that it is the underlying pulmonary contusion (PC) which is the major cause of the poor prognosis following a flail chest along with rib fractures causing secondary problems of pain and muscular splinting (Fig. 3.5). Fulton in an animal study also concluded that PC is mainly a progressive condition starting with parenchymal injury worsening over the initial 24 h [28].

The pathophysiology of pulmonary contusion (PC) is still not fully understood, but primarily involves alveolar and capillary wall rupture leading to intra-alveolar hemorrhage and flooding resulting in ventilation-perfusion (V/Q) mismatch and subsequent hypoxia. The area of PC is often localized to the area adjacent to rib fractures (Fig. 3.6). These patients often tend to develop type 1 respiratory failure due to underlying ventilation-perfusion mismatch and arteriovenous shunting.

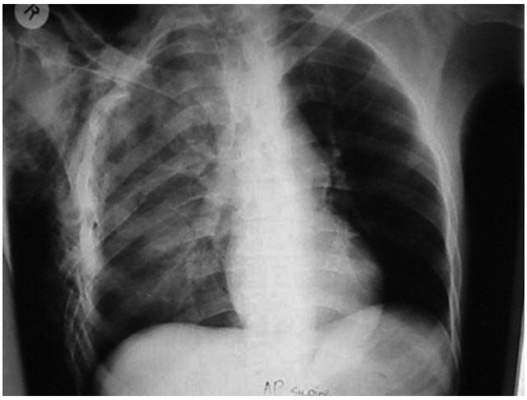
Fig. 3.5 Chest radiograph with a right-sided flail chest injury: multiple segmental rib fractures and a pulmonary contusion are evident

After any impact, the initial edematous phase is associated with worsening edema and infiltrates, and soon the airway is occupied by blood, tissue debris, and various inflammatory markers followed by reduction in surfactant production. By 24–48 h, alveolar collapse begins to appear and increasing extravasation of blood into the alveoli continues. This combination of collapse,

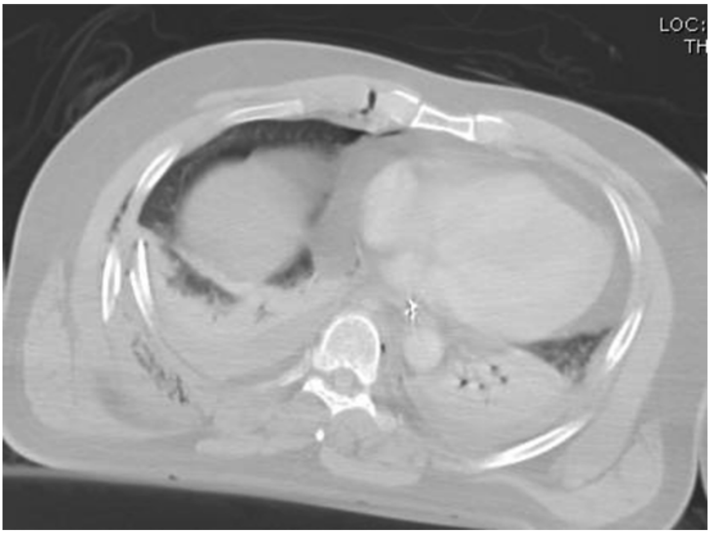

Fig. 3.6 This CT scan demonstrates how the area of pulmonary contusion is typically adjacent to the area of greatest deformation of the injury to the ribs or chest wall, in this case near the posterior fractures of the lower right ribs (case courtesy of W. Drew Fielder, MD, FACS)

reduction in surfactant production, and fluid-filled alveoli are collectively responsible for pulmonary hypertension, ventilation-perfusion mismatch, and decreased compliance. These changes also increase the likelihood of acute respiratory distress syndrome in these patients. The peak effect following a pulmonary contusion starts at around day three and resolves by the seventh day unless complicated by other coexisting factors such as mechanical ventilation, pneumonia, and head injury. The primary effects following rib fractures and pulmonary contusion are due to splinting of the intercostal muscles resulting from pain which results in limited expansion and a restrictive pattern of lung disease. This is followed by the development of atelectasis and retention of secretions which, if not managed well by physiotherapy and suctioning, could potentially form an obstructive mucous plug, not only further aggravating atelectasis but also leading to lung collapse and pneumonia. All these factors are responsible for hypoxia, which worsens overtly during the initial 8 h, as ventilation starts to cease to the involved part of the lung.

The development of PC in a patient with thoracic trauma and flail chest appears to follow three basic phenomena [29]:

(a) The spalling effect—this occurs at the site where shock waves meet the lung tissue most importantly at the interface between gas and liquid. This may result in alveolar disruption at the point of initial contact.
(b) The inertial effect—this effect could be compared to diffuse axonal injury of the brain and occurs as the lighter alveolar tissue is sheared off from the heavier hilar structures since the rate of acceleration is different for both of them due to different densities.
(c) The implosion effect—this effect is seen due to passage of pressure waves through gas bubbles. Once these gas bubbles are exposed to these pressure waves, they tend to implode, rebound, and then expand beyond their original volume leading to tiny explosions followed by tissue damage. This effect is also seen in areas of the body other than the lung that contain air and gas, such as the stomach, intestines, and middle ear.

Table 3.2 Types of pulmonary contusion [30]

Type 1 • The highest incidence among all reported types of pulmonary contusion • Occurs due to direct chest wall compression against the lung parenchyma
Type 2 • It is due to the impact and shearing of lung tissue against the vertebral bodies
Type 3 • Overlying fractured ribs lead to direct injury and contusion of the underlying lung tissue
Type 4 • This type often has an underlying pleuropulmonary adhesion associated with previous lung injury

As the pathophysiology is not very well understood, Wagner et al. had proposed a classification of pulmonary contusion, to better understand the etiological factors associated with PC (Table 3.2). This classification is primarily based upon the underlying mechanism.

One of the important histological findings of PC is extensive pulmonary hemorrhage otherwise referred to as “hepatization of the lung.” This initial damage to the lungs is then followed by interstitial edema within 1–2 h of the primary insult. At 24 h, these changes further worsen and are accompanied by extensive inflammatory cell infiltrates along with loss of primary structure and extensive edema. At 48 h, predominantly macrophages and neutrophils are seen invading the field along with the presence of increased fibrin. These changes usually resolve by day 10 unless secondary complications like pneumonia or sepsis set in. In patients with flail chest, early mortality has been largely attributed to massive hemothorax or PC, whereas the late mortality has largely been infective like pneumonia and adult respiratory distress syndrome (ARDS).

Inflammation, altered alveolocapillary permeability, pulmonary edema, V/Q mismatch, increased arteriovenous shunting, and loss of pulmonary compliance are the most important underlying pathogenic mechanisms of PC contributing to varying degrees of mortality and morbidity (Fig. 3.7). The amount of injured lung has often been linked to both the short- and long-term prognoses of the disease. Hence, another classification has been proposed based on the

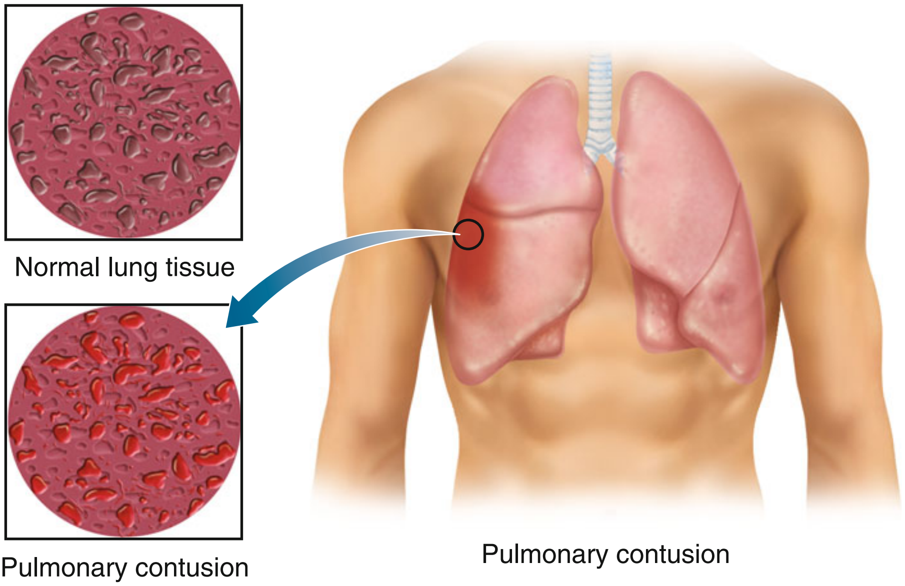

Fig. 3.7 Artist's rendition of the pathological change or "hepatization" of the lung that occurs with a severe pulmonary contusion

Table 3.3 Severity of pulmonary contusion [31]

Mild • Less than 18 % of lung volume affected • Usually managed by noninvasive ventilation
Moderate • 18–28 % of the lung volume affected • Intubated on a case-to-case basis
Severe • More than 28 % of lung volume affected • Almost all patients need intubation

volume of the lung affected by the trauma (Table 3.3).

It is quite normal to blame the direct pulmonary injury for all the complications encountered; however, there is growing evidence pointing toward the underlying molecular and inflammatory mechanisms as a contributing factor in the injury caused due to PC. There is a complex interplay of various cytokines, the complement cascade, macrophages, and other inflammatory mediators producing various effects not only on the lungs but also varied systemic effects. The inflammatory mediators which are released in turn lead to damage to the alveolocapillary basement membrane, hypoxia, and pulmonary vascular hypertension along with the release of various toxic free oxygen radicals [32–34]. The subcellular level of insult occurring in this patient population is mostly inflammatory in nature:

1. Inflammatory response in pulmonary contusion—acute inflammatory response is the hallmark of pulmonary contusion which usually starts with infiltrates of polymorphonuclear leukocytes (PMNs) and activation of tissue macrophages, the complement pathway, and the coagulation pathway. These PMNs once activated could lead to damage which is usually not limited by the anatomical boundary. Various animal models have gone on to prove that the neutrophil accumulation is one of the key events in the pathogenesis of PC [35–38]. The potent chemotactic factors for the PMNs belong to four major families of chemokines (CXC, CC, C, and CXC3), which are primarily chemotactic for neutrophils and hence play a role in the pathogenesis of PC and the acute lung injury. Once they reach the site of injury, various secondary products like free oxygen radicals, eicosanoids, and proteolytic enzymes are released which further damage the pulmonary parenchyma, further worsening the lung injury.

Hence, the primary effect which the PMNs produce on the lung is oxidant mediated and may also impair alveolar fluid transport. Increased necrosis and apoptosis of the cells within the alveolar epithelium secondary to PMN infiltration have been observed in PC. Seitz et al., however, have challenged this hypothesis by demonstrating that increased neutrophil infiltration in cases secondary to PC is not associated with apoptosis of type II cells. Further studies defining the role of these inflammatory mediators are warranted for a better understanding of the pathophysiology [39].

2. Role of monocytes and macrophages—the role which these scavenger cells play in the pathogenesis of pulmonary contusion is not very clear, but the augmented release of T-helper type 2 (Th2) cells by monocytes has been observed at around 2 h post contusion [40]. Also, increased alveolar macrophages have been found to be associated with increased apoptosis of type II pneumocytes [41]. There are two main hypotheses which have been proposed to explain apoptosis in lung injury mainly in animal models including "neutrophil hypothesis" and "epithelial hypothesis" emphasizing the role of the respective cells in apoptosis and underlying pathophysiology [42].

   The role of toll-like receptors (TLR) more specifically TLR-2 and TLR-4 secreted from the alveolar epithelium has also been studied in various murine models. The exact detailed mechanism of the damage produced by them is still to be elucidated [43, 44].
3. Surfactant dysfunction in pulmonary contusion—alveolar type II cells are the primary cells responsible for the secretion of surfactant which plays an extremely important role in pulmonary mechanics and in regulating the alveolar surface tension. There have been studies looking at the composition of bronchoalveolar lavage (BAL) and explaining the role of surfactant in PC. The results from these studies could potentially be translated into effective therapeutic modalities. In one of the studies in rat models of PC, rats at 24 h after trauma were found to have a decreased concentration of surfactant aggregates in cell-free BAL. A decrease in surfactant aggregates was also found on a pulsating bubble surfactometer at 24 h, which improved by 48–72 h, post trauma, although still less when compared to a normal healthy lung. This decrease in surfactant returned to near normal by 96 h [45].

Table 3.4 Important effects of FC and PC on pulmonary mechanics

Pulmonary contusion	(a) Ventilation-perfusion mismatch (b) Increased shunt (c) Increased total lung water (d) Decreased compliance (e) Impaired diffusion (f) Increased pulmonary vascular resistance	1. Hypoxia 2. Hypercarbia 3. Increased work of breathing 4. Tachypnea 5. Rhonchi and wheeze 6. Hemoptysis
Flail chest	(a) Pain (b) Muscular splinting (c) Inability to clear secretion (d) Atelectasis and collapse	

Local and systemic effects—Table 3.4 enumerates the important effects which PC and FC have on pulmonary mechanics.

The effect of PC, however, is not restricted to one lung or just the respiratory system, but it tends to have a widespread effect involving not only the contralateral lung but also the entire body system [27]. These contusions are primarily a laceration to lung parenchyma leading to alveolocapillary leakage, reduced compliance, and increased shunt with impaired diffusion due to thickened alveolar septa. Increased pulmonary vascular resistance is also noted on the affected side, although this could be argued to be a protective mechanism in order to decrease the shunt fraction [46, 47]. The effect of PC on the contralateral lung has also been noted and is extremely variable in severity. Porcine models have demonstrated a delayed capillary leak in the contralateral lung, with thickened septa affecting diffusion, increased vacuolation, and edema along with increased neutrophil infiltration noted in both the affected side and the contralateral lung. Patients with PC have also decreased capacity of bacterial clearance, thereby increasing the chances of secondary bacterial infection, which may or may not be localized to the affected side and, eventually if not controlled, may spread on to the contralateral lung and also lead to systemic infections. In animals, PC has also been shown to decrease the systemic cellular immunity [40] thereby further increasing the chance of secondary infections and decreasing survival if not managed properly.

Conclusion Flail chest and underlying pulmonary contusion may range from a benign condition to a rapidly progressing and potentially fatal disorder, which is not necessarily a localized process but has potential widespread effects involving the contralateral lung and varying degrees of systemic effect. As is clear from the discussion above, rib fractures are important primarily due to three main reasons—as an indicator of underlying visceral injury, as a significant source of pain necessitating adequate pain control, and as an indicator of significant mortality and morbidity. The systemic effects are usually secondary to the massive release of various proinflammatory cytokines, proteolytic enzymes, activation of the complement, and coagulation cascade leading to variable mortality and morbidity.

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4 The Current Treatment of Flail Chest Injuries

Niloofar Dehghan

Abbreviations

CPAP	Continuous positive airway pressure
K-wire	Kirschner wire
ICU	Intensive care unit
ORIF	Open reduction internal fixation
PEEP	Positive end-expiratory pressure

Historic Treatment

The treatment of flail chest injuries has undergone dramatic evolution over the last hundred years [1]. In the first half of the twentieth century, treatment was focused on mechanical stabilization of the chest wall. At the time, chest wall instability was thought to be the main cause of morbidity and mortality, as opposed to parenchymal lung injury. Stabilization was performed by bracing or adhesive strapping or traction of the chest wall, to immobilize and prevent painful paradoxical chest wall motion [2, 3] (Figs. 4.1 and 4.2).

In the second half of the century, the concept of "internal pneumatic stabilization" became a popular treatment strategy for stabilization of flail chest injuries [1]. In the 1970s, it was thought that internal pneumatic stabilization of the flail chest injury was a critical component of chest wall stabilization. The use of positive pressure mechanical ventilation was believed to allow for internal stabilization of the flail chest, and obligatory prolonged mechanical ventilation became a standard of care for treatment of flail chest injuries. It was not uncommon for patients to undergo tracheostomy and long-term positive pressure ventilation for 2–3 weeks until rib fractures had consolidated to some extent, regardless of the patient's pulmonary function [4].

It wasn't until 1975 that the work of Trinkle et al. cast doubt on this theory and practice [5]. In this retrospective matched cohort study, patients treated with obligatory mechanical ventilation (group 1) were compared to those who were treated for underlying lung injury by use of diuretics, intercostal nerve blocks, and pulmonary toilet (group 2). The results demonstrated that obligatory mechanical ventilation leads to higher rate of complications (23 % vs. 2 %, $p<0.01$), longer hospital stay (22.6 vs. 9.3 days, $p<0.005$), and increased mortality (21 % vs. 0 %, $p<0.01$). The authors concluded that treatment of the underlying lung injury is more important than treatment of the paradoxical chest wall motion by internal pneumatic stabilization. Other authors confirmed these findings and confirmed high rates of complications in patients treated with obligatory mechanical ventilation [6]. It was recognized that mechanical ventilation should be

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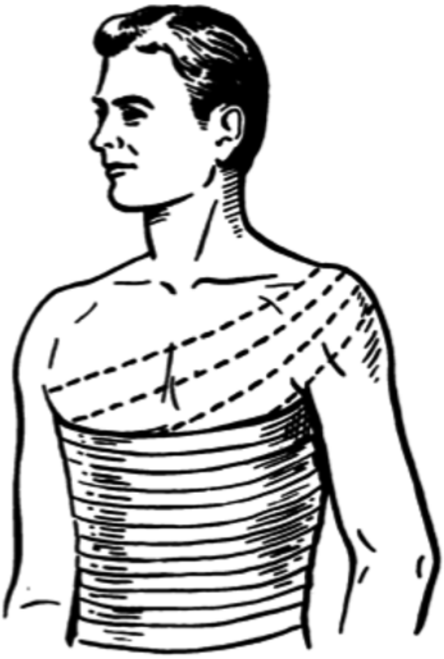

Fig. 4.1 Chest stabilization by strapping (Used with permission, Jensen 1952 [3])

Fig. 4.2 Traction used for stabilization of flail chest injury in a patient with sternum fracture. Traction tongs used to stabilize the sternum with four pounds of traction by use of overhead frame (Used with permission, Jensen 1952 [3])

used to correct pulmonary dysfunction and gas exchange abnormalities, rather than treat chest wall instability [5, 6].

Over the next decades, the main treatment strategy remained nonoperative, focusing on supportive mechanical ventilation in patients with respiratory dysfunction; pain management with use of epidural catheters, intercostal nerve blocks, or intravenous narcotic administration; and chest physiotherapy to clear secretions and prevent atelectasis [7–9]. Surgical fixation of the flail chest was reported; however, this was performed in rare circumstances. The methods of fixation included Kirschner wires (K-wires) [10, 11] and Judet struts [12], which are outdated modes of fixation compared to current modern technique of plates and screw fixation [8, 13] (Figs. 4.3, 4.4, 4.5, and 4.6).

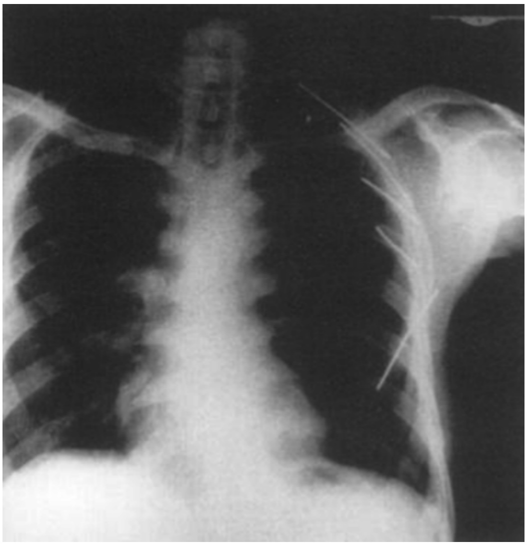

Fig. 4.3 Use of Kirschner wires for fixation of multiple rib fractures (Used with permission [11])

Modern Treatment Strategies

The current modern treatment of flail chest injuries includes nonsurgical and surgical treatment strategies. A summary of these is outlined below, and further details may be found in Chaps. 5–10.

Mechanical Ventilation

Current recommendations state that obligatory mechanical ventilation solely for the purpose of overcoming chest wall instability, in the absence

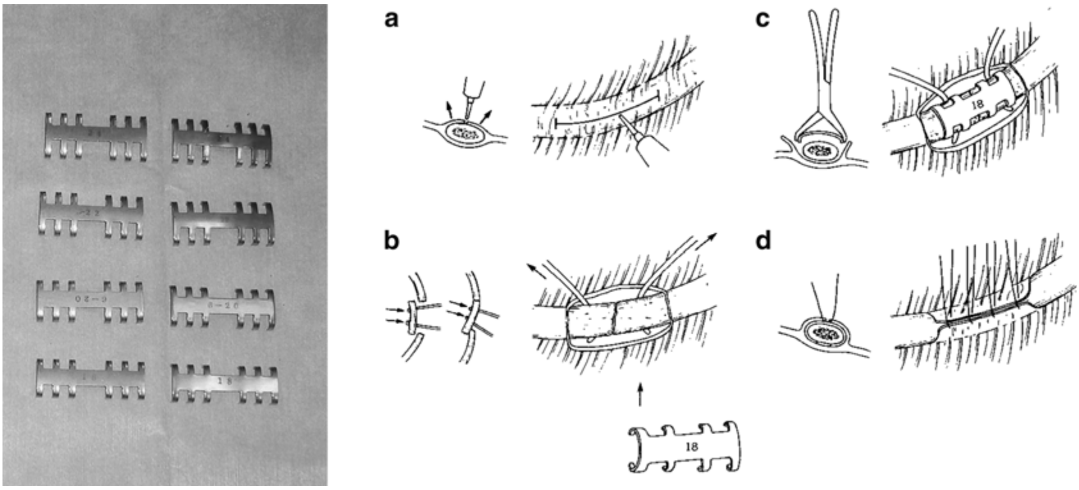

Fig. 4.4 Judet struts used for fixation of fractured ribs (Used with permission [12])

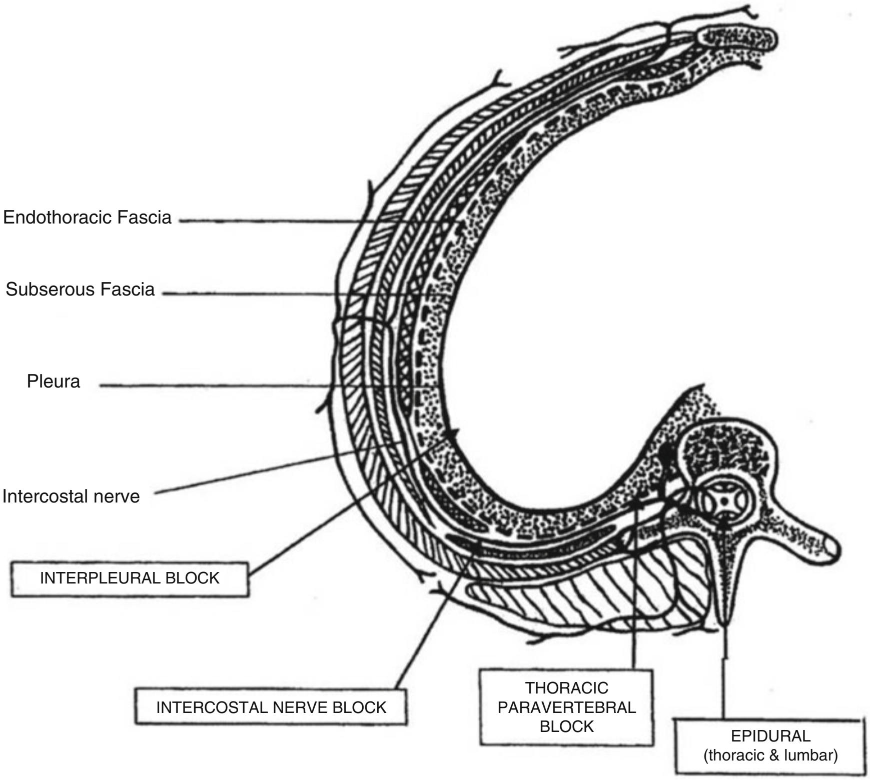

Fig. 4.5 Anatomic locations of regional anesthesia for treatment of flail chest injuries (Used with permission [14])

of respiratory failure, should be avoided [15]. Patients in respiratory distress should receive supportive mechanical ventilation and be weaned from the ventilator at the earliest time possible. Positive end-expiratory pressure (PEEP) and continuous positive airway pressure (CPAP) should be included in the ventilatory regimen [15].

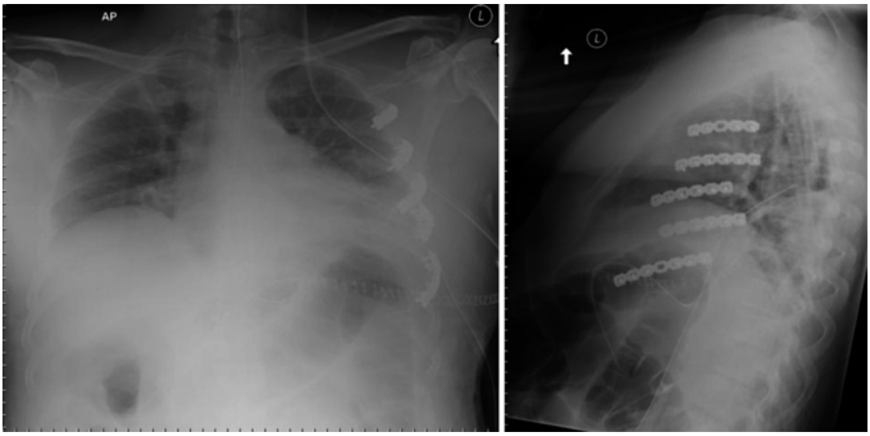

Fig. 4.6 Surgical treatment of multiple rib fractures with plate and screw fixation

Tube Thoracostomy

Patients with pneumothorax and/or hemothorax and signs of respiratory distress should undergo urgent tube thoracostomy. However, not all patients with flail chest injuries require chest tube utilization. Patients with a small pneumothorax may not require a chest tube initially; however, their condition should be monitored. If there is progression of pneumo-/hemothorax, or respiratory distress, the use of tube thoracostomy should be reconsidered. The use of positive pressure ventilation has the potential to turn a relatively small-sized or occult pneumothorax into a tension pneumothorax. Therefore, patients who require positive pressure ventilation should be monitored for development of obstructive shock and tension pneumothorax and undergo urgent tube thoracostomy if needed.

Pain Management

The optimal pain management is the key for treatment of patients with flail chest injuries. Pain management strategies include the use of regional anesthesia such as epidural catheters, intercostal nerve blocks, interpleural nerve blocks, and paravertebral blocks (Fig. 4.5) [14–16]. Other modes of pain management include use of oral and intravenous narcotic administration and patient-centered analgesia [1, 15]. The use of epidural catheters has been reported to be the most preferred method and leads to improved outcomes and lower complications when compared to other modalities [1, 15, 17]. Randomized controlled trials comparing epidural catheters to intrapleural catheters have demonstrated superiority of epidural catheters, with decreased pain, improved tidal volumes, and negative inspiratory pressures [17]. Epidural catheters have also been compared to intravenous narcotic use and have exhibited improved outcomes, such as improved subjective pain perception, pulmonary function tests, and lower rates of pneumonia, as well as decreased length of time on a mechanical ventilator or ICU stay [1, 15, 18]. They have also been shown to have lower rate of complications such as respiratory depression, somnolence, and gastrointestinal symptoms [15].

Chest Physiotherapy

Chest physiotherapy includes clearing pulmonary secretions with frequent suctioning and inspiratory spirometry, including incentive spirometry in those who have not been intubated [15, 19]. Aggressive chest physiotherapy should be practiced to minimize the likelihood of respiratory failure and decrease the risk of infection. However, percussive chest physiotherapy in a patient with multiple rib fractures must be carefully tailored to the patient's specific area of injury to avoid inflicting unnecessary pain. In this regard, direct communication between the treating physician and the physiotherapist is mandatory.

Surgical Fixation

Surgical fixation of flail chest injures includes ORIF with use of plates and screws or intramedullary nail fixation (Figs. 4.6–4.9). In the past decade, surgical fixation has become more popular than previously, although it is still not common practice. The increase in surgical fixation has been a result of multiple published studies in the early 2000s which report improved outcomes with surgical fixation of patients with flail chest injuries [7, 10–13, 20–22]. There have been several retrospective and nonrandomized comparative studies [11, 21, 22], as well as three randomized clinical trials [10, 12, 23] that demonstrate significantly superior clinical outcomes in patients treated with surgical fixation, compared to nonoperative treatment. The reported improved outcomes with surgical fixation compared to nonoperative treatment include decreased time on mechanical ventilation [10–12], decreased length of stay in the intensive care unit (ICU) [10–12, 21], decreased chest infections [10–12], earlier return to work [12], decreased chronic pain [21], and decreased long-term respiratory dysfunction [24, 25].

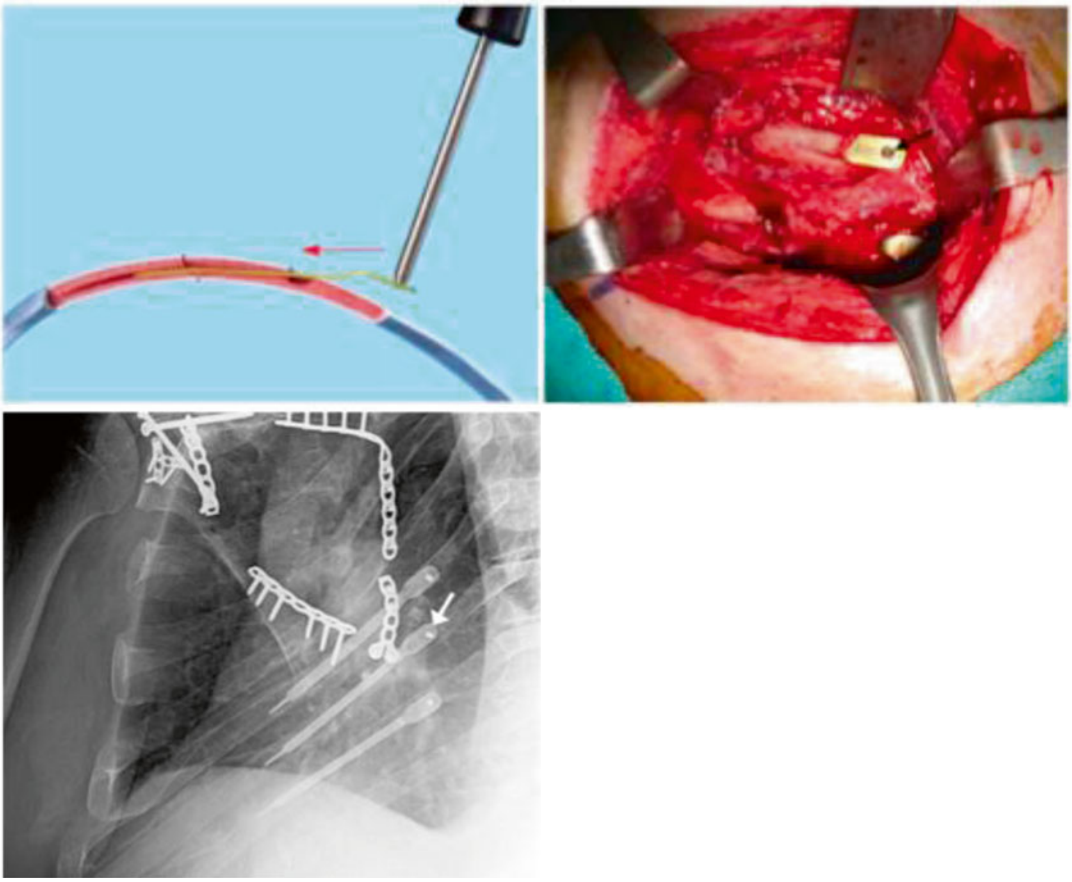

Fig. 4.7 Surgical fixation of fractured ribs with locked intramedullary implants (*arrow*). This patient has also undergone plate fixation of an associated scapular/glenoid fracture (Used with permission [8])

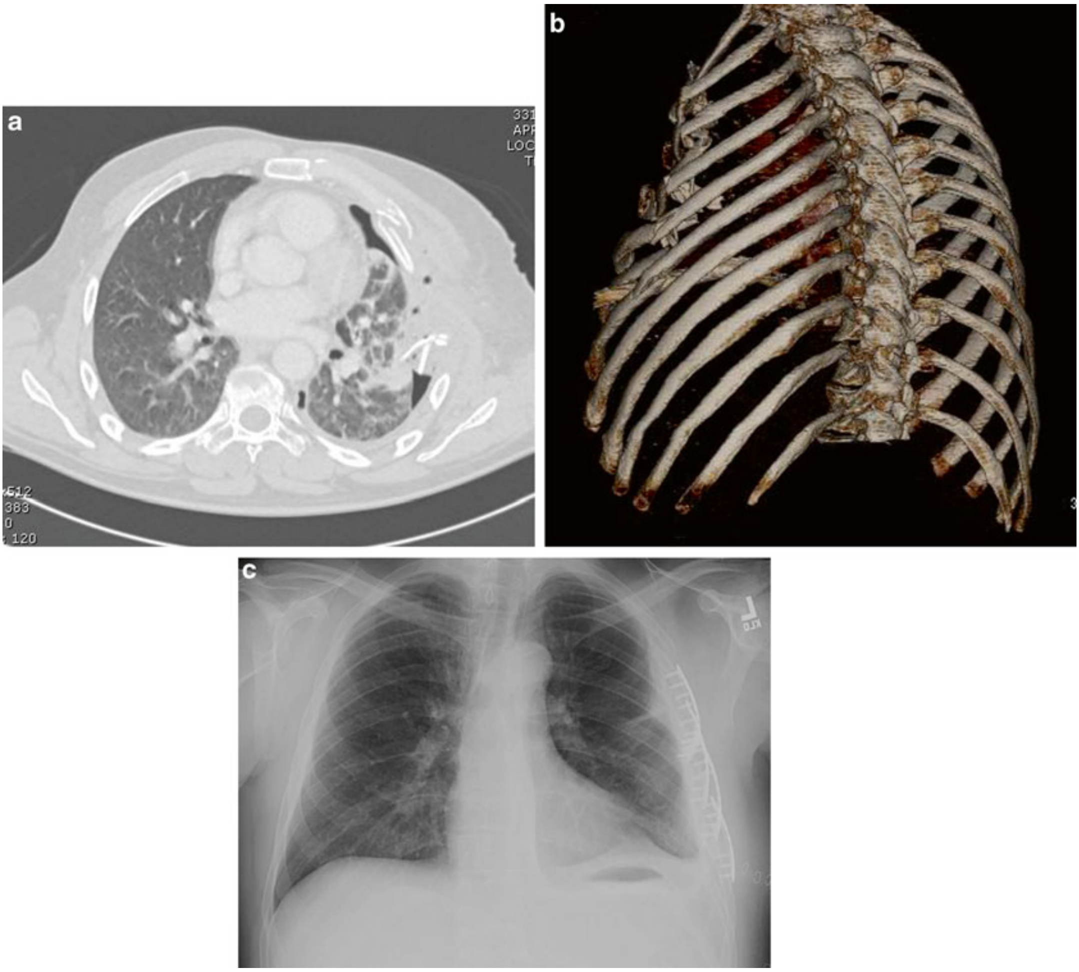

Fig. 4.8 (**a**) A CT scan demonstrates severe chest wall displacement with a flail segment in a polytrauma patient. There is an associated pneumothorax and significant lung parenchymal injury from displaced and penetrating ribs. (**b**) The 3D CT scan reconstruction demonstrates the anterolateral location of the flail segment. This type of 3D reconstruction is a valuable tool in the assessment of, and surgical planning for, these injuries. (**c**) Contemporary treatment through an anterolateral thoracotomy incision with plate fixation of four ribs, stabilization of the flail segment, and rapid re-expansion of the lung. Pulmonary function improved rapidly, and the patient was extubated promptly (case courtesy of W. Drew Fielder, MD, FACS)

However, randomized clinical trials in this area are limited. While studies demonstrate improved outcomes with surgical fixation, they have been criticized for small sample size, outdated methods of surgical fixation, and vague inclusion/exclusion criteria. High-quality studies and level I evidence in this area are still lacking.

Current Treatment Practices in North America

A recent study which utilized data from the National Trauma Databank examined current treatment practices for treatment of patients with flail chest injuries [16]. This study identified 3,467 patients with flail chest injury across 199

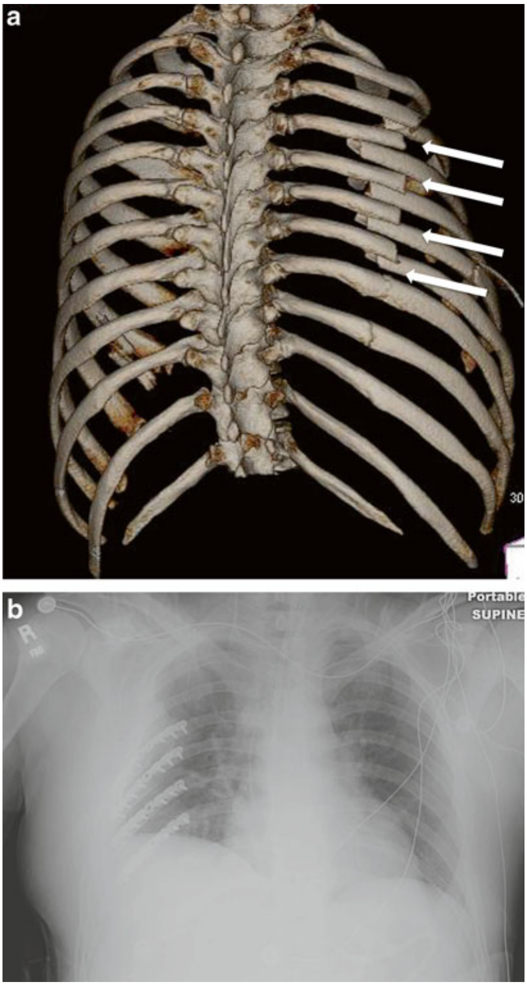

Fig. 4.9 (**a**) Multiple adjacent right posterior rib fractures with shortening and displacement resulting in an unstable chest wall injury. Modern imaging techniques, such as the use of 3D reconstructions of standard CT scans, greatly facilitate the surgeon's overall comprehension of the injury pattern, fracture location, and potential surgical approaches. (**b**) This patient had primary open reduction and internal fixation of the flail segment through a posterior approach (see Chap. 8) with an excellent clinical outcome. However, current National Trauma Databank information suggests that less than 1 % of trauma patients with this type of flail chest injury are treated in this fashion (case courtesy of W. Drew Fielder, MD, FACS)

centers in North America from 2007 to 2009. The results revealed that mechanical ventilation was required in 59 % of this patient group. The mean length of time on mechanical ventilation was 7.2 days for all patients and 12.1 days in the 59 % of patients who required mechanical ventilation. ICU stay was required in 82 %, and chest tubes were utilized in 44 % of patients. Only 8 % of patients received epidural catheters for pain management. Epidural catheters have been demonstrated to be the most effective mode of pain management for flail chest injuries [1], and perhaps its use is under utilized in this patient population. Surgical fixation of rib fractures was performed in 0.7 % of patients. Despite the recent interest in surgical fixation of flail chest injuries, according to this study, it appears that the majority of these patients are still being treated nonoperatively in North America.

Summary

Treatment of flail chest injuries includes operative and nonoperative management. Obligatory mechanical ventilation for the purpose of overcoming chest wall instability, in the absence of respiratory failure, should be avoided. Patients in respiratory distress should receive supportive mechanical ventilation, while PEEP and CPAP should be included in the ventilatory regimen. Optimal pain management is the key, and epidural catheters have been reported to be the most preferred method to improve outcomes and lower complications compared to other modalities. In the recent decade, there has been increased interest for surgical fixation of these injuries; however, further research and large-scale randomized clinical trials in this area are warranted to determine the best treatment strategy.

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The Nonoperative Management of Flail Chest Injury

5

Shalini Nair, Akhilesh Tiwari, and Andrew Baker

Investigation of Thoracic Injury

Thoracic trauma can lead to several different injuries, and investigations should be tailored to rule these out. A thorough approach should include both nonimaging studies and radiological investigations.

Nonimaging Studies

Apart from routine blood investigations, emphasis should be laid on interpretation of:

Arterial Blood Gases These can be used to gauge the severity of accompanying lung parenchymal injury. Hypoxemia and respiratory acidosis imply significant involvement of lung parenchyma and affect gas exchange.

Electrocardiogram Sternal injury may result in mediastinal involvement. Cardiac morbidity may be foreseen from the electrocardiogram.

Serum cardiac enzymes Troponin and creatinine phosphokinase should be evaluated serially. An upward trend may imply cardiac injury.

Radiological Investigation

A comprehensive set of imaging studies includes:

- *Chest X ray:* It is an integral part of management of thoracic trauma. Though it has a poor sensitivity in assessing rib fractures, it gives an initial assessment of the extent and severity of underlying injury. While evaluating clinically, the site and number of ribs fractured should be carefully assessed and correlated with the X ray. A chest radiograph can help diagnose lung contusion, hemothorax, pneumothorax, and mediastinal widening suggesting heart and great vessel injury (Fig. 5.1). Fractures involving upper ribs especially first and second ribs, along with the clavicle and scapula fractures, suggest high-velocity injury and a high likelihood of damage to intrathoracic structures [1].
- *Lung ultrasound:* Many of the injuries resulting from thoracic trauma are better demarcated by ultrasonography than on a radiograph. Ultrasound (USG) also has the advantage of being carried out bedside when compared to a CT thorax. USG can be very helpful to detect the presence of hemothorax, pneumothorax,

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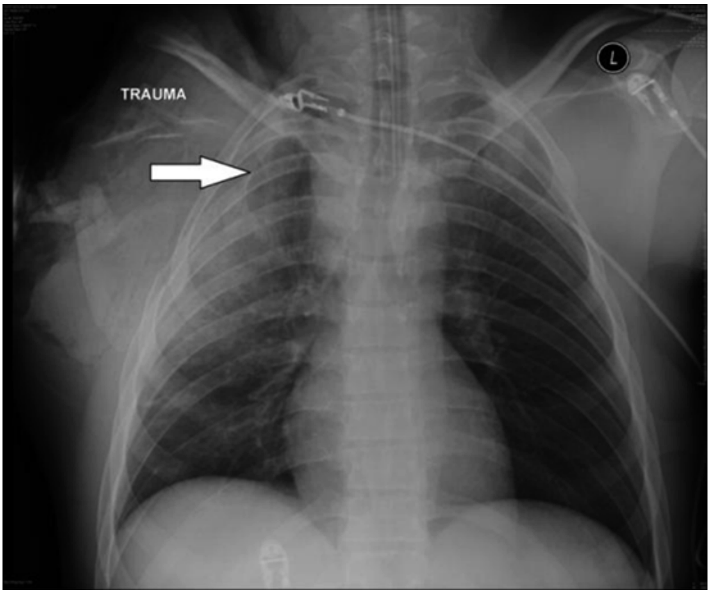

Fig. 5.1 Radiograph of flail chest with underlying lung contusion (indicated by *arrow*)

and pulmonary contusion. Once diagnosed, USG can also be very helpful to quantify and drain the hemothorax (Fig. 5.2).

On an USG, absence of lung sliding and the presence of lung point are considered diagnostic of pneumothorax. On the M mode, the absence of lung sliding is seen as absence of the normal granular pattern of the lung below the pleural line (Fig. 5.3). Other signs of pneumothorax can also be found. In Fig. 5.3, the linear pattern of the chest wall seems to extend below the pleural line. This is also called the stratosphere sign [2].

Lung USG can be used to diagnose pulmonary contusion and helps distinguish basal atelectasis from contusion after thoracic trauma (Fig. 5.4). The presence of a pulmonary contusion is associated with significant morbidity and long-term sequelae.

- *CT thorax:* is the gold standard for estimating the extent of thoracic injury, though difficulty in mobilizing the patient limits its value. Figure 5.5 shows a CT thorax with flail chest and underlying lung contusion and pneumothorax.

Nonoperative Treatment

The role of surgery in management of a flail chest has been limited in the past, and nonsurgical management alone has been the gold standard.

The principles of nonoperative treatment include:

- Immediate recognition and treatment of accompanying life-threatening injuries like hemo-/pneumothorax
- Bronchial hygiene and chest physiotherapy
- Adequate analgesia
- Optimizing fluid therapy
- Ventilation and treatment of hypoxemia

Immediate Therapy Sandor [3], while evaluating their case series, reiterated the importance of accompanying lesions in flail chest and stated that survival was based on correction of hypoxemia by decompressing a tension pneumothorax and aspiration of the bronchi. Undetected and untreated pneumothorax may account for many of the fatal cases.

Fig. 5.2 Ultrasound guided drainage of a retained hemothorax (see text for details). Courtesy of www.Criticalecho.com with permission

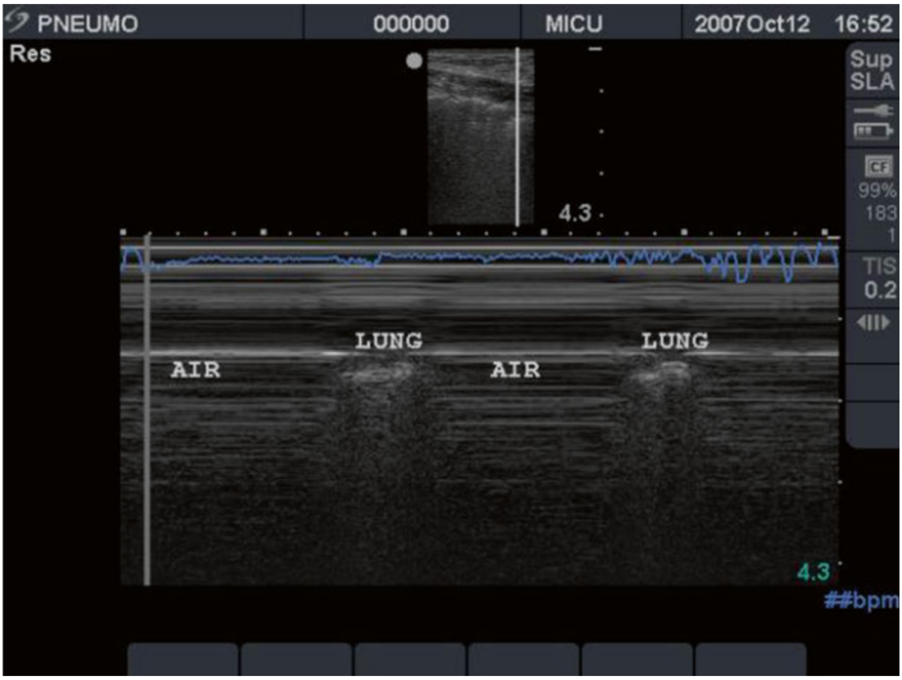

Fig. 5.3 Ultrasound demonstrates several findings consistent with a pneumothorax (see text for details). Courtesy of www.Criticalecho.com with permission

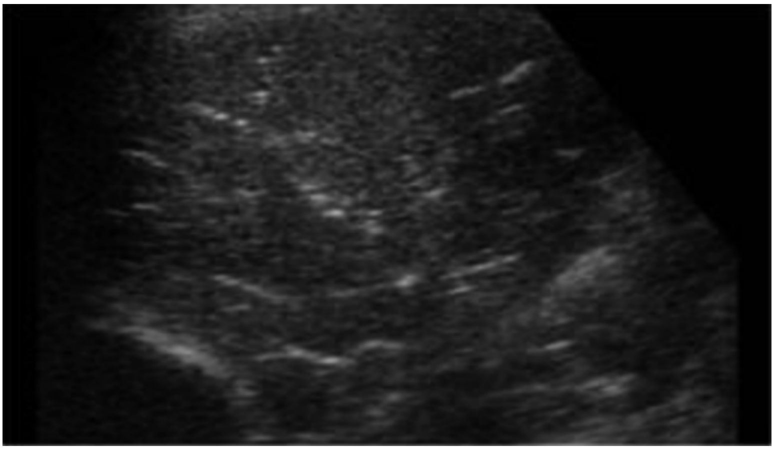

Fig. 5.4 Courtesy of www.Criticalecho.com with permission

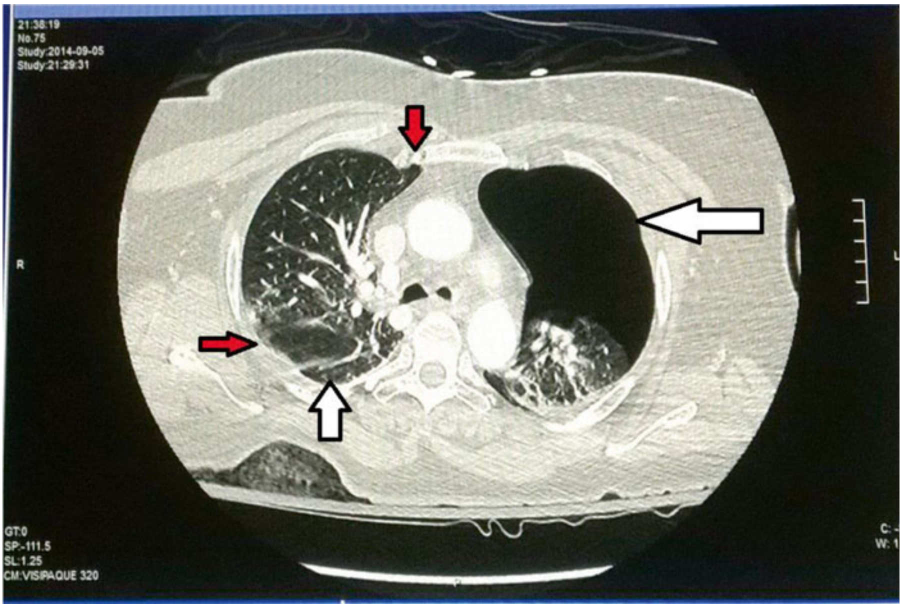

Fig. 5.5 CT thorax: showing a right-sided pneumothorax (*white arrow*), sternal fracture (*downward arrow*), left-sided flail segment (*red-colored sideward arrow*), and contused lung (*upward white arrow*)

In a series by Miller et al., of the 82 patients studied, 70 had associated pneumothorax or hemothorax. Immediate evacuation of the pleural space is life saving in thoracic trauma [4].

Bronchial Hygiene Retained secretions along with compromised cough due to pain can worsen hypoxemia. In the series by Sandor [3], delay in aspirating bronchial secretions caused three of the patients to deteriorate and two of them recovered immediately after bronchoscopy and lavage. Due to discontinuity of the flail segment with the rest of the thoracic cavity, coughing is not effective. The forceful expulsive component of cough is dissipated in paradoxical motion of the chest wall [4]. Chest physiotherapy, deep breathing exercises, and incentive spirometry are an integral part of the management of flail chest. Preventing basal atelectasis goes a long way in preventing hypoxemia.

Analgesia Pain contributes significantly to increased respiratory insufficiency in flail chest. Limited ability to cough and splinted, shallow breathing contribute to retained bronchial secretions and atelectasis. Analgesia therefore is a crucial component of management in flail chest. The various modalities of pain relief available are:

- Intravenous narcotics
- Epidural narcotic/anesthetic
- Intercostal nerve block
- Intrapleural anesthesia
- Thoracic paravertebral block

IV Narcotics Administration of narcotics has evolved from intermittent administration with poor pain control to patient-controlled analgesia (PCA). The latter enables the patient himself to control administration of bolus doses, in addition to a baseline flow in the wake of increased pain. This has increased patient comfort manifold.

However, the disadvantages of narcotics limit their usefulness in thoracic trauma. In the cohort of patients with flail chest, with a compromised breathing reserve, narcotic-induced respiratory depression is always a concern. Sedation, cough suppression, and hypoxemia are the other worrisome features of narcotic use.

Epidural Analgesia (EA) The pain management guidelines for blunt thoracic trauma provide a level 1 recommendation for epidural analgesia. The advantage of this modality is that it provides analgesia while the patient remains awake and cooperative for bronchial toileting. EA has been found to reduce the duration of mechanical ventilation in comparison to parenteral opioids [5, 6], improve pulmonary function (Forced Vital Capacity, lung compliance, decrease airway resistance) at 72 h [7], reduce the incidence of nosocomial pneumonia [5], and improve pain control with cough and deep breathing [7–9].

However, a meta-analysis of randomized controlled trials on the effect of epidural analgesia in patients with traumatic rib fractures showed no benefit of EA on primary outcomes such as mortality, ICU length of stay, and hospital length of stay [10].

Adverse Effects EA results in a higher incidence of hypotension than other modalities [7–9]. Other disadvantages of EA are that it is technically more challenging and needs expertise. Epidural hematoma, epidural abscess, and respiratory insufficiency due to a higher level of insertion are rare possibilities. Combining a narcotic with an anesthetic agent can help reduce the anesthetic-induced adverse effect.

Applicability By extracting the data from the national trauma data bank, Dehghan et al. found that EA was utilized in only 8 % of the patients. EA, however, was the preferred mode of analgesia [11]. In ventilated patients where motor assessment is not feasible, this mode of analgesia has significant risk and is not preferred.

Intercostal Nerve Block This modality involves injection of anesthetic agent into the posterior segment of the intercostal space of one rib above and below the fractured rib. Continuous infusion of anesthetic agent is feasible to produce effective analgesia. However, shorter duration of effect, multiple injections, and difficulty in cases of higher rib fractures makes this modality less favorable.

Intrapleural Analgesia This technique involves injection of anesthetic agent into the pleural cavity through a pleural catheter or through an existing thoracostomy tube. Introduction of a catheter runs the risk of creating a pneumothorax, whereas injection through an existing chest tube may warrant the tube to be clamped which can result in the development of a tension pneumothorax. For these reasons, intrapleural analgesia has not been a very popular modality of pain relief.

Thoracic Paravertebral Block This modality involves injection of anesthetic agent into the paravertebral space. Though it has a few advantages with respect to a lower incidence of hypotension and easier technique in comparison to EA, it is not much preferred due to lack of evidence regarding the benefit of this technique.

Nonsteroidal Anti-inflammatory Drugs When used alone, they are not good for pain relief in thoracic trauma. However, they are of immense importance when used in conjunction with opioids, as they reduce the dose needed for effective analgesia. Increased risk of coagulopathy, gastritis, and platelet dysfunction are factors unfavorable for their use in trauma.

Newer Modalities of Pain Relief A multimodal approach using concomitant use of multiple agents is preferable as a single agent leads to an unacceptable side effect profile. There cannot be a standardized protocol for choice of analgesic agent. It needs to be individualized based on factors such as site of involvement, number of ribs fractured, age, and accompanying thoracic and extrathoracic injuries.

Fluid Therapy

The landmark results from Trinkle et al. [12], in 1975, revolutionized the management of flail chest. They emphasized the damage from excessive fluid therapy which worsened the already contused lung. The management protocol devised by Trinkle et al. [12] included:

1. Restriction of IV fluids to less than 1,000 ml during resuscitation and 50 ml per hour thereafter.
2. Lasix 40 mg given intravenously immediately upon admission and daily for 3 days.
3. Salt-poor albumin 25 g (100 ml) given daily to maintain plasma oncotic pressure.
4. Blood loss replacement only with plasma or whole blood, or a combination of these, not with crystalloid solutions.

This sets the trend for increasing use of colloids rather than crystalloids to reduce lung edema. Animal studies have reiterated this approach [13].

The use of colloids in intensive care has undergone a periodic change from the safe trial [14] suggesting albumin to be safe to the CHEST trial [15] which concluded that starch (hydroxylethyl starch) increased mortality. Fluid restriction to an absolute volume is also not recommended to prevent hypoperfusion and organ damage. Dynamic assessment of intravascular volume status using stroke volume variation, pulse pressure variation, inferior venacaval collapsibility index and passive leg raise is routinely used in the ICU to judge fluid administration. The emphasis now is on preventing fluid overload rather than fluid restriction or on the choice of fluid.

Ventilation

- *Fundamentals of ventilation in flail chest:* Management of flail chest underwent a transition when external splinting using adhesives and bandages gave way to internal pneumatic stabilization with the advent of mechanical ventilation [16]. The aim of treatment was based on the myth that spontaneous respiratory effort would increase the paradoxical movement, thereby increasing respiratory insufficiency. Hence, management of flail chest without prolonged mechanical ventilation and often tracheostomy was considered to be fatal [17].

  In animal models, it was clearly shown with electromyographic evidence that there was increased force generated by external intercostal muscles, the most important for spontaneous inspiration. Therefore, cranial movement of a flail segment was not affected even when there was paradoxical inward movement in the anteroposterior dimension [18]. The mechanics of respiration were thus not much affected.

  Trinkle et al. were the first to elaborately prove that associated parenchymal injury, if dealt with efficiently, would yield good results even in the absence of ventilation [12]. Shackford et al. demonstrated that ventilation increased mortality and suggested that it should be used only to correct gas exchange abnormalities rather than chest wall instability [19]. The strongest proponents of internal pneumatic stabilization also agree on the fact that prolonged continuous positive pressure ventilation using deep sedation and muscle relaxants has a role only in anterior rib fractures. For posterolateral fractures, ventilation cannot prevent the flail segment from falling back on the lung parenchyma and increasing the damage [20].

- *Mode of ventilation:* Avery et al. introduced the concept of invasive mechanical ventilation (IMV) as a mode of stabilizing the chest wall in comparison to external surgical fixation [16]. However, the concept of prolonged ventilation with complete cessation of any spontaneous effort by using muscle relaxants and requirement of tracheostomy was not very appealing. Antonelli et al., for the first time, compared invasive with noninvasive ventilation (NIV) and showed no benefit of the former for mortality, while NIV reduced the incidence of serious complications and shortened the ICU stay [21]. Tanaka et al., using historical controls treated with IMV, compared the efficacy of NIV in patients with flail chest and found that the latter reduced the incidence of pulmonary complications and lowered the need for IMV [22]. The prospective controlled trial by Gunduz et al. reiterated that NIV caused fewer deaths (7 Vs 4) and pulmonary complications (10 Vs 4) in comparison to intermittent positive pressure ventilation IPPV. Oxygenation was poorer in the first 48 h in this group, probably due to difficulty in adjusting to the interface and pain. However, there was no need to intubate any patient on this account [23]. A recent systematic review and meta-analysis comparing NIV in chest trauma concluded that NIV did not have a mortality benefit. However, NIV significantly improved oxygenation, reduced serious complications and reduced need for invasive mechanical ventilation [24].

  The positive airway pressure delivered keeps the airway open and prevents chest wall distortion, and positive end-expiratory pressure (PEEP) prevents collapse and atelectasis. This improves gas exchange and reduces respiratory insufficiency. Gunduz et al., while comparing continuous positive airway pressure CPAP to IPPV, found better chest wall stability with CPAP. The high flows of 80–100 l/min causing positive pleural pressure and minimal load of the high gas flow system help sustain the chest wall stability [23].

- *Contraindication of NIV:* NIV would be contraindicated in instances where the interface between face and mask would be harmful or the positive pressure would be deleterious. This would include the following:
  1. Apnea
  2. Shock
  3. Faciomaxillary injury
  4. Head injury
  5. Esophageal injury
  6. Low sensorium
  7. Excessive airway secretion and poor cough

  The use of NIV warrants close monitoring and repeated bedside evaluation of the patient for early recognition of worsening respiratory insufficiency and need for intubation.

- *Indication for IPPV:* It is now indisputable that routine use of IPPV is not needed in the management of flail chest [12]. IPPV is indicated based only on clinical criteria. Richardson et al. [25] outlined clinical criteria for intubation and use of IPPV while evaluating the efficacy of selective management of flail chest and pulmonary contusion. These were:
  1. Hypoxia and respiratory distress
  2. Major associated injuries such as shock or severe neurologic injury
  3. The necessity for general anesthesia
  4. Obstruction of the airway

  Hypoxia was defined as a P02 less than 55 mmHg on room air in patients maintained on Fi 02 = 0.20 or less than 60 mmHg receiving supplemental oxygen.

More than 50 % patients with flail chest required intubation due to accompanying injuries, most commonly, severe head injury or a need for laparotomy. Though half of flail chest patients needed IPPV, the duration of ventilation was short at an average of <3 days [26]. Lucas et al. and Shankaran et al. also tried evaluating predictors for immediate intubation in patients with flail chest. Accompanying injuries (head injury and need for laparotomy), shock (need for multiple transfusions), and bilateral flail chest have been a few predictors for intubation [26, 27]. Age and radiological extent of contusion do not predict clinical severity of hypoxemia or need for intubation [25, 28].

- *Modes of IPPV:* There is no ideal mode of ventilation for management of flail chest. Pinella et al. compared controlled mode of ventilation to intermittent mode of ventilation in two varying time periods in flail chest patients. They did not find any mortality benefit or reduction in duration of ventilation in the two groups. Oxygenation was observed to be better in the group using intermittent ventilation [29].

  With contusion to underlying lung, peak pressure may raise high during ventilation. In such instances, use of a pressure-controlled mode could be beneficial to prevent barotrauma. Newer modes like airway pressure release ventilation (APRV) with optimum T high (time with high pressure limit) and T low (time with low pressure) help maintain PEEP and deliver adequate volume with less risk for barotrauma.

  High-frequency oscillation ventilation is another mode where a very high frequency of respiration with low tidal volume helps maintain adequate minute ventilation with lower risk for barotrauma.

  In cases of unilateral lung involvement, independent lung ventilation of the normal lung using a double lumen endotracheal tube is also feasible.

- *Ventilator settings:* In the era of internal pneumatic stabilization, the impact of positive end-expiratory pressure (PEEP) was realized by McGee and Trinkle [30]. In canine models, they were able to demonstrate reduction in the size of lung contusion by application of PEEP. The effect was reproduced in humans by Sladen et al. by progressively increasing the PEEP to 10–15 cm of H_2O [31]. Flail chest is very often accompanied by pulmonary contusion. A low tidal volume ventilation, as in acute respiratory distress syndrome (ARDS) with high PEEP, is advocated in this scenario too. A lung protective strategy with plateau pressure <35 cm H_2O using 6 ml/kg tidal volume and open lung therapy with high PEEP helps optimize oxygenation. This method of ventilation runs the risk of increasing the intrathoracic pressure and reducing the venous return to the right heart, thereby causing hemodynamic instability. Therefore, optimization of PEEP should be based upon the peak airway pressure and hemodynamic stability.

Steroids

The concept of using steroids in flail chest dates back to the regimen laid out by Trinkle et al. [12]. Steroids are believed to reduce the inflammation in the underlying contused lung. Experimental studies in animals have shown reduction in volume of contusion in the lungs on administration of steroids within 30 min of induced injury [32]. A similar instance of benefit from steroids is assumed in ARDS. Though randomized controlled trials (RCT) have shown benefit by curtailing inflammation [33], their role in therapy is not well established. A meta-analysis of eight RCTs and ten cohort studies revealed a trend toward reduced mortality in the ICU, but nonsignificantly increased 60-day mortality. In influenza-related ARDS, steroids significantly increased mortality [34]. Similarly, the Eastern Association for the Surgery of Trauma (EAST) guideline gives a level 2 recommendation not to administer steroids in the contused lung [35].

Antibiotics

Prophylactic use of antibiotics even in the presence of lung contusion is not indicated in flail chest. The role of antibiotics arises only if pneumonia develops. 44 % of patients with flail chest still develop pneumonia, more so, with contusion of underlying lung [36]. The choice of antibiotic should be guided by culture and sensitivity reports with a narrow spectrum to prevent development of resistance.

Outcome

Rib fractures occur in 39 % of thoracic trauma [37] and flail chest develops in one out of 13 patients with fractured ribs [12]. It is associated with high mortality and long-term morbidity. The average mortality is estimated to be 10–20 % [38].

Borman et al., while evaluating mortality in flail chest, estimated it to be 20 % with 68.5 % occurring within 24 h. They attributed it to the severity of injury and the fact that evacuation time was short in their series; many of the non-salvageable victims were still alive when they reached the hospital [39]. Trinkle et al. [12] considered untreated hemopneumothorax to be the leading cause of early mortality in flail chest, while Athanasiadi et al. did not find hemopneumothorax to have any impact on mortality [40].

Delayed mortality is predominantly secondary to prolonged ventilation and its complications. ARDS, pneumonia, and sepsis have been contributory.

Risk Factors Affecting Outcome

1. *Accompanying injuries* play an important role in determining the outcome. Injury severity score (ISS) has been shown to be a strong predictor of morbidity and mortality [40, 41]. Head injury has been consistently found to be the commonest accompanying injury and is associated with increased mortality [42, 43]. Killic et al. found ISS to increase from 55.7 with flail chest alone to 75 when accompanied with a cranial injury and mortality increased from nil to 19 % [44].
2. *Age:* Flail chest occurring in the elderly has always been associated with poor prognosis. Fragile bones with low elasticity are thought to make them predisposed to severe injury. Richardson et al. opine that the elderly usually sustain flail chest with minor injury without much damage to the underlying lung parenchyma and hence may not have a bad outcome in comparison to the young with greater damage to the lung [13].

   Albaugh et al. analyzed age-adjusted outcome of flail chest injury in the elderly. They found a 130 % increase in mortality for every 10-year increase from the second decade onwards [45]. Miller and colleagues too observed a linear relation of age with mortality in patients 40 years or older. However, younger patients did not have a similar relation [4].
3. *Pulmonary contusion:* Flail chest or pulmonary contusion when present alone lead to death in 16 % of patients, whereas when both exist together, the mortality increased to 42 % [46]. The presence of contusion also increases morbidity with a higher chance of developing pneumonia, ARDS, and the need for ventilation [47, 48].

Long-Term Sequelae

The initial follow-up studies focused on the effect of persisting chest wall deformity and its effect on lung physiology. Landercasper et al. and Beal and Oreskovich found abnormal spirometry and persistence of chest pain in the survivors of flail chest [49, 50]. Kishikawa and his colleagues first recognized the effects of lung contusion on long-term sequelae [51]. They found that lung functions returned to normal within six months if there was no underlying lung contusion, whereas gas exchange mechanisms continued to be impaired for many years if lung was contused [51].

Summary

The nonoperative management of flail chest has come a long way over the last few decades [52]. However, high mortality, morbidity, and complication rates still prevail. More dynamic methods of fluid management, vigorous bronchial hygiene, and ever-evolving ventilation techniques should be utilized to improve outcome in this cohort of patients.

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Biomechanics of Rib Fracture Fixation

6

Michael Bottlang and William B. Long

Introduction

Despite recent advances in osteosynthesis hardware and clinical evidence of improved outcomes and reduced cost [1, 2], rib fixation remains underutilized [3] and might be indicated in a broader range of cases than is currently performed [4]. This fact has been demonstrated by a recent survey among 238 trauma, orthopedic, and thoracic surgeons: 76 % agreed that rib fracture fixation was indicated in select patients, but only 26 % had ever performed or assisted in rib fracture repair [5]. The slow adoption of rib fixation with contemporary implants can likely be attributed to two factors: (1) the challenges inherent to rib fracture fixation and (2) a long (60 year) history of rib fracture fixation with implants that provided marginal fixation and were difficult to use [6]. To better appreciate the recent advances in rib fracture fixation, this chapter first reviews biomechanical and clinical challenges inherent to rib fracture fixation and then provides an overview of historic implants and their shortfalls. It concludes with a description of contemporary implants for rib fracture fixation, including the biomechanical rationale underlying their design and evidence from basic science and clinical studies.

Inherent Challenges of Rib Fracture Fixation

When the combined evidence from biomechanical and clinical studies reported on rib fracture fixation over the past 60 years is reviewed, five inherent challenges unique to rib fractures emerge that deserve special consideration for rib osteosynthesis.

Ribs Are Always Load Bearing

Unlike all other fractures, rib fractures cannot be protected from physiologic loading during the healing period, since the rib cage has to support respiration, coughing, and patient mobilization. Therefore, rib osteosynthesis needs to instantly deliver sufficient stability to restore normal rib function. From a biomechanical perspective, the stability of a rib fixation construct is characterized by two aspects: its strength and durability. Strength describes the maximal load a construct can sustain before fixation failure occurs. How strong should a rib fixation construct be? Ribs not only need to tolerate respiratory loading but also patient mobilization, resuscitation interventions, and coughing. Since coughing by itself can lead to spontaneous rib fractures, Rehm argued that an ideal rib fixation construct should restore the full strength of the native rib [7]. Durability describes the construct's ability to sustain prolonged dynamic loading. Assuming 12 respiratory cycles

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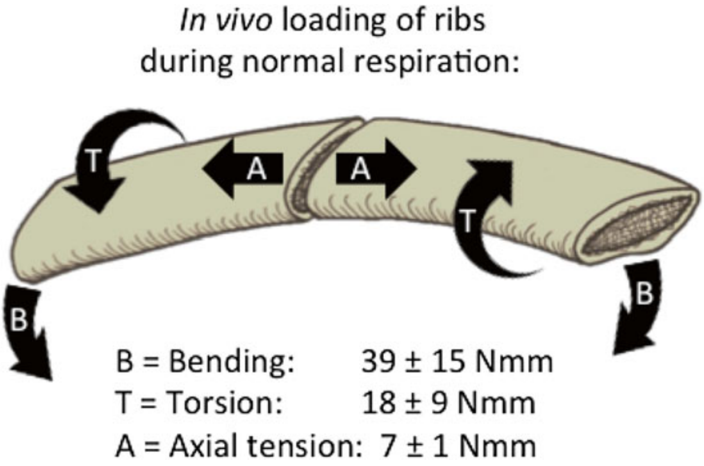

Fig. 6.1 Rib loading during normal respiration was measured by Rehm et al.'s [7] finding that bending is the dominant loading mode

per minute and a 3-week period until a fracture callus can stabilize the rib fracture sufficiently to unload the fixation construct, an implant has to sustain well over 360,000 respiratory loading cycles [8]. Rib loading during respiration has been measured in vivo in six patients (17–50 years) undergoing rib resection for bone graft harvesting [7]. A 1.5 cm gap osteotomy in ribs 5, 6, or 7 was bridged with a small fragment plate that was instrumented with strain gauges. The instrumented plate captured torsional, axial, and bending loads during spontaneous respiration. Highest loads were measured in bending (39 ± 15 Nmm), followed by torsion (18 ± 9 Nmm). Axial loading was in tension (7 ± 1 N) (Fig. 6.1). Rib bending loads during coughing of 924 Nmm have been extrapolated from thoracic pressure reports [9].

For the biomechanical evaluation of the stability of a rib fixation construct, two tests are desirable: A dynamic test for at least 360,000 loading cycles at or above respiratory loading and a static test to failure to determine the construct strength. The latter test will also reveal the failure mode, which is caused by implant breakage, fixation failure, or rib fracture adjacent to the implant. While simplified biomechanical tests are crucial to detect and eliminate design flaws, results cannot predict clinical performance due to several inherent limitations. For example, biomechanical testing cannot replicate complex in vivo loading, and it cannot account for secondary stabilization due to callus formation, adjacent ribs, and/or intercostal soft tissues. Therefore, prospective clinical studies are an essential complement of biomechanical studies in order to assess implant function in the clinical realm. Despite the obvious need for combined biomechanical and clinical evaluation of implants, this strategy remains rare at best among the many implants that have been employed for rib osteosynthesis.

Ribs Are Highly Elastic

Unlike most long bones that have a cylindrical cross section to maximize bending rigidity, ribs have a pronounced oval, tear-shaped cross section [10] and nonuniform cortex distribution [11] to maximize elastic flexion in bending (Fig. 6.2). The rib cross section is on average approximately half as wide as high [10]. Moreover, the anterior and posterior cortices are considerably thicker than the superior and inferior cortices, which are on average only 0.5 mm thick [10]. Owing to their oval cross section, thin inferior and superior cortices, and curved structure, ribs can elastically bend more than any other skeletal structure. Schultz et al. demonstrated that 0.75 kp loading caused 3–8 cm deflection of ribs 4–10 without

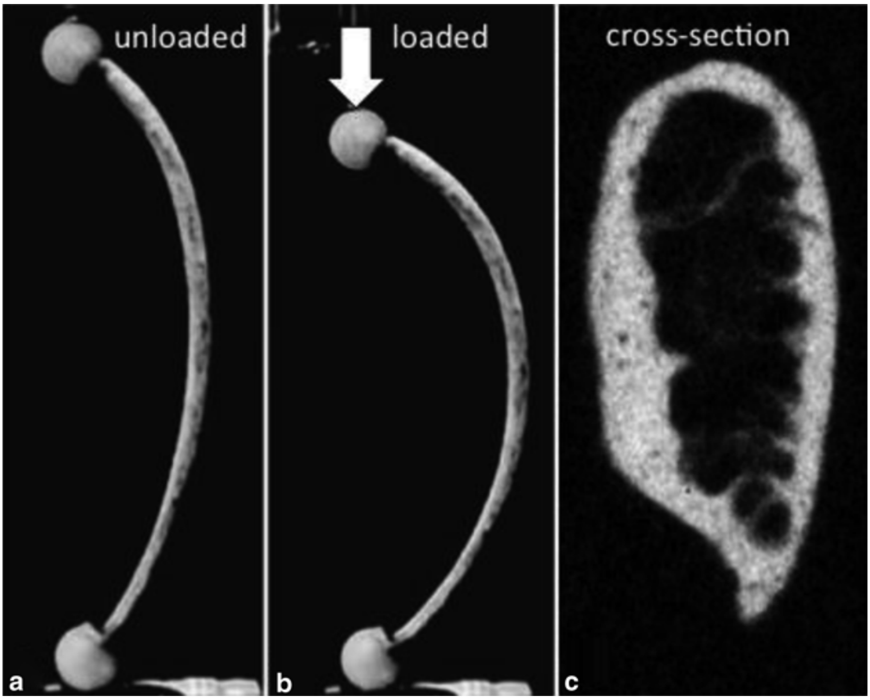

Fig. 6.2 The same rib is shown relaxed (**a**) and loaded (**b**). Ribs can elastically flex more than any other long bone due to their pronounced oval cross section and non-uniform cortex distribution. (**c**) This cross-section of a rib demonstrates it's oval nature

inducing failure [12]. In a more drastic description, Fick stated that the sternum in children can be compressed up to the spine without inducing a rib fracture [13].

Accounting for the high bending elasticity of ribs is of crucial importance for implant design. If a rib plate is stiffer than the rib itself, it will resist bending and will induce high stresses at the plate end (Fig. 6.3). This in turn will either lead to pullout of the outermost screws, or to rib fracture through the outermost screw hole [7, 14, 15]. Since the bending strength of ribs decreases by approximately 50 % from age 50 to 80 [16], prevention of stress risers caused by overly stiff implants becomes an even greater concern in the elderly population, particularly in patients with osteopenic bone. From a clinical perspective, implants designed for normal bone may not perform reliably in osteopenic bone. From a biomechanical perspective, it is therefore crucial that rib implants are tested not only in specimens representative of normal bone quality but also in osteopenic rib specimens.

Ribs Are Thin

The average width of ribs 4–9 reported for 5 human cadavers ranges from 6.0 to 7.6 mm [10]. Approximately 2/3 of this width is comprised of the intramedullary canal that provides little structural support for implant fixation. Among ribs 4–9, the average thickness ranges from 0.9 to 1.4 mm for the inner cortex and from 0.7 to 0.9 mm for the outer cortex. Hence, bicortical screws have on average less than 2 mm of cortex thickness to gain secure and durable purchase. Since the holding power of conventional screws is directly proportional to the length of engagement in cortical bone, it becomes apparent that screw stripping during insertion and screw loosening or pullout after insertion were common modes of failure before the advent of modern locking plates [15, 17, 18]. Intramedullary fixation with Kirschner wires can overcome this limitation by providing a line contact between the implant and the rib canal, thus distributing loads more evenly, rather than concentrating load

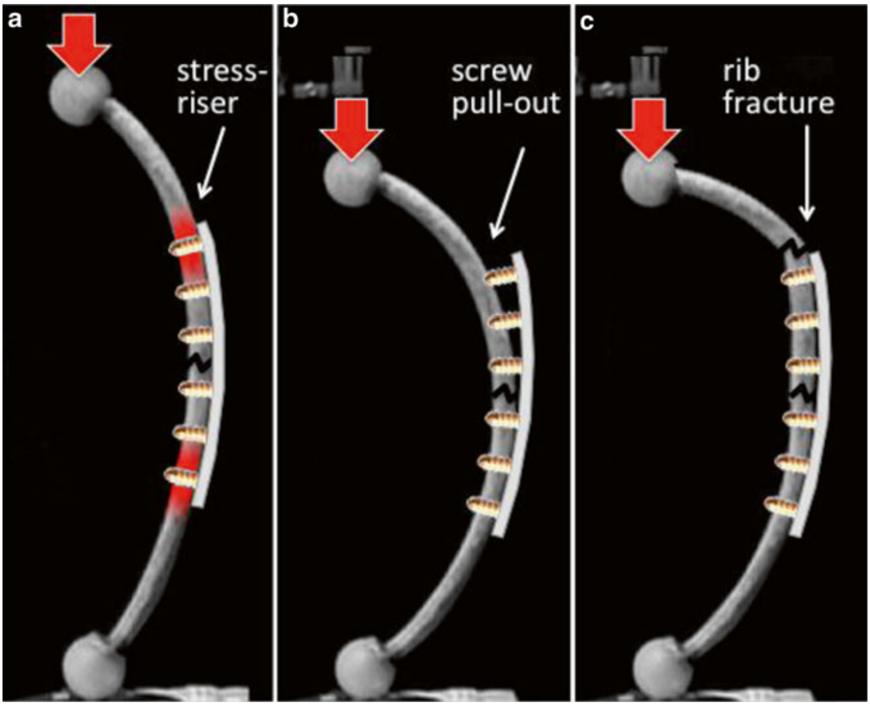

Fig. 6.3 Stiff implants will resist bending and induce stress risers at the plate end (**a**), leading to screw pullout (**b**) or rib fracture (**c**) at the plate end

transfer to discrete screw fixation points. However, Kirschner wires are also prone to migration [19–22] and cutting out through the cortex in the presence of osteoporotic bone, which can have serious negative clinical consequences [17, 23].

Ribs Have a Complex Geometry

The principles of fracture fixation with plates and screws require that a rib plate traces the rib diaphysis and remains in contact with the rib surface over the entire plate length to achieve a durable fixation construct [24]. Fitting a short plate for fixation of a single rib fracture can readily be accomplished by out-of-plane bending to the general curvature of the rib. However, contouring a longer plate for bridging of a comminuted fracture or multiple fractures is complicated for three reasons [25]: First, the outer surface of a rib is not part of a cylinder but rather conical [10]. Therefore, when bending straight plates towards the rib surface, longer plates tend to diverge off the rib (Fig. 6.4a). Second, fixation of a flail segment often requires long plates that can span the fractures on both ends of the unstable rib segment [26]. With increasing length, plates are more likely to deviate from the narrow rib surface. Finally, the rib surface is twisted around the rib longitudinal axis [10], requiring twisting of plates [15]. Despite this complexity, contouring of plates to the rib surface is important since deficient contouring may lead to suboptimal fixation and patient discomfort due to prominent hardware [17]. Consequently, intra-operative contouring of plates to the rib surface can be difficult and time-consuming and may yield suboptimal plate fit and fixation strength [15, 24].

A recent biomechanical analysis of ribs delineated the complex rib surface geometry into three basic parameters pertinent for plate contouring, namely the general “out-of-plane” curvature, the conical contour, and the twist characteristic for ribs three through nine (Fig. 6.4b, c) [10]. The general curvature ranges from $3.8 \pm 1.5\ \mathrm{m}^{-1}$

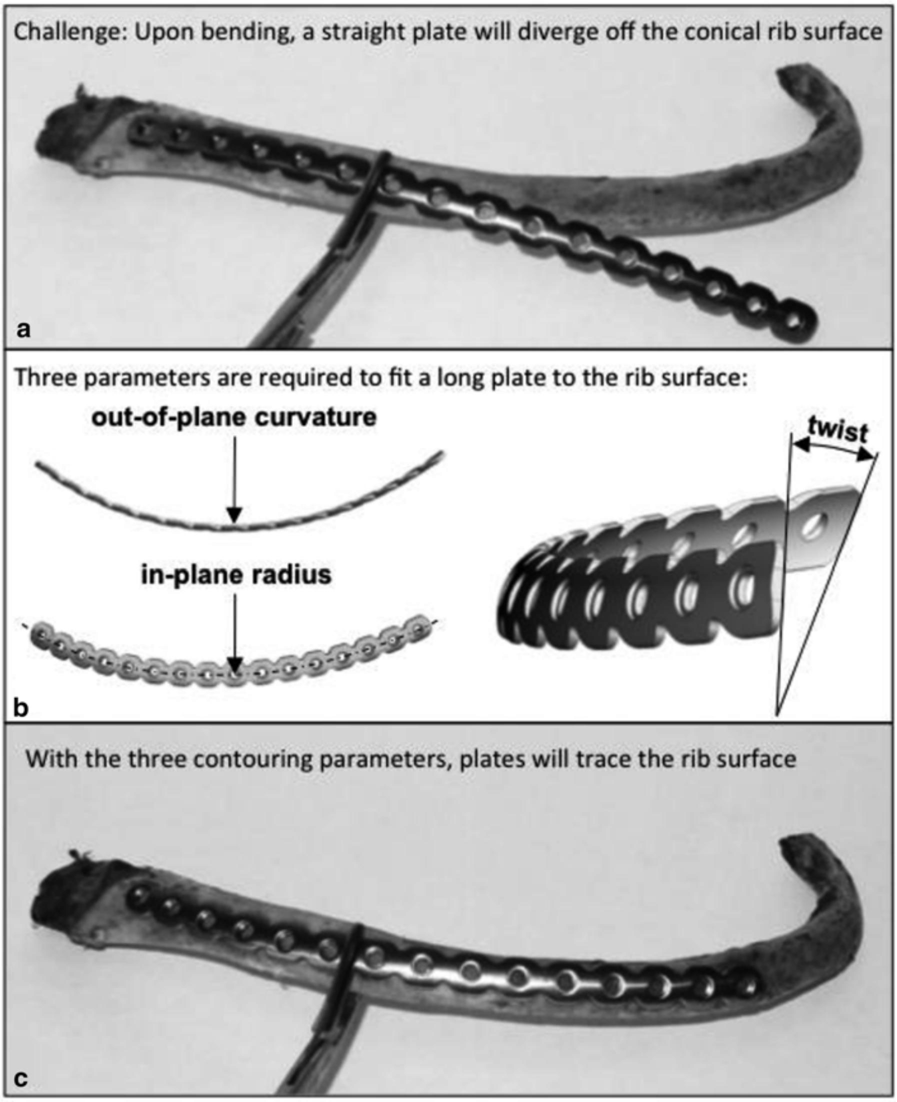

Fig. 6.4 To avoid the typical plate diversion from the conical rib surface (**a**), a plate must have the appropriate "in-plane" radius and twist in addition to the "out-of-plane" curvature (**b**). After accounting for these three contouring parameters, a long plate will trace the rib surface (**c**)

at the lateral aspect of rib 7 to 17.3 ± 1.7 m^{-1} at the anterior portion of rib 3. The conical contour of the rib surface requires rib plates to be contoured with an in-plane radius of 20–40 cm in order to trace the rib surface upon plate bending to the general rib curvature. Finally, rib surfaces have a characteristic twist of 40° to 60°. Left ribs are twisted clockwise and right ribs are twisted counterclockwise, for which reason plates contoured to a right rib surface may not fit the contralateral left rib. Clinically, in fracture situations where a long plate is required, anatomically precontoured rib plates may not only reduce the time and complexity of the operative procedure, but may also support durable, low-profile fixation to minimize implant-induced discomfort in the presence of a thin soft-tissue envelope. For fracture patterns where a shorter (6–8 hole) plate is sufficient, simpler plate designs may suffice.

Rib Fractures Can be Complex

Implants for rib osteosynthesis have to accommodate a wide range of fractures. Since the extent of rib fractures is generally underestimated on radiographs, a preoperative CT scan is recommended to better assess the extent and type of fractures [27]. Intramedullary fixation or short plates can stabilize a simple fracture in a less-invasive manner, but may not be able to bridge and stabilize a comminuted, unstable fracture zone. Long bridging plates that can suspend a flail segment by spanning both associated fractures have been considered fundamental for operative stabilization of a flail chest [26, 28]. Long pre-contoured plates can furthermore serve as a reduction template to restore the physiologic geometry of a comminuted fracture zone or flail segment. From this consideration, it appears unlikely that a single fixation device can satisfy the competing demands for less-invasive fixation of simple fractures and spanning fixation of comminuted fracture or flail segments.

In summary, implants for rib fixation should ideally be strong enough to support peak loading, sufficiently elastic to prevent stress risers, able to provide durable fixation in the presence of thin, osteoporotic ribs, anatomically contoured to eliminate the complexity of intra-operative implant bending, and able to stabilize simple as well as comminuted fractures. Given this list of essential implant requirements, it becomes apparent why many prior implants fell short of expectations and hindered the adoption of surgical fixation as an effective clinical tool for management of rib fractures. Furthermore, it becomes evident that dedicated implants for rib fracture fixation have many potential clinical advantages.

Historic Approaches

This review focuses on extramedullary and intramedullary implants for rib fixation. It does not include wiring techniques or external stabilization with fixators and elevators, which have been abandoned due to their lack of practicality and their inability to provide consistent and pain-free stabilization.

Extramedullary Fixation

Historically, three different modes for fixation of plates to ribs have been used, which are wire or suture cerclage, screw fixation, and elastic claws. Early rib plates were applied with sutures or cerclage wires. The 1917 Surgery Manual of Bier et al. describes the application of Hansmann's bone plate for stabilization of simple, transverse rib fractures using trans-cortical sutures (Fig. 6.5a) [29]. In 1972, Paris et al. introduced rib struts that were up to 40 cm long to span and suspend multiple flail rib segments [30]. These struts were applied along the rib, between ribs, or across ribs using sutures and were routinely removed upon fracture healing (Fig. 6.5b). Low-profile plates for cerclage fixation that did not require routine removal were introduced by Thomas in 1978 [31] and by Vecsei in 1980 [32] (Fig. 6.5c). Both plates had lateral slots to prevent cerclage wire slippage. In addition, the Vecsei plate had small surface spikes to prevent slippage of the flat plates on the rib surface. The flat cross-sectional profile of the plate (1 mm × 14 mm) precluded in-plane contouring; therefore, these plates were only available up to a length of 8 cm and did not allow bridging of a flail segment. Furthermore, tightening of cerclage wires could cause cortical transection and poses a risk to the neurovascular structures at the inferior aspect of ribs [7].

With the introduction of standardized implants and instruments by the Arbeitsgemeinschaft für Osteosynthesefragen (AO), standard small fragment, 1/3 tubular, and reconstruction plates quickly became the most frequently used plates for rib fracture fixation [33]. These standard plates accommodate in-plane contouring and provide sufficient stability to suspend a flail segment. However, it quickly became apparent that these plates were too stiff and caused stress concentrations that contributed to screw pullout, most prominently of the screws at the plate end, or total loss of fixation [15, 17, 18, 33]. It is important to note that screws at that time were not self-tapping, non-locking, and that tapping of cortical screw holes was not routinely performed. Furthermore, Labizke stated that standard plates required bending and twisting in this situation,

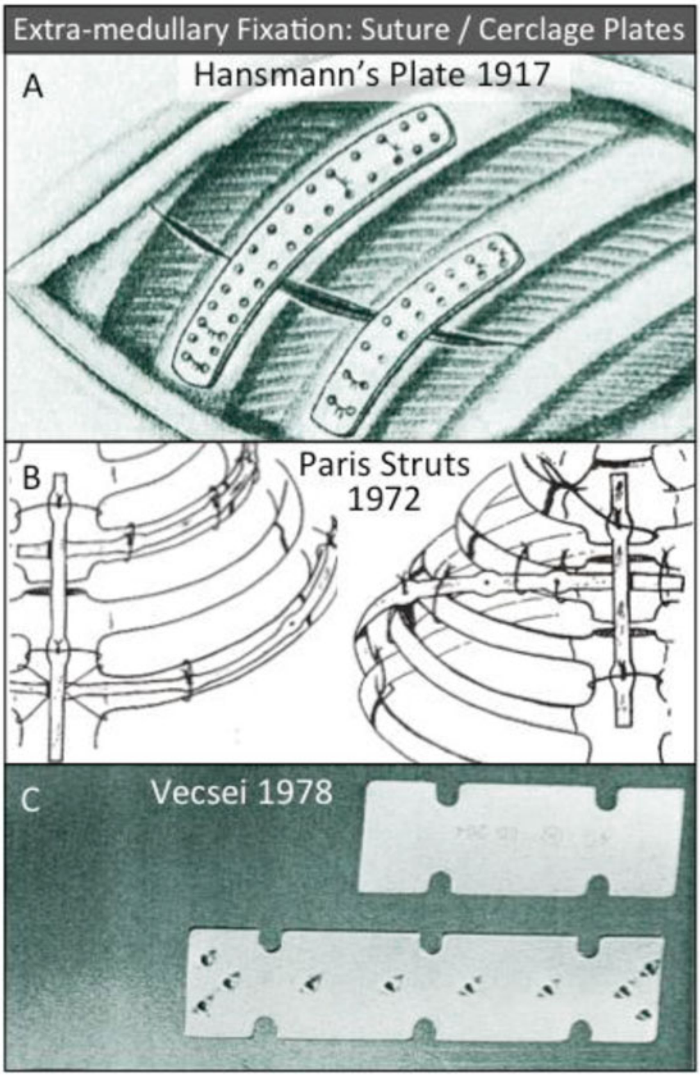

Fig. 6.5 Early plates and struts were attached to ribs with wire or suture cerclage

making their application technically demanding and time-intensive [15]. For plate contouring of standard plates, Oyarzun recommended that the rib fracture should be reduced first, a template should be contoured to the rib surface, and a plate should be contoured to the template using bending irons, pliers, or a bending press [24]. This complexity frequently required a team approach, whereby the general/thoracic surgeon provided the operative exposure and collaborated with the orthopedic service for plate fixation [3].

The limitations common to generic plates prompted a subsequent generation of rib plates that utilized claws for fixation, with the hope of providing better fixation than screws and simpler fixation compared to cerclage techniques [15, 34]. The Judet plate (1973) had clawed end sections and a flat central section of 5.3 cm length suitable for spanning a single fracture [34, 35]. It was only 0.7 mm thick, which facilitated bending of the claws to the rib using a special forceps (Fig. 6.6a). The Labitzke claw plate was the first rib plate specifically designed to accommodate in-plane bending [15]. Its "self-gripping" claws also allowed supplemental fixation with 2.7 mm screws (Fig. 6.6b). It was sufficiently flexible to closely conform to the conical surface over long rib sections. While the Labitzke plate could span both

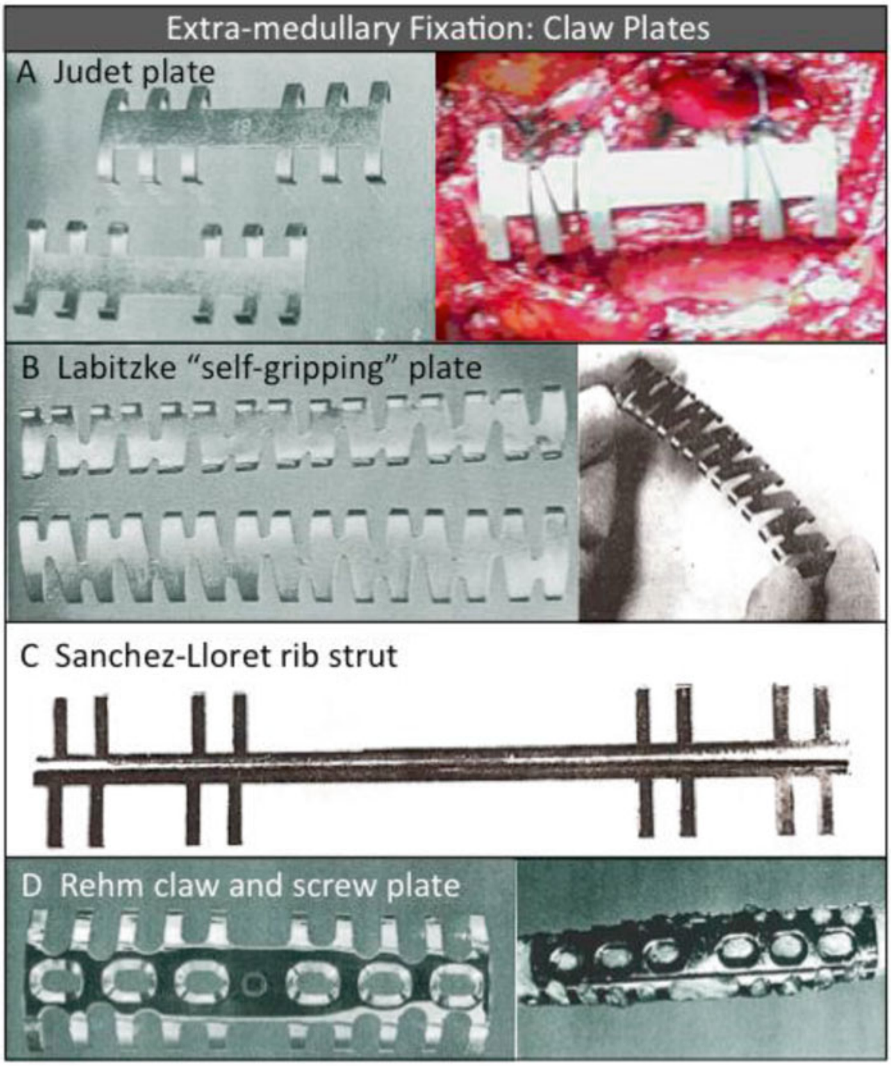

Fig. 6.6 Rib plates with "claw" fixation were introduced to overcome poor fixation of generic plates with (non-locking) screws

fractures of a flail rib segment, its high flexibility necessarily limited the ability to suspend a flail segment. Moreover, since claw fixation required soft-tissue stripping to provide an adequate grip for the claws, the long and continuously clawed Labizke plate required extensive soft-tissue denudation along the rib [7]. Stating the fundamental need for rigid spanning of a flail segment, Sanches-Lloret introduced 13–19 cm long rib struts with clawed end sections to bridge fractures on each side of the flail rib segment with a single implant (Fig. 6.6c) [26]. The circular midsection of the struts accommodated contouring but lacked the low profile of plates.

In an extensive biomechanical evaluation of rib plates, Boetsch and Rehm documented that rib fixation with Judet, Vecsei, and Labizke plates restored only 21 %, 23 %, and 8 %, respectively, of the strength of the native rib due to their thin plate cross section and poor fixation [36]. Conversely, they found that overly stiff conventional plates induced screw pullout and rib fracture at the plate end. They concluded that a plate should be sufficiently flexible to prevent stress risers at the plate end, yet sufficiently strong to withstand loading. Given an adequate stiffness, they furthermore concluded that longer plates yield stronger fixation constructs. Based on their findings, they developed a novel rib plate that combined claw and screw fixation options (Fig. 6.6d). Their plate was 70 mm long, straight, and tapered toward the ends to reduce stress concentrations.

Most interestingly, in 1986 Rehm also developed and tested the first resorbable rib plate [7]. The 6-hole plate was 5 mm thick, made of Polyglactin, and accommodated 3.5 mm cortical screws. Their initial approach to use resorbable screws was abandoned due to screw breakage during insertion. Static and dynamic testing of resorbable plates applied with stainless steel screws delivered encouraging results, yielding stiffness and strength values in line with the native rib. However, in an animal study, plates had completely dissolved prior to their first 6-week evaluation point. Their experience emphasizes the fact that encouraging biomechanical results cannot be extrapolated into the clinical realm without in vivo data.

Intramedullary Fixation

Intramedullary fixation of rib fractures with Kirschner wires has been successfully performed throughout the past 50 years [37]. Kirschner wires serve as splints to hold a fracture or flail segment in a more anatomic position and prevent paradoxical motion without obtaining rigid fixation (Fig. 6.7a). In this context, it is important to note that rib fractures do neither require perfect reduction nor absolute stabilization to generate "direct" bone healing, which resembles direct but slow remodeling across a perfectly reduced fracture site. Due to abundant blood supply, rib fractures heal spontaneously by normal ("secondary") fracture healing, which is faster and stronger than primary bone healing, and which is stimulated by small interfragmentary motion [38]. Accordingly, Voggenreiter stated that "*the purpose of operative chest wall stabilization is not a totally stable osteosynthesis, and primary fracture healing is not worthwhile*" [18]. This fact supports less-invasive, intramedullary rib fixation, whereby fractures neither need to be completely exposed nor perfectly reduced. This approach not

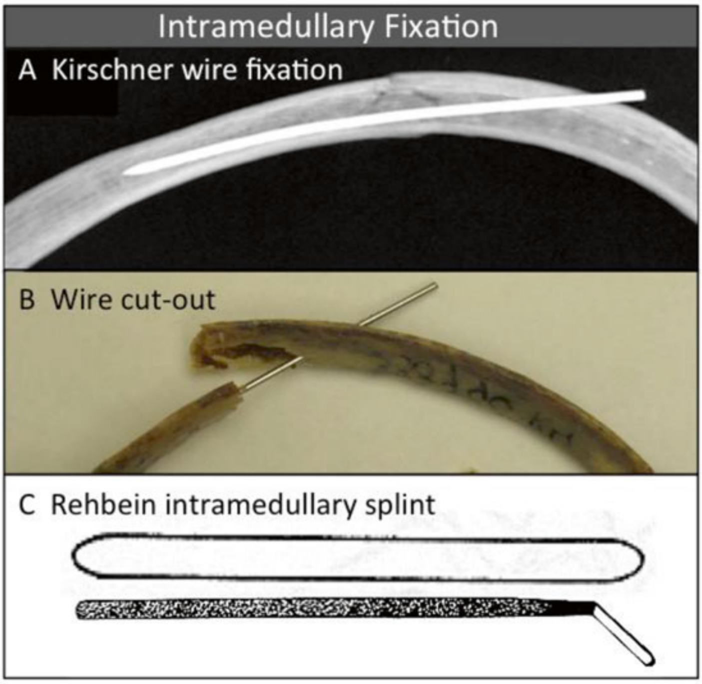

Fig. 6.7 Intramedullary fixation of rib fractures with Kirschner wires (**a**) is prone to cutout (**b**). Rehbein splints (**c**) had improved cutout resistance and rotational stability

only reduces the surgical complexity but also adheres to the principles of modern biological osteosynthesis that aims to minimize soft-tissue injury, particularly the periosteum from which the fracture callus forms.

Compared to plating, intramedullary fixation of rib fixation with Kirschner wires has several important benefits. Kirschner wires can be inserted through smaller incisions in a less-invasive approach, requiring less resection of intercostal soft tissue than plating [39]. Kirschner wires follow the canal shape upon insertion, while plates require intra-operative contouring to match the rib surface [17, 24]. Intramedullary implants are better tolerated than plates that remain on the surface of the rib and require removal due to persistent discomfort in 5–15 % of cases [40, 41]. Furthermore, intramedullary implants derive fixation strength by confinement in the rib canal, while plate fixation can be prone to screw loosening and plate pull-off, especially in the presence of osteoporotic bone [17, 42]. Most importantly, intramedullary implants allow fixation of posterior rib fractures, where access for plating can be severely restricted by the scapula and latissimus dorsi [43]. The clinical efficacy of rib osteosynthesis with Kirschner wires has been described in a number of case series that reported good to excellent results [19, 37, 39, 44, 45]. In 1972 Dor presented his first 100 cases of flail chest stabilization with Kirschner wires and described a mortality rate of only 16 % in severely injured patients [45]. After two decades of experience in rib fracture fixation with Kirschner wires, Samarrai and associates concluded that this technique had given the most satisfactory results when compared with other fixation techniques [39]. While the clinical utility of intramedullary fixation of rib fractures has been well established, there are two persistent limitations. First, the thin and circular cross section of Kirschner wires provides poor rotational stability and is prone to cutting out through the cortex, especially in the presence of osteoporotic bone (Fig. 6.7b) [17, 23]. Second, Kirschner wires can dislodge and migrate, which may cause discomfort, loss of fixation, or harm [19, 21, 34, 43]. Cases of intraspinal and intracardiac migration of Kirschner wires from ribs were reported as recently as 2012 [20] and 2014 [22], respectively. Albrecht and associates reported abandoning the use of Kirschner wires because of their migration risk and propensity for cutout, despite their relative ease of use and sufficient stabilization [43]. At the present time, with the availability of superior intramedullary devices, the use of Kirschner wires alone for rib fracture fixation is not recommended.

To address these persistent problems, the Rehbein plate, an intramedullary plate with a rectangular cross section designed to provide improved rotational stability, was introduced in 1972 (Fig. 6.7c) [46]. One end of the plate was designed to be left out of the canal and was sutured to the rib to limit migration. Nevertheless, it remains unclear how these rectangular Rehbein plates were reliably inserted and advanced through the fracture site along the intramedullary canal. Rush pins were also proposed in place of Kirschner wires [37]. Interestingly, no biomechanical or clinical studies on the performance of Rehbein plates or Rush pins exist. Even more surprising is the fact that until most recently, Kirschner wire fixation of rib fractures has neither been formally evaluated or improved despite 50 years of clinical experience that revealed both its potential and its obvious complications.

Contemporary Implants for Rib Fracture Fixation

This section provides an overview of currently available implants for rib fracture fixation, describes their features aimed at addressing the five challenges inherent to rib fracture fixation discussed earlier, and summarizes biomechanical and clinical evidence of their performance.

To date, four types of implants for rib fracture fixation exist: the MatrixRIB anatomic plate and splint system, the StraTos clip and bar system, the RibLoc U-plate system, and resorbable implants (including Biobridge). In contrast to historic implants described in the previous section, all contemporary metallic implants are made from titanium alloy rather than stainless steel. Titanium implants are approximately twice as flexible but comparable in strength to stainless steel implants, for which reason titanium has become the material of choice to support elastic fixation of rib fractures.

MatrixRIB System

This system combines anatomic plates and intramedullary splints to provide a comprehensive solution that accommodates the large variety of fracture patterns and anatomic locations encountered in complex flail chest injuries (Fig. 6.8a, b). Specifically, it consists of a set of anatomically contoured rib plates that contains four left and four right plates of 300 mm length, which suffice to accommodate the surface geometry of ribs 3–9, as well as short 6-hole plates for fixation of simple fractures. Long plates allow bridging of comminuted fractures and spanning of multiple fractures to suspend flail segments. Plates may be cut intraoperatively to the desired length. All plates are made of titanium alloy and are 1 mm thick to allow for elastic, low-profile fixation. Screw holes of these locking plates are threaded to engage with correspondingly threaded heads of locking screws. This eliminates screw stripping during insertion and provides improved fixation strength compared to standard screws (Fig. 6.8c). For intramedullary fixation of simple, isolated fractures in a less-invasive manner, the

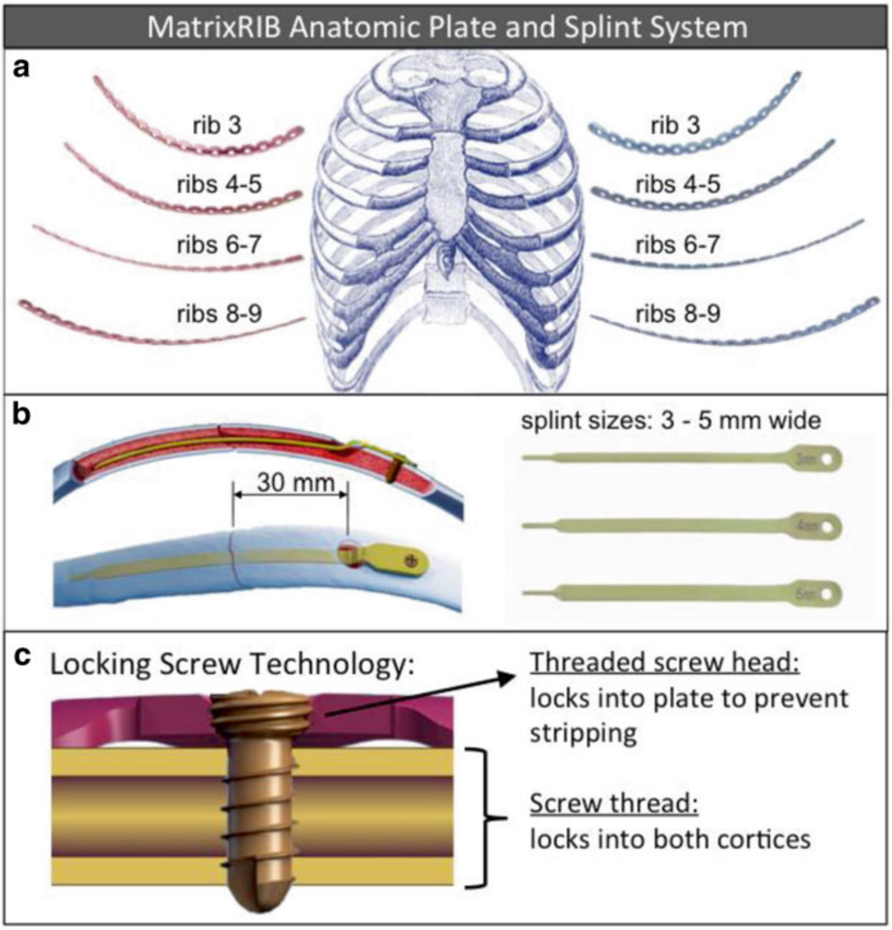

Fig. 6.8 The MatrixRIB System combines anatomic plates (**a**) and intramedullary splints (**b**). Locking screws (**c**) for plate and splint fixation securely lock into the implant and rib cortices

MatrixRIB system contains pre-contoured intramedullary splints that have a rectangular cross section to provide torsional stability and resistance against cutout. Splints are secured to the rib with a single locking screw to prevent migration. The splint tip is tapered and sloped to facilitate splint insertion along the medullary canal.

Biomechanical Evidence Three aspects of the MatrixRIB system have been evaluated and are summarized in the following section: The stability of plate constructs [47], the stability of intramedullary splint constructs [9], and the anatomic fit of plates [25].

The anatomic shape of MatrixRIB plates and splints was derived from the biometric rib analysis of Mohr et al. [10]. The actual fit of the anatomic plate set was assessed in 109 human ribs by measuring the length over which plates traced the rib surface without any manual plate contouring [25]. The results demonstrated that the anatomic plates could trace the surface of ribs 3–9 over a plating length ranging from 13 to 15 cm (corresponding to an 11–13 hole plate) without contouring. In addition, the twist of MatrixRIB plates was compared to the anatomic twists of the surface of the 109 rib specimens. On average, the anatomic plates approximated the twist of the corresponding rib surfaces within 3.7° and 8.7° along an 8 cm and 16 cm long plate, respectively. These findings demonstrated that anatomic rib plates may largely eliminate time-consuming and complex intraoperative contouring and facilitate the spanning of flail segments with long plates.

The stability of anatomic plate constructs was characterized by assessing construct stiffness, durability, strength, and failure modes in 20 human cadaveric ribs [47]. Each specimen was subjected to a sequence of four tests to determine the strength of intact ribs, the stiffness of plate constructs, the durability of constructs during dynamic loading (360,000 cycles of 200 N mm^{-1} loading, corresponding to fivefold respiratory loading) [7], and the residual strength and failure mode of constructs after dynamic loading. Results demonstrated that rib plates did not increase the native stiffness of ribs. By combining flexible plating with locking screw fixation, all constructs survived 360,000 loading cycles and retained a strength after dynamic loading that corresponded to 77 % of the native rib strength.

Rib splint constructs were characterized in the same manner to assess construct stiffness, durability, strength, and failure modes in 22 paired ribs in direct comparison to Kirschner-wire constructs [9]. The stiffness of splint constructs (2.0 ± 1.0 N mm^{-1}) and Kirschner-wire constructs (2.5 N mm^{-1}) was comparable ($p = 0.05$). All constructs sustained 360,000 loading cycles without catastrophic failure. After dynamic loading, splint constructs remained 48 % stronger than Kirschner-wire constructs and were 26 times stronger than required to sustain physiologic respiration [7]. Loading to failure demonstrated the most important difference between splint and Kirschner-wire constructs: five of the 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 (Fig. 6.7b). In contrast, all splint constructs retained functional reduction and fixation after loading to failure and demonstrated at most a mild bending of the elastic splint shaft (Fig. 6.9a). Therefore, rib splints provided superior strength and prevented the complications of implant migration and cutout seen with Kirschner wires.

Clinical Evidence The clinical performance of MatrixRIB implants has been assessed in a prospective observational study on 20 consecutive patients who underwent stabilization of flail chest injury with anatomic plates and intramedullary splints [48]. Data collection included patient demographics, injury characterization, surgical procedure details, and postoperative recovery. Follow-up was performed at 3 and 6 months to assess pulmonary function, durability of implants and fixation, and patient health. Surgical stabilization was achieved on average with five plates and one splint. Intra-operative contouring was limited to minor adjustments (<1 min) in 14 % of plates. Postoperative duration of ventilation was 6.4 ± 8.6 days. Total hospitalization was 15 ± 10 days. At 3 months, patients had regained 84 % of their expected Forced Vital Capacity (%FVC), and there was no mortality. Among the 91 rib plates, 15 splints, and 605 screws used in all patients, there was no hardware failure and no

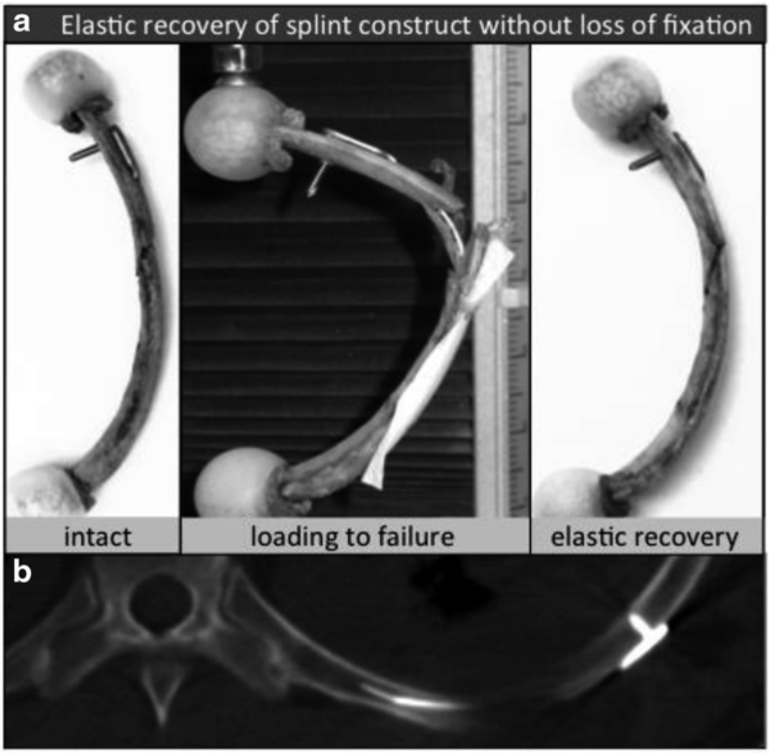

Fig. 6.9 (**a**) After loading to failure, elastic fixation with splints retained fixation and did not lead to splint cutout. (**b**) While splints provide a less-invasive alternative for stabilization of posterior fractures, care must be taken to ensure proper distance of the splint tip to the spine

loss of initial fixation. There was one incidence of wound infection, and implants were removed in one patient after fractures had healed. The study concluded that MatrixRIB implants provided reliable fixation, largely eliminated the need for intra-operative implant contouring, and accommodated the wide range of fractures encountered in flail chest injury. Similarly, additional case series reporting on the use of MatrixRib implants in 11 patients [49], 21 patients [50], and 50 patients [51] reported a very low rate of implant-related complications. One case report documented a delayed fracture of a MatrixRIB plate [52]. A plate spanning a rib resection in a 21-year-old male patient broke 25-months post-op after direct impact during soccer practice. Additionally, splints should not be used for posterior (paraspinal) rib fractures that do not provide sufficient intramedullary canal length medially to accommodate the splint (Fig. 6.9b) [48].

RibLoc U-Plating System

The RibLoc system (Acute Innovations, Hillsboro, OR) was originally designed for stabilization of single rib fractures in a less-invasive manner. The titanium implant employs the innovative approach of capturing both ends of a fractured rib in U-shaped clips that are connected by an anterior bridge (Fig. 6.10a). Each clip is attached to the rib with two screws that fully penetrate the rib and engage into the back of the clip to allow reliable screw tightening independent of bone quality. RibLoc implants are available in 46, 61, and 76 mm length and are indicated for treatment of flail chest, acute pain, chest wall deformities, and non-unions. Most recently, the system was expanded to include RibLoc U+ implants for stabilization of multiple adjacent fractures with a single implant (Fig. 6.10b). These implants have an elongated anterior bridge

Fig. 6.10 (**a**) U-shaped clips of the RibLoc system capture each side of a fractured rib. Clips are fixed with screws that penetrate both rib cortices and lock into the back of the clips. (**b**) RibLoc U+ implants provide an elongated anterior bridge for spanning of multiple fractures

with additional holes for bone screws and are available up to a length of 215 mm. The anterior bridge can be intraoperatively contoured to the surface of the rib. The manufacturer references a biomechanical study by Sales et al. to substantiate the claim that the RibLoc U-plate is biomechanically more stable compared to a longer anterior plate [53].

Biomechanical Evidence The biomechanical study by Sales et al. tested the U-plate concept on 5 cm long preproduction prototypes in direct comparison to rib fixation with 10 cm long locking plates. Fixation constructs were dynamically loaded to ±2 N mm^{-1} loading for 50,000 cycles, corresponding to 48 h of normal respiration. Since the first three U-plate specimens with a 0.8 mm thick anterior bridge proved too fragile, testing was continued with four improved prototypes that had a 1.6 mm thick anterior bridge. The decline in construct stiffness during dynamic loading was measured to infer construct stability. Construct stiffness decreased during dynamic loading from 6.3 to 6.1 N mm^{-1} for U-plate prototypes ($n=7$) and from 7.3 N mm^{-1} to 6.6 N mm^{-1} for locking plates ($n=8$). Based on these results, they concluded that U-plate fixation is more durable than standard anterior fixation. It is important to note that specimens were not tested to failure in order to assess their strength or durability. No further biomechanical studies on RibLoc implants have been published to date.

Clinical Evidence RibLoc implants were evaluated in one prospective clinical trial that investigated stabilization of painful non-unions [54]. After resection, non-unions in 5 patients were stabilized with RibLoc implants. One-month follow-up radiographs demonstrated that in two of these 5 patients, one screw partially backed out, but implants remained stable on 6-month follow-up radiographs.

StraTos System

The StraTos clip and connecting bar system (MedXpert, Eschbach, Germany) was designed for suspension of the chest wall and sternum to correct chest deformities (i.e., pectus excavatum). It resembles a direct advancement of the rib strut with clawed end sections of Sanchez-Lloret [26]. The original StraTos system comprised end plates with claw fixation and a connecting bar that could be cut to length and rigidly attached to the end plates (Fig. 6.11a). In addition to pectus correction, the system is indicated for bridging of flail segments and chest wall defects. It has recently been expanded to include StraCos plates that have a design similar to the claw fixation of the StraTos clips, but that can be used without a connection bar for fixation of a single rib fracture (Fig. 6.11b).

Clinical Evidence Four clinical studies report on a total of 60 cases for the StraTos System for surgical fixation of rib fractures, chest wall defects, and pectus excavatum repair [55–57]. There was only one implant failure by fatigue breakage of the connecting bar used for pectus repair 30 months after implantation [57]. One study treated 18 patients with either the StraTos system ($n = 12$) or the MatrixRIB system [58]. They report that either of the two titanium systems provided a lightweight but strong support for rib fixation and chest wall reconstruction. However, they concluded that the reduced soft-tissue dissection around the rib required for the Synthes system may represent an advantage in trauma patients. This concern is shared in a recently invited commentary on contemporary management of flail chest injuries [59]. It stated that claw fixation posed a high risk of injuring or impinging the neurovascular bundle along the inferior edge of the rib, and that injury to the intercostal nerve may be a source for chronic pain.

Bioabsorbable Implants

Resorbable implants are gaining increasing interest due to their obvious benefit of eliminating the need for implant removal, albeit the need for

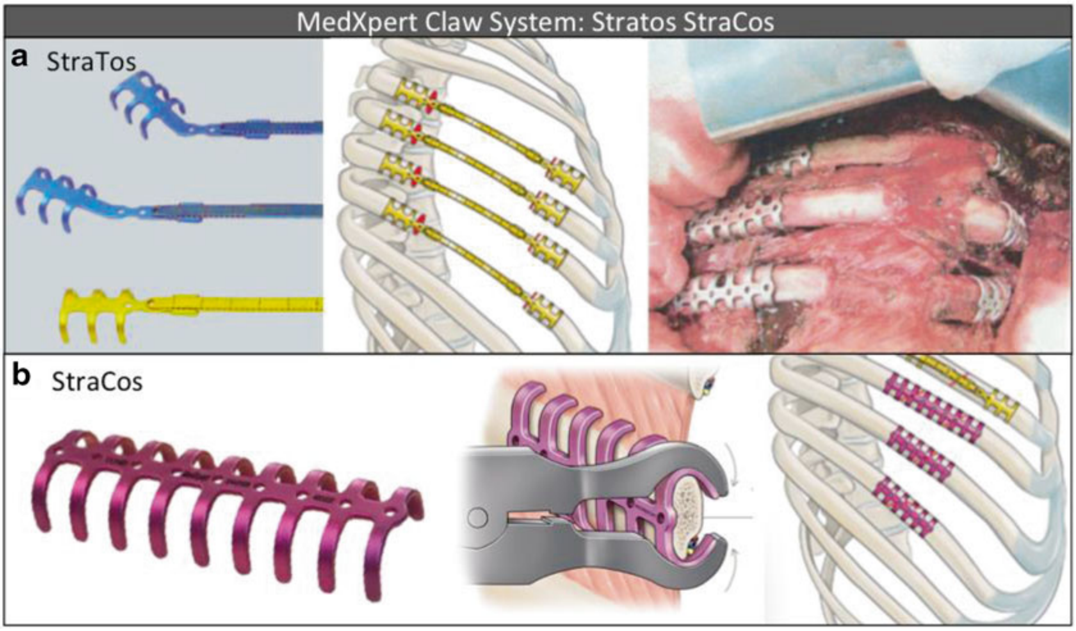

Fig. 6.11 (**a**) With the Stratos system, claw plates are first attached to corresponding rib segments and subsequently connected by bars. (**b**) StraCos claw plates provide an alternative for fixation of single fractures. For fixation, claws are tightly bent around the rib with a special forceps

Fig. 6.12 (**a**) Resorbable implants in form of a mesh (Inion OTPS mesh) can be cut to shape with a scissor, heated, and formed around the rib. (**b**) Absorbable plates applied with screws proved too weak, for which reason supplemental fixation with suture cerclage was recommended. (**c**) Commercially available BioBridge absorbable plates are sutured to the rib in a trans-cortical compression suture technique

implant removal is becoming increasingly rare with the advent of low-profile and elastic titanium implants [48]. Additional benefits include their radiolucency and high elasticity, which prevents stress-shielding-induced porosis or delayed healing [60].

Contemporary bioabsorbable implants are used in the form of a plate or mesh to stabilize rib fractures (Fig. 6.12a). Campbell et al. evaluated the absorbable mesh of the Inion Orthopaedic Trauma Plating System (OTPS, Inion, Tampere, Finland) in a biomechanical study on 15 porcine ribs [61]. The mesh was cut to size, heated to 70 °C, molded around the fractured rib, and additionally secured with two 2.8 mm resorbable screws on each fracture site after predrilling and tapping. Compared to intact ribs, OTPS mesh constructs were 37 % less stiff and restored 81 % of their native strength. The same group evaluated OTPS mesh constructs clinically in 32 consecutive patients who received operative stabilization of rib fractures [62]. Their cohort exhibited a 19 % wound infection rate and one non-union. After a follow-up of 33 months, 60 % of the patients experienced chest wall stiffness. While the authors stated that the OTPS mesh could easily be wrapped around comminuted fractures, it also emphasizes the invasive resection required for mesh application.

Mayberry et al. reported the use of absorbable plates (Macropore, San Diego, CA) for rib fracture repair in 10 patients (Fig. 6.12b) [60]. The 10-hole plates were 2.4 mm thick and made of a polylactide (70 % L-lactide-co-D and 30 % L-LACTIDE). The straight plates were heated to 60 °C, molded to the rib, and applied with three screws in each fracture side. Radiographs 24 h post-surgery demonstrated loss of reduction in two of the initial 8 patients, for which reason the final two patients received additional suture cerclage. The author concluded that reliable fixation requires both screws and suture cerclage. It is important to note that absorbable screws are too soft for a self-tapping design, for which reason the extra step of tapping after predrilling is always required.

Marosco et al. applied absorbable plates of the OTPS system to stabilize 44 fractures in 13 flail chest patients [63]. Within 3 months, 10 fixation failures (23 %) were noted, demonstrated by recurrence of fracture displacement. This is likely a conservative estimate of fixation failure, since absorbable implants are radiographically invisible and can only be identified by their screw holes in ribs. It is therefore not possible to assess the failure mode (plate fracture or screw breakage), and failure of fixation can only indirectly be identified in cases of recurrent displacement of the rib fracture. After this pilot study, Marosco et al. conducted a prospective randomized clinical trial of operative stabilization of flail chest injury [1]. Inion OTPS absorbable 6- or 8-hole plates were used for the surgical stabilization group ($n=21$) (Fig. 6.12b). At 3 months of follow-up, healing and reduction were analyzed on CT scan reconstructions. While the author stated that fractures would be expected to have completely healed at this time, only 11 out of 21 patients demonstrated complete healing, 7 were partially healed, and 3 were classified as "non-healing." Furthermore, 8 patients were classified as having "residual overlapping rib ends," but the report did not elaborate on the incidence of fixation failure. It should be noted that the OTPS system was specifically developed for malleolus fractures in the presence of appropriate immobilization, is not indicated for rib fractures, and is not available for sale in North America.

BioBridge (Acute Innovations) is the only bioabsorbable implant that is marketed in North America for rib fractures (albeit its specific indications include metacarpal bones, long bones, the appendicular skeleton, and thorax; Fig. 6.12c). The BioBridge plate is made of a biodegradable copolymer that contains 70 % L-lactide-co-D and 30 % L-lactide. It is 110 mm long, is 14 mm wide, and has 18 staggered holes for attachment using polyester or nylon braided suture. The manufacturer recommends a compression suture technique in which the suture wraps superiorly over the rib and then passes through inferior holes drilled through the rib. It can be cut to size with a shear and is flexible, and multiple plates can be stacked to increase length or strength of fixation. Since the implant is not designed to withstand the stress of weight bearing, appropriate additional immobilization or fixation is used for fracture fixation at the surgeon's discretion. To date, there are no published biomechanical or clinical studies on Biobridge implants. As such, the potential benefits of this new generation of absorbable implants remain offset by a lack of biomechanical and clinical data documenting their ability to provide durable and stable fixation of rib fractures.

In conclusion, several implant solutions exist today that address fully or in part the inherent challenges unique to rib fracture fixation. These contemporary implant designs combined with advanced implant materials should simplify the osteosynthesis procedure and should provide durable fixation. Given this more user-friendly and reliable implant technology, indications for rib fixation may gradually expand to reduce mortality, disability, and the duration of return to function. However, as holds true for any new technology, biomechanical and clinical evidence must be scrutinized before adapting new osteosynthesis implants, especially if such novel implants deviate considerably in design or material from traditional implant solutions with an established track record.

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7

Indications for Operative Management of Flail Chest Injuries

Jaclyn Farquhar and S. Morad Hameed

There are no absolute indications for operative repair of a flail chest (FC) injury. Several studies have reported on the indications for rib fracture repair; however, there is a relative lack of quality data regarding this. In many of these studies, the simple presence of a FC is an indication for fixation [1–6], although not all FC injuries necessitate surgical repair, and certain accompanying injuries may negate the benefits provided by surgical fixation.

Current management practices for FC are still mostly nonoperative (see Chap. 4). In fact, current opinion in many centers is that FC can be appropriately managed conservatively and that surgical intervention has an "unfavorable risk-benefit profile" [7].

Even amongst those surgeons who potentially could be performing these procedures, support for FC fixation is mixed. In 2009, 405 American trauma, orthopedic, and thoracic surgeons, mostly from academic Level I trauma centers, were surveyed on the indications for rib fixation. Thirty-four percent believed that failure to wean from a ventilator by 7 days was an appropriate indication for fixation of FC, while a vast majority (92 %) did not support surgery in patients not requiring mechanical ventilation [8]. This is despite the fact that a significant percentage of polytrauma patients with FC injury who are not initially intubated will, with time, develop respiratory failure and require intubation and ventilation [4] (Fig. 7.1).

Current opinion is changing however, as three recent randomized, controlled trials [9–11] as well as a meta-analysis [12] present strong arguments for both short- and long-term benefits following operative management of the FC.

A current review of the relative indications and contraindications for the fixation of chest wall injuries is presented. However, further research with randomized, controlled trials is urgently needed in this controversial field.

Indications

Anterolateral Flail Chest with Respiratory Failure and Without Significant Underlying Pulmonary Contusion

The most common indication for surgical fixation of an FC, and that with the strongest evidential support, is for respiratory failure with an anterolateral flail segment without severe underlying pulmonary contusion (PC) [4, 9, 10, 13, 14]. Patient profiles from two randomized clinical trials on this topic were consistent with this indication.

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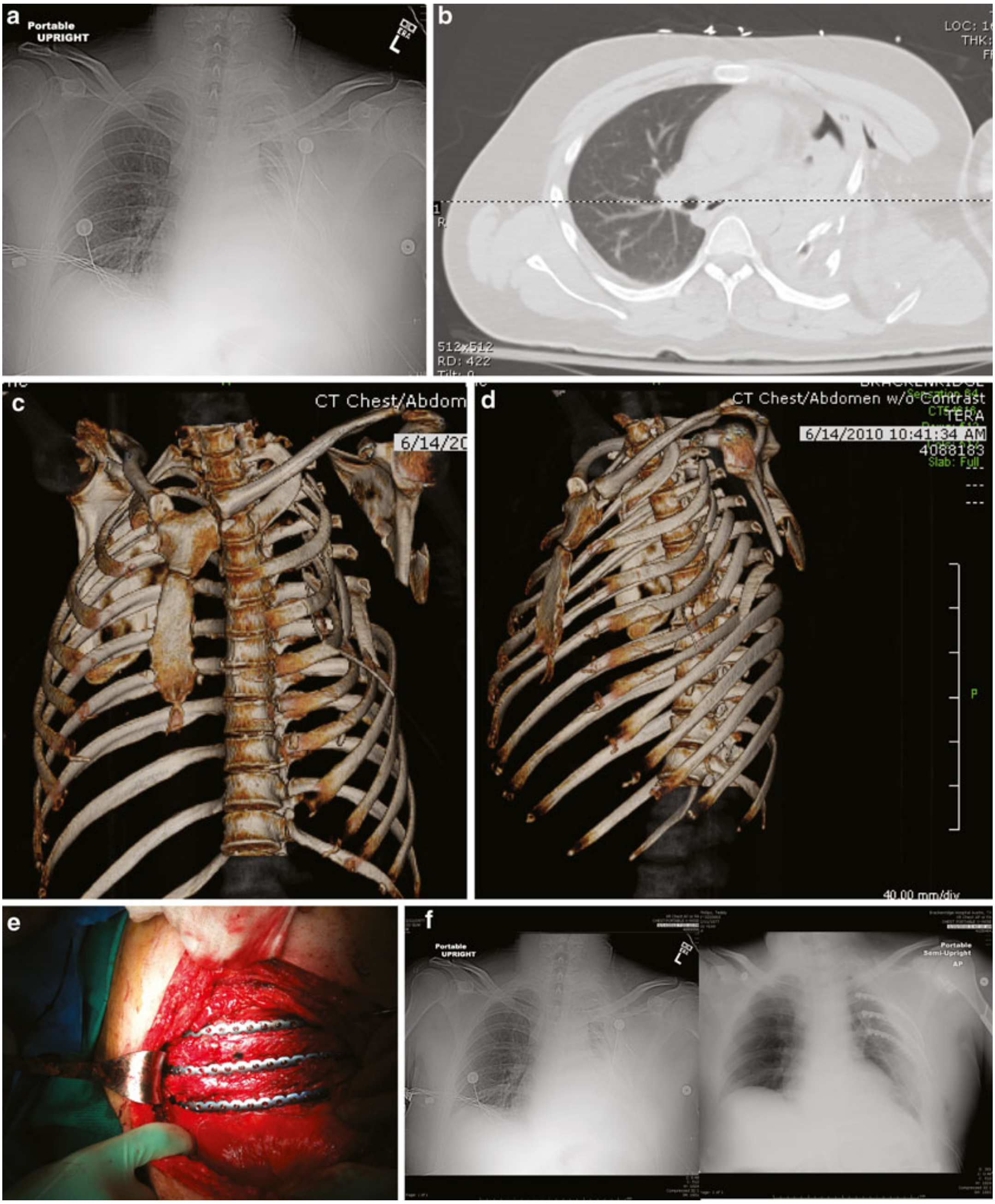

Fig. 7.1 (**a**) A patient with a severe chest wall injury with a number of indications for surgery including severe deformity with a flail segment, inability to wean from a ventilator, intraparenchymal lung penetration, and severe respiratory compromise. (**b**) A CT scan of the chest demonstrating the severity of the injury. (**c**, **d**) We have found three-dimensional CT scan reconstruction to be very valuable in the assessment of these injuries as it enables the surgeon to grasp the overall clinical deformity, evaluate the fixation required for each rib, anticipate potential obstructions (i.e., the scapula), and plan the surgical approach. (**e**) An intraoperative photograph demonstrating fixation of the three most displaced ribs through a lateral thoracotomy type approach. It is not necessary to plate every rib in this setting: simply repairing enough to stabilize the flail segment is the operative goal. (**f**) Comparative preoperative and postoperative radiographs demonstrating the successful re-establishment of chest wall dimensions and contours. The patient received operative care on post-injury day 3, extubated on post-injury day 4, and discharged on post-injury day 7 (Case courtesy of W. Drew Fielder, MD FACS)

Tanaka et al. described a group of 18 FC patients being ventilated for acute respiratory failure whose chest wall injuries were managed surgically with Judet struts. Their outcomes were compared to randomized controls managed nonoperatively. Approximately two-thirds of the patients had a mild or moderate underlying lung contusion. They found short- and long-term benefits to operative repair, including a decrease in duration of ventilatory support, decreased length of stay (LOS) in the intensive care unit (ICU), lower rates of pneumonia, improved pulmonary function tests (PFTs), and decreased time to return to work [9]. Marasco et al.'s 23 operative patients did not have severe PC underlying their FC and were managed with resorbable rib-specific plates. All patients were already ventilated with no prospect of weaning for the next 48 h. Their time of ventilatory support and ICU LOS were also significantly reduced following fixation [10] (Fig. 7.2).

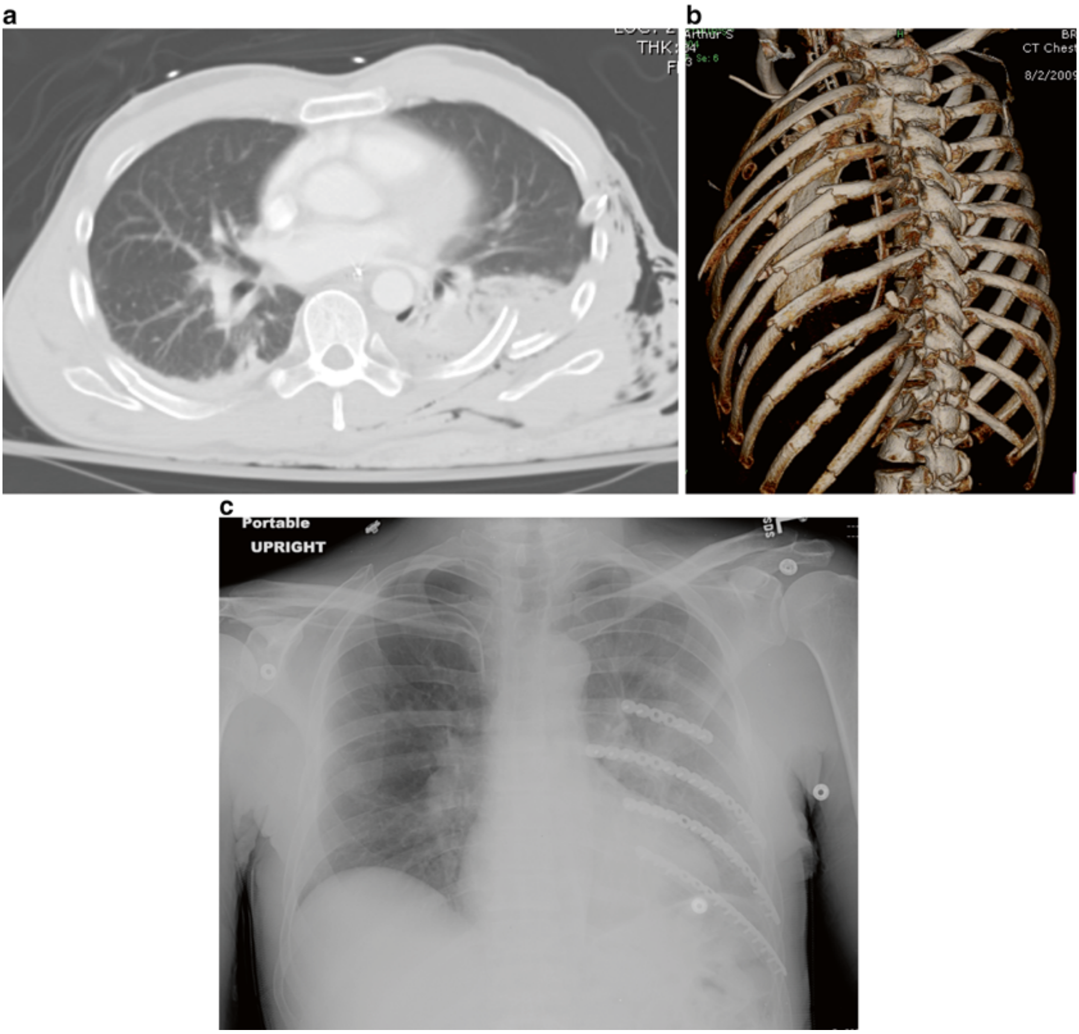

Fig. 7.2 (**a**) A CT scan of a patient with chest wall injury, multiple consecutive rib fractures, and a flail segment. The actual morphology of the fractures is difficult to determine from the plain CT scan. (**b**) The three-dimensional reconstruction scan demonstrates the overall pattern and location of the fractures and specifically the segmental nature of the more inferior rib fractures. This type of information assists in surgical planning and implant selection. (**c**) Surgical fixation of the flail segment was performed: the segmental fractures required the use of longer implants to span both fracture sites (Case courtesy of W. Drew Fielder, MD FACS)

Level II studies also support this indication. Lardinois et al. conducted a prospective trial in which 66 patients with anterolateral FC had fixation with 3.5 mm pelvic reconstruction plates. They found greater than expected improvement in PFTs at 6 months and found patients with anterolateral FC with respiratory failure and minimal lung contusion recovered exceptionally well. In particular, they recommended early intervention in elderly patients meeting these criteria in order to avoid prolonged ventilatory support and to preserve thoracic physiology. They noted the elderly is at particular risk for rapid deterioration with what may seem to be a relatively minor injury, but, due to their limited reserve, do not fare well after traumatic injuries [13].

When contemplating surgical fixation of a chest wall injury, the absence of severe underlying PC may be particularly important. Altered physiology has been demonstrated following these injuries [15, 16] that results in a lesser benefit to surgical fixation, as evidenced by a lack of improvement in length of mechanical ventilation when compared to matched controls [17].

Respiratory Compromise in Non-intubated Patients

Operative repair is not limited to patients requiring mechanical ventilation. Early signs of respiratory compromise in non-intubated FC patients should prompt assessment of the patient's progress or deterioration, trauma physiology, and how well they would tolerate mechanical ventilation. Respiratory status can be monitored by arterial blood gas evaluation and observed clinically and radiographically. Haasler et al. supports chest wall stabilization for progressive chest cavity shrinkage as observed on sequential chest radiographs [18]. In a prospective study by Granetzny et al., 20 non-intubated FC patients were randomized to surgical or nonsurgical management, and significant improvements were seen in ventilator days, ICU LOS, total LOS, rates of pneumonia and deformity, as well as PFTs at 2 months in the operative group [11]. Althausen et al. showed the same short-term improvements in their retrospective case-controlled study with locking reconstruction plates in non-intubated patients with respiratory compromise in spite of appropriate analgesic measures and maximal nonoperative measures [4]. In these patients, surgical stabilization allows for improvement in respiratory dynamics through chest wall stabilization, leading to better pain control, allowing more efficient secretion clearance [13].

Thoracotomy for Other Indications

The "on the way out" strategy is a more traditional indication for fixation. This term describes the fixation of associated rib fractures upon exit from the chest cavity during a thoracotomy performed for other indications (see below). Molnar describes it as the only definite indication for FC fixation [19]. The Eastern Association of the Surgery of Trauma (EAST) Practice Management Guidelines on FC gives this a Level III recommendation [20]. Scenarios in which thoracotomy may be indicated include massive acute hemothorax (>1,500 ml immediately after thoracostomy tube placement or >200 ml/h output from a chest tube for 3 h [21]), cardiovascular injury, tracheobronchial injury, diaphragm injury, pulmonary laceration with ongoing air leak, or retained hemothorax (Chap. 11). The authors of many studies support this practice: [1, 3, 17, 22–26] however, less than one in five surgeons who manage acute trauma patients in the USA describes this as a valid indication [8].

Failure to Wean from Mechanical Ventilation

Intubated FC patients who are failing to wean from the ventilator, as mentioned above, should also be considered for operative fixation. While only a third of surveyed surgeons endorse this indication [8], and supporting evidence is limited to expert opinion, this has traditionally been an accepted indication [1, 26, 27]. With new technologies and new studies being produced on a regular basis, however, it is anticipated that,

Table 7.1 Summary of indications for flail chest fixation and level of supporting evidence

Indication	References	Strongest level of evidence
Anterolateral flail chest with respiratory failure and without significant underlying pulmonary contusion	Tanaka[a], Marasco[a], Althausen, Lardinois, Davignon	Randomized controlled trial (Level I)
Respiratory compromise in non-intubated patients	Granetzny[a], Althausen, Haasler, Lardinois, Pettiford	Randomized controlled trial (Level I)
Thoracotomy for other indications	Althausen[a], Ahmed[a], Nirula 2010, Teng, Mayberry, Molnar, Voggenreiter, EAST, McDowell, Moore, Paris, Pettiford	Retrospective case-controlled study (Level III)
Failure to wean from mechanical ventilation	Althausen[a], Nirula 2006[a], Nirula 2010, Mayberry, EAST, Pettiford	Retrospective case-controlled study (Level III)
Deformity too significant to heal spontaneously	Althausen[a], Moore, Pettiford	Retrospective case-controlled study (Level III)
Intractable pain	Nirula 2006[a], Nirula 2010, Nirula 2009, Teng, Pettiford	Retrospective case-controlled study (Level III)

[a]Denotes reference with strongest level of evidence

while this will remain an operative indication, it will not be the primary one. Secondary benefit may also be achieved in patients with underlying PC who have persistent flail segments and are failing to wean from the ventilator [13]. It is difficult to outline specific indications for fixation in this setting: there are a variety of factors that will influence the decision in this regard. In general, a failure of a ventilated patient to improve with time, and with no reasonable expectation for doing so, represents a relative indication for fixation. This is a decision that should be made after a multidisciplinary discussion involving the traumatologist, surgeon, and intensivist (Table 7.1).

Severe Deformity Unlikely to Heal Spontaneously or Intractable Pain

Certain other scenarios, such as severe deformities that appear too significantly displaced to heal on their own [24], or patients with intractable pain [1, 2], need to be considered on a case by case basis.

Contraindications

The various benefits of FC fixation are described in detail elsewhere, but the major advantage is the ability to quickly and safely discontinue mechanical ventilation. Risks of prolonged intubation and mechanical ventilation include pneumonia, sepsis, atelectasis, barotrauma, myopathy, tracheostomy, and possibly death [28–30]. As with the above indications, these contraindications are all relative (Table 7.2).

Significant Pulmonary Contusion

Many studies have commented on the impact underlying PCs have on the recovery of patients with FC. Reid and Bard first described the physiological disturbances associated with lung contusions in 1965 [31], and Kishikawa et al. helped delineate longer-term effects, including loss of pulmonary parenchyma secondary to fibrosis resulting in prolonged dyspnea, decreased functional residual capacity, and low PO2 [15, 16]. Management of PC remains supportive, with intubation, mechanical ventilation, and tracheostomy as indicated for prolonged recovery.

Due to what is now known of the underlying pathophysiology, most authors do not recommend FC fixation with associated PC [1, 2, 13, 19, 32]. In general, simple chest wall stabilization will not improve the prognosis of the underlying lung injury. Indeed, Voggenreiter et al. showed that surgical fixation of FC with PC resulted in no significant reduction in days of mechanical ventilation, while FC fixation in

Table 7.2 Summary of contraindications for flail chest fixation and level of supporting evidence

Contraindication	References	Strongest level of evidence
Significant pulmonary contusion	Voggenreiter[a], Nirula 2010, Nirula 2009, Lardinois, Molnar, Richardson	Retrospective case-controlled study (Level III)
Severe head injury	Lardinois[a], Marasco, Molnar	Case series (Level IV)
Associated injury requiring prolonged intubation	Pettiford	Expert opinion (Level V)
Fractures of the first and second ribs	Marasco, Lardinois	Expert opinion (Level V)
Injuries preventing fixation surgery	Marasco	Expert opinion (Level V)

[a] Denotes reference with strongest level of evidence

patients without PC had dramatic improvement in ventilatory parameters and significantly earlier extubation [17].

Severe Head Injury or Associated Injury Requiring Prolonged Intubation

In a similar theme, patients with severe head injury are also not particularly good candidates for early FC fixation, nor are any other patients with injuries necessitating prolonged intubation. Most of these patients have been excluded from studies to date, however, because they would not benefit from chest wall stabilization with the opportunity for early extubation. Therefore, early fixation seems an unnecessary risk and cost with little potential benefit. Once these patients have stabilized or improved from their head injuries, however, and are subsequently having difficulty weaning from the ventilator, secondary fixation may help with delayed recovery and weaning [20].

Fractures of the First and Second Ribs

Fractures of the first and second ribs should not be repaired for two reasons. First of all, the surrounding musculoskeletal structures provide tremendous stability to this region, promoting healing without intervention. Secondly, the proximity of the subclavian vessels and brachial plexus increases the surgical risk significantly without associated benefit [10, 13, 19].

Injuries Preventing Fixation Surgery

From a practical perspective, injuries preventing the actual procedure (i.e., an unstable spinal injury may preclude lateral positioning until repaired) would be a contraindication to fixation.

An open fracture with significant contamination should not be a contraindication to fixation. Patient age should also not be a contraindication to fixation; however, comorbidities must be assessed in order to determine appropriateness for surgery (cardiovascular disease, anticoagulants, shock).

Discussion

Until the results of ongoing studies comparing state-of-the-art nonoperative management of FC and PC with surgical fixation become available, each case of FC must be assessed individually for its appropriateness for fixation. Therapeutic decision-making must account for the short- and long-term consequences of FC and PC for individual patients and injury patterns and for the potential benefits of surgical fixation in both the acute and long-term phases of recovery. The short- and long-term risks of surgery (including lung injury, infection, hemorrhage, implant failure or migration, and chronic pain), which remain incompletely understood, must also be considered on an individual basis before committing patients to operative intervention.

In specific populations, such as older patients, non-intubated patients, or patients requiring thoracotomy for unrelated injuries, the balance of benefits and risks of surgical fixation may favor an operative approach. As large randomized controlled trials are published, specific indications for surgical repair of FC will become better defined.

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Surgical Approaches for Rib Fracture Fixation

8

Aaron Nauth

General Guidelines for Selecting a Surgical Approach

When selecting a surgical approach for rib fracture fixation, it is important to remember that the goal of surgery is to stabilize the chest wall adequately to restore the mechanics of breathing, reduce deformity and pain from displaced/unstable fractures, and facilitate patient respiration and pulmonary toilet. Patients with flail chest and unstable chest wall injuries often have multiple fractured ribs and individual ribs fractured in multiple locations. In addition, they may have bilateral rib fractures and/or associated sternal fractures. In order to achieve the goal of a stable chest wall, it may not be necessary to fix all of the fractured ribs or to fix all of the fractures in an individual rib. In general, preference is given to fixation of the most displaced and unstable rib fractures, which are often accessible through a single surgical approach. In patients with a flail segment, where multiple fractures have occurred in the same rib, one of the rib fractures (e.g., anterior or posterior) are typically more displaced, whereas at the other end of the flail segment, the fractures are typically "hinged" or minimally displaced (see Fig. 8.1). In the author's experience, fixation of the displaced fractures alone is often all that is required to adequately restore chest stability, although there is some controversy in the literature on this point [1]. If only one "side" requires fixation, this can commonly be achieved through a single surgical approach.

Axial and three-dimensional (3D) reconstructions of computed tomography (CT) scans of the thorax are extremely helpful in defining the location, displacement, and number of rib fractures (see Fig. 8.1) and should be obtained in all patients undergoing surgery. These images are used for preoperative planning regarding which ribs will require fixation and the location of the fractures that need to be addressed.

In the author's experience, all rib fracture fixation can be performed using one of three surgical approaches either alone or in combination [2, 3].

1. The lateral thoracotomy (anterior or posterior)
2. The posterior paramedian approach
3. The inframammary approach

It is important to recognize that ribs 1 and 2 are difficult to access surgically and fracture fixation of these ribs is generally not performed. In addition, ribs 11 and 12 are floating ribs (not structurally important) and rarely require surgical fixation.

There are several steps involved in the surgical approach and rib fracture fixation that are common to all of the surgical approaches. First, the author

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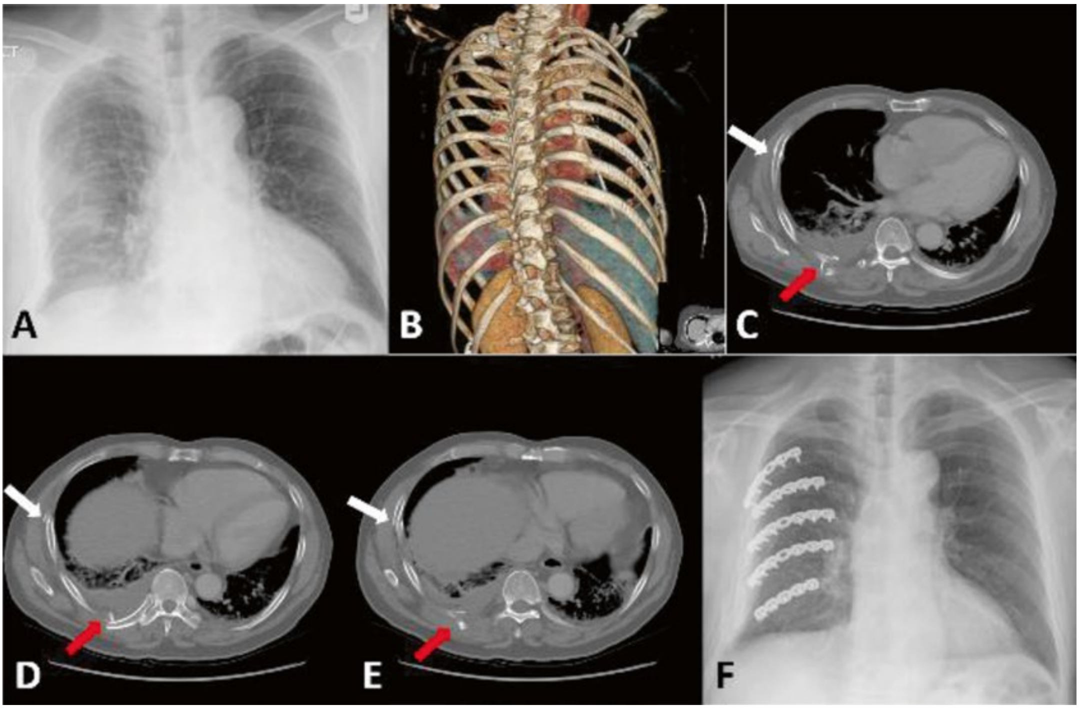

Fig. 8.1 (**a**) AP chest radiograph in a 72-year-old male demonstrating a right-sided flail chest and multiple displaced right rib fractures. (**b**) 3D CT reconstruction in the same patient demonstrating multiple right-sided, posterior rib fractures with substantial displacement. (**c**, **d**, and **e**) Axial CT images in the same patient demonstrating multiple displaced posterior rib fractures (*red arrows*) and multiple minimally displaced anterolateral rib fractures (*white arrows*). (**f**) Postoperative PA chest radiograph in the same patient demonstrating fixation of multiple right-sided, posterior rib fractures performed through a posterior paramedian approach. The minimally displaced anterolateral rib fractures were not fixed

performs the surgical preparation with the original chest tube in situ (if one has been placed) and then removes it once dissection has been carried out down to the fractured ribs and the pleural space opened. This is done to minimize the risk of developing a tension pneumothorax during induction of anesthesia and with positive pressure ventilation. The pre-existing chest tube is removed to minimize the risk of infection. Second, once dissection down to the fractured ribs is complete, the pleural space is entered through the area of greatest disruption (usually in the region of the most displaced and unstable rib fractures) using a miniature rib spreader. Irrigation and suction of the pleural space is then performed to remove any retained hemothorax (see Fig. 8.2). Deflation of the lung is not required for rib fracture fixation, and the lung can be gently retracted to allow sufficient access to the pleural space. Third, whenever possible muscle sparing approaches that utilize intermuscular intervals or split muscles in line with their fibers (rather than transecting them) are used [4, 5]. Finally, prior to closure, a new sterile, large bore (32 or 36 F) chest tube is placed through a separate incision caudal to the surgical incision and tunneled in the subcutaneous tissues to the pleural space to maximize the distance between the skin and the hardware used for rib fracture fixation.

Lateral Thoracotomy (Anterior or Posterior) (See Figs. 8.3 and 8.4)

The anterior or posterior lateral thoracotomy is the preferred approach for anterolateral or posterolateral fractures, respectively. The two approaches are extensile and easily combined to allow broad exposure of the hemithorax. For both approaches, the patient is positioned in lateral decubitus with

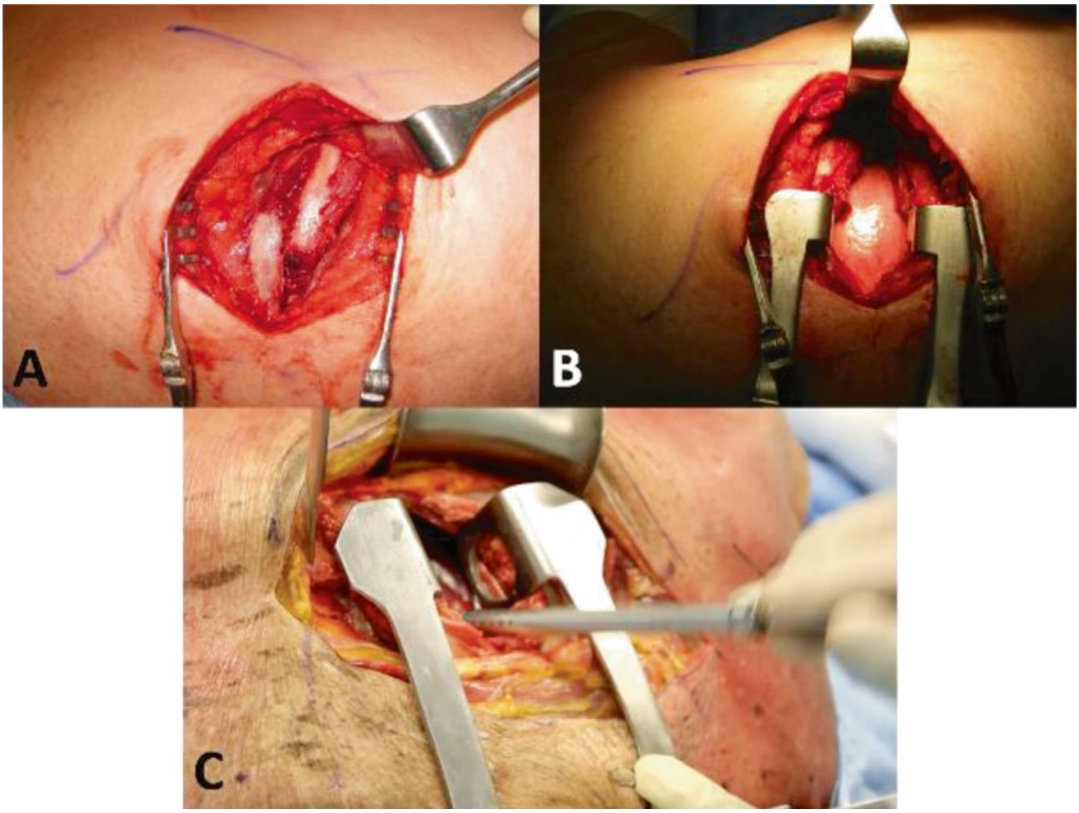

Fig. 8.2 (**a** and **b**) Intraoperative photographs of a patient undergoing rib fracture fixation surgery demonstrating displaced and overlapped rib fractures with subsequent placement of a miniature rib spreader to gain access to the pleural cavity for evacuation of hemothorax. (**c**) Photograph of a cadaver demonstrating suction of the pleural cavity using a pool sucker following placement of rib spreader

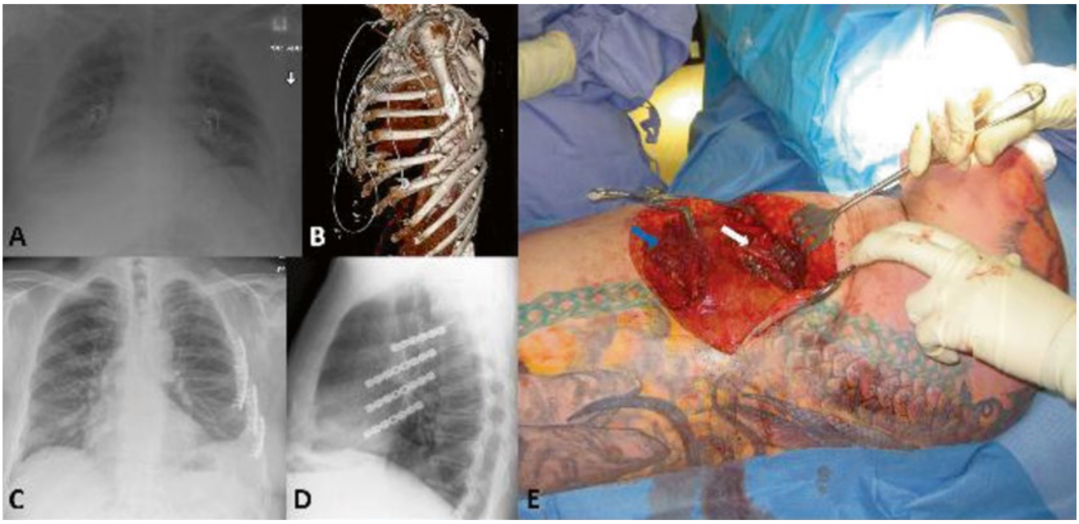

Fig. 8.3 (**a**) AP chest radiograph in a 48-year-old male demonstrating a left-sided flail chest and multiple displaced/comminuted anterolateral rib fractures. (**b**) 3D CT reconstruction in the same patient demonstrating multiple left-sided, anterolateral rib fractures with substantial displacement/comminution. (**c** and **d**) Postoperative PA and lateral chest radiograph in the same patient demonstrating fixation of multiple left-sided, anterolateral rib fractures performed through an anterolateral approach. (**e**) Intraoperative photograph demonstrating the anterolateral approach in this patient for fixation of anterolateral rib fractures. Muscle-splitting windows in the serratus anterior (*white arrow*) and external oblique (*blue arrow*) have been used to access rib fractures

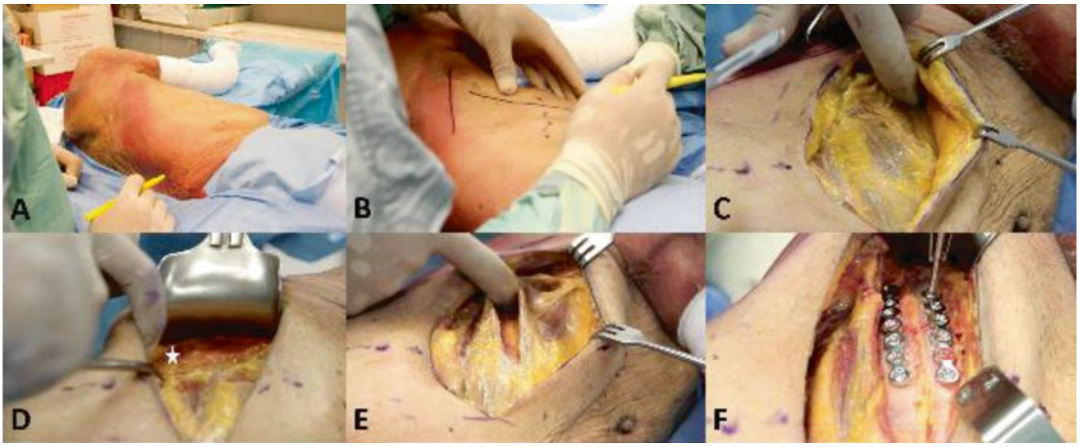

Fig. 8.4 Cadaver pictures demonstrating the anterolateral approach. (**a**) Patient positioning in lateral decubitus position with the arm free-draped over a padded Mayo stand. (**b**) Anterolateral incision marked out anterior to the lateral border of the scapula. (**c**) Anterolateral incision exposing the serratus anterior. (**d**) Posterior retraction of the latissimus dorsi exposing the long thoracic nerve on the lateral border of the serratus anterior (*white star*). (**e**) Blunt dissection is used to create a muscle-splitting window in the serratus anterior to expose anterolateral rib fractures. (**f**) Plating of multiple rib fractures through a split in the serratus anterior

the side of desired rib fracture fixation facing up. The upper arm is placed on a padded Mayo stand and can be free-draped to allow movement of the arm (and scapula) during the procedure to improve exposure. A curvilinear incision centered over the fractured ribs is made (posteriorly or anteriorly based on the location of the displaced fractures). The ribs are counted out to confirm the incision is at the appropriate level to allow access to the rib fractures requiring fixation. The use of specific landmarks from the 3D CT reconstructions (such as the tip of the scapula, the xiphoid process, or the manubriosternal junction) is often helpful in identifying the correct level.

For the anterolateral approach, the latissimus dorsi is identified and retracted posteriorly to expose the serratus anterior. Deep dissection to expose the fractured ribs is carried out by splitting the muscle fibers of the serratus anterior in line. Typically two separate windows in the serratus anterior fibers are created (with fixation of 2–3 ribs per muscle window performed). Care must be taken to protect the long thoracic nerve and artery on the lateral border of the serratus anterior, as well as the thoracodorsal nerve and artery on the undersurface of latissimus dorsi. Fixation of more caudal fractures may require splitting of the external oblique muscle fibers.

For the posterolateral approach, deep dissection is carried out in the interval between the latissimus dorsi caudally, the trapezius superolaterally, and the inferior scapular border superomedially (the so-called triangle of auscultation—see Fig. 8.5), or the latissimus dorsi can be split in line with its fibers depending on the location of the fractured ribs. The underlying serratus anterior is split in line with its fibers to expose the fractured ribs. Once again, care must be taken to protect the long thoracic nerve and artery as well as the thoracodorsal nerve and artery. Following fracture fixation, muscle splits or intervals are re-approximated with interrupted resorbable suture.

Posterior Paramedian Approach (See Figs. 8.1 and 8.5)

The posterior paramedian approach is the preferred approach for posterior fractures adjacent to the spine. While it is possible to extend this approach proximally or distally as desired, it is

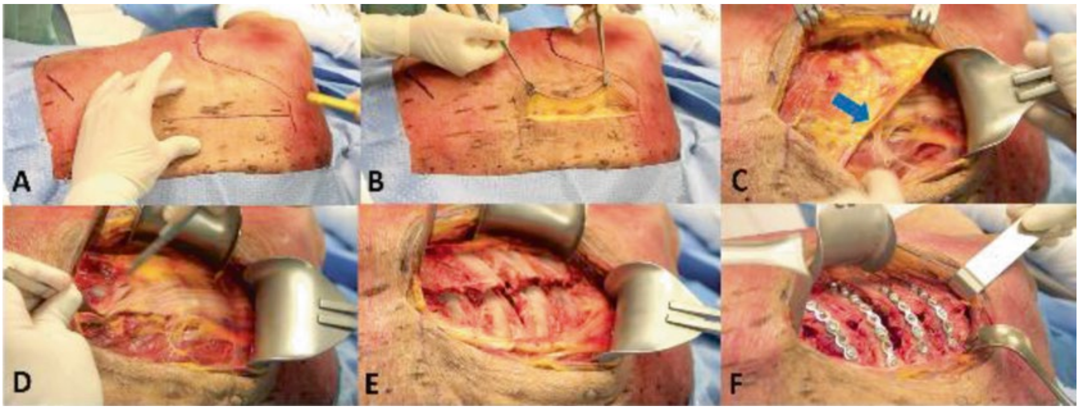

Fig. 8.5 Cadaver pictures demonstrating the posterior paramedian approach. (**a**) Patient positioning in lateral decubitus position with the arm free-draped over a padded Mayo stand. The posterior paramedian incision is marked out parallel and lateral to the spinous processes. (**b**) The posterior paramedian incision. (**c**) The "triangle of auscultation." The trapezius has been retracted superiorly, the inferior border of the scapula is just lateral to the retractor, and the latissimus dorsi is inferior (*blue arrow*). (**d** and **e**) The underlying erector spinae is reflected laterally to expose the underlying posterior rib fractures. (**f**) Plating of exposed posterior rib fractures

not extensile in the anterior-posterior plane, and fixation of fractures other than those that are located posteriorly requires a separate incision and approach. The patient is positioned in lateral decubitus with the side of desired rib fracture fixation facing up. The upper arm is placed on a padded Mayo stand and can be free-draped to allow movement of the arm during the procedure to improve exposure. A vertical linear incision centered over the fractured ribs is made parallel to the spinous processes. Deep dissection is carried out in the interval between the latissimus dorsi, trapezius, and the inferior scapular border (triangle of auscultation), exposing the underlying erector spinae muscle. The erector spinae is then elevated toward the midline to expose the posteriorly fractured ribs.

Inframammary Approach (See Figs. 8.6 and 8.7)

The inframammary approach is the preferred approach for anterior fractures and costochondral dislocations. It is extensile and can be combined with the anterolateral thoracotomy approach for anterolateral fractures. However, exposure of posterior fractures requires a separate incision and change of patient positioning. For the inframammary approach, the patient is positioned supine with the arm extended at 90° to the thorax. Free draping of the arm is not required. A horizontal incision inferior to pectoralis major is made along the inframammary crease. Deep dissection is carried out underneath the pectoralis major and breast tissue exposing the serratus anterior fibers and the costochondral junctions if necessary. The pectoralis minor muscle originates from the third to fifth ribs at the costochondral junctions and may require elevation for rib fixation. Serratus anterior fibers are split in line to expose the underlying ribs as required. Caudally, splitting of the external oblique fibers may be necessary for exposure depending on the location of desired rib fracture fixation.

Conclusions

Rib fracture fixation for flail chest or unstable chest wall injuries is a relatively novel procedure, and there is very little literature regarding the

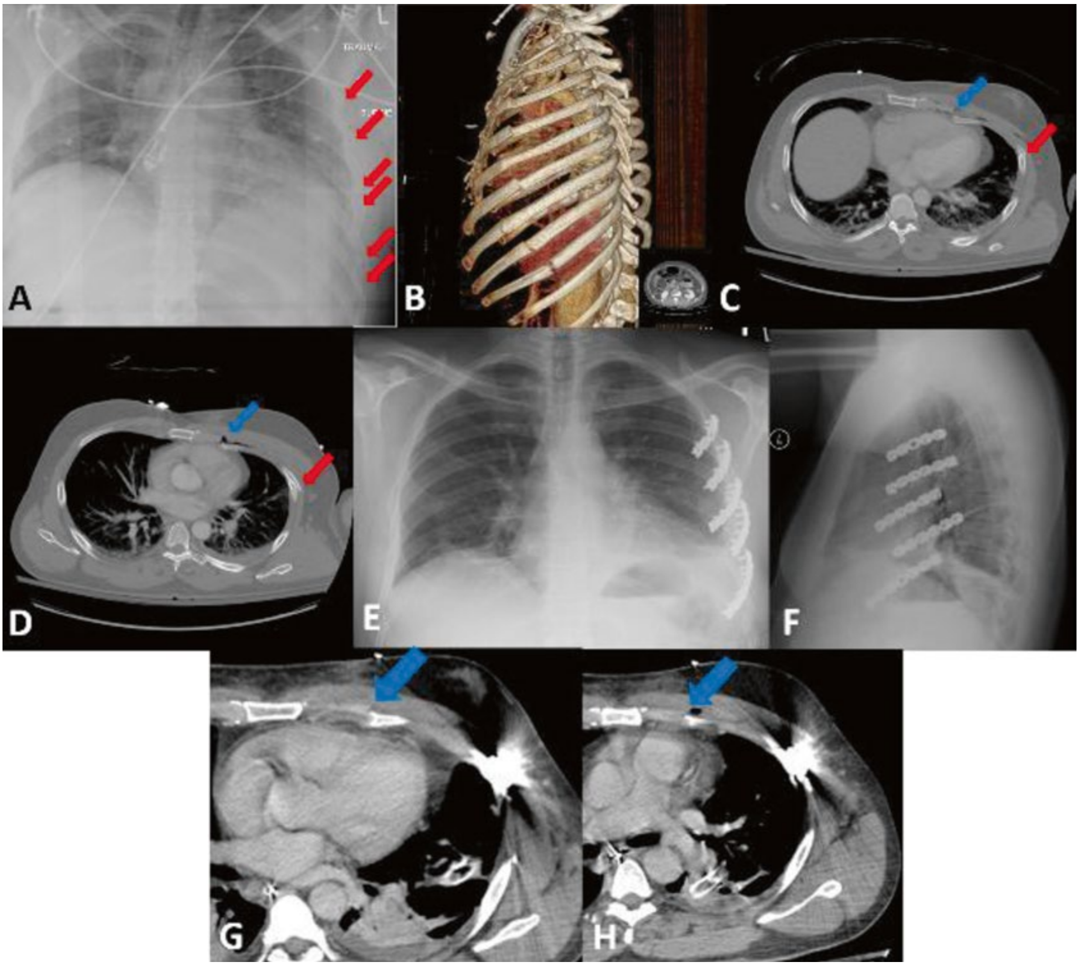

Fig. 8.6 (**a** and **b**) Preoperative AP chest radiograph and 3D CT reconstruction demonstrating multiple displaced, left-sided, anterolateral rib fractures (*red arrows*). (**c** and **d**) Axial CT images demonstrating displaced anterolateral rib fractures (*red arrows*) and costochondral dislocations (*blue arrows*). (**e** and **f**) Postoperative PA and lateral radiographs demonstrating plate fixation of multiple left-sided, anterolateral rib fractures. (**g** and **h**) Postoperative axial CT images demonstrating reduction and transosseous suture fixation of costochondral dislocations (*blue arrows*)

various surgical approaches that can be used. Three common surgical approaches have been described that can be used alone or in combination to treat the majority of rib fractures. Selection of a surgical approach is based on a careful review of preoperative imaging and identification of those rib fractures that require fixation to restore stability to the chest wall or reduce significant deformity. This typically does not require fixation of all rib fractures and can often be achieved through a single approach. There is currently no available literature comparing various surgical approaches, fixation techniques for rib fracture fixation, or limited fracture fixation versus fixation of all/most fractures. Further research is needed to clarify these issues.

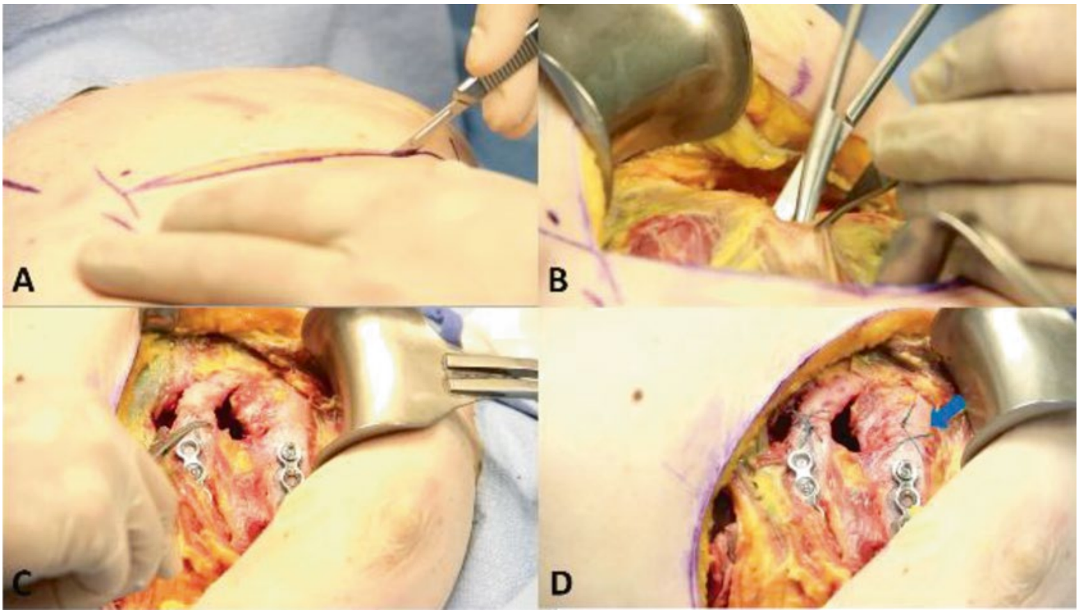

Fig. 8.7 Cadaver pictures demonstrating the inframammary approach. (**a**) The inframammary incision is made inferior to the pectoralis major in the inframammary crease. (**b**) The pectoralis major and breast tissue are elevated to expose the serratus anterior and pectoralis minor. A muscle split is performed in the serratus anterior to expose the anterolateral rib fractures and costochondral dislocations. (**c** and **d**) The exposed anterolateral rib fractures are plated and the costochondral dislocations are fixed with transosseous suture (*blue arrow*)

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Principles of Plate Fixation: Rib Fracture Applications

9

Richard J. Jenkinson

General Goals of Rib Plating

Indications for rib plating remain to be clearly defined. Current indications for consideration of acute rib plating of chest trauma patients, at my institution, include an unstable flail segment and/or severe deformity of the chest wall. We use the definitions of an ongoing randomized trial to define either a flail segment or a severe deformity (Table 9.1). If patients have ongoing symptoms attributable to non-healed or mal-united rib fractures, then a delayed chest wall reconstruction can be considered. In a patient with severe chest wall deformity, the goals of the rib fracture surgery are self-evident. The area of significant displacement needs to be exposed, realigned, and stabilized in an appropriate position. However, when stabilizing a flail segment, it can be challenging to define how many fractures need surgical stabilization. Often, many ribs are fractured at several locations, sometimes in relatively inaccessible locations, or bilaterally potentially requiring multiple exposures and/or repositioning of the patient.

In general, the goal of surgery for a patient with a flail chest is to stabilize the flail segment so that paradoxical chest motion is eliminated. Stabilization of a certain minimum number of ribs and fracture sites is required to provide adequate stability to each particular chest injury. Unfortunately, clear guidelines from the literature do not exist to determine this number. Intraoperatively, I will assess the stability of the chest wall after each rib fracture is stabilized with simple manual pressure on the flail segment. If the previously unstable segment is moving as a unit with the rest of the chest wall, then we can consider the goal of surgery fulfilled. A common scenario results when the flail segment is badly displaced at one site, while hinged at the second fracture site. Stabilization of only the displaced fracture is almost always sufficient to provide stability to the segment, since the hinged fracture is locally stabilized by soft tissues which were not disrupted by the large initial displacement. I will generally stabilize a minimum of three ribs since this number is readily accessed through a single incision. With each subsequent rib fracture that is stabilized, there is less motion across the fractures and reduced stress borne by the plate. Stabilization of an inadequate number of ribs may result in lack of clinical improvement from persistent instability of the flail segment and possibly failure of the implants.

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Table 9.1 Indications for rib plating

Indications for consideration of rib plating	
Flail chest	1. Three or more unilateral segmental rib fractures 2. Three or more bilateral rib fractures 3. Three or more unilateral rib fractures combined with sternal fracture/dissociation
Severe deformity of chest wall	1. 100 % displacement of three or more ribs 2. Marked loss of thoracic volume/caved in chest (>25 % volume loss) 3. Overriding of three or more ribs (>15 mm each) 4. Displaced rib fractures associated with intraparenchymal injury

General Principles of Bone Healing

When a bone is fractured, several biologic processes are brought into action as the body attempts to stabilize the injured skeleton. Bone healing occurs through two distinct biologic mechanisms known as primary bone healing and secondary bone healing [1].

Primary bone healing uses the histologic unit of the cutting cone with osteoclasts moving directly across the fracture, to remove dead bone, after which new bone is directly laid down by osteoblasts. This biologic mechanism requires direct contact between the bone cells and a mechanically rigid environment (absolute stability) [2]. Fractures in many parts of the appendicular skeleton are typically treated with techniques that optimize primary bone healing such as lag screw application and compression plating. These techniques rely on an anatomic reduction (perfect apposition of the injured bone ends) and absolute stability with compression across fracture surfaces. Application of these absolute stability techniques to the treatment of rib fractures, however, is impractical and not recommended. Ribs are small, rather soft bones which are prone to relatively transverse fractures with fragmentation at the fracture site. As a result, perfect reduction and absolute stability are often technically impossible. The constant movement of the thoracic cage during respiration further complicates the ability to achieve absolute stability across a rib fracture.

Secondary bone healing is the other major biologic bone healing strategy available to mend fractured bones. This is the biologic strategy at work during the routine nonoperative healing of the injured skeleton, including rib fractures. Secondary bone healing proceeds in three phases. The first is the inflammatory phase which forms a fracture hematoma. This stops ongoing bleeding and recruits inflammatory and osteogenic cells to the injured area via immune mechanisms. Following the initial inflammatory phase, the reparative phase modifies the fracture hematoma into soft callus which is composed of woven bone and provides some initial stability. The third phase is known as remodeling where the soft callus is remodeled into lamellar bone with resulting hard callus. This provides a durable structural repair to the injured bone. The time course of this process varies, but, in general, the inflammatory phase occurs over the first 2–3 weeks following injury; the reparative phase predominantly from 2 to 8 weeks; and the remodeling phase for 8 weeks to years following the injury. The injured bone remodels in response to the forces that influence it (Wolf's law); however, there will almost always be a permanent enlargement of hard callus noticeable following repair by secondary bone healing.

Successful bone healing requires a sufficient blood supply and a stable biomechanical environment. For callus to form, strain (a measure of stability) needs to be less than 10 % [3]. When a fracture has insufficient stability, the strain on the tissues will be too great to form bony callus. As a result, weak fibrous tissue forms between the bone ends rather than bridging callus and results in a nonunion. This occurs in the context of rib fractures when a fractured rib or multiple rib segments remain mobile and fail to heal. Nonunion is seen in flail chest patients and is often associated with pain, disability, and deformity. As a result of these issues, surgical stabilization of

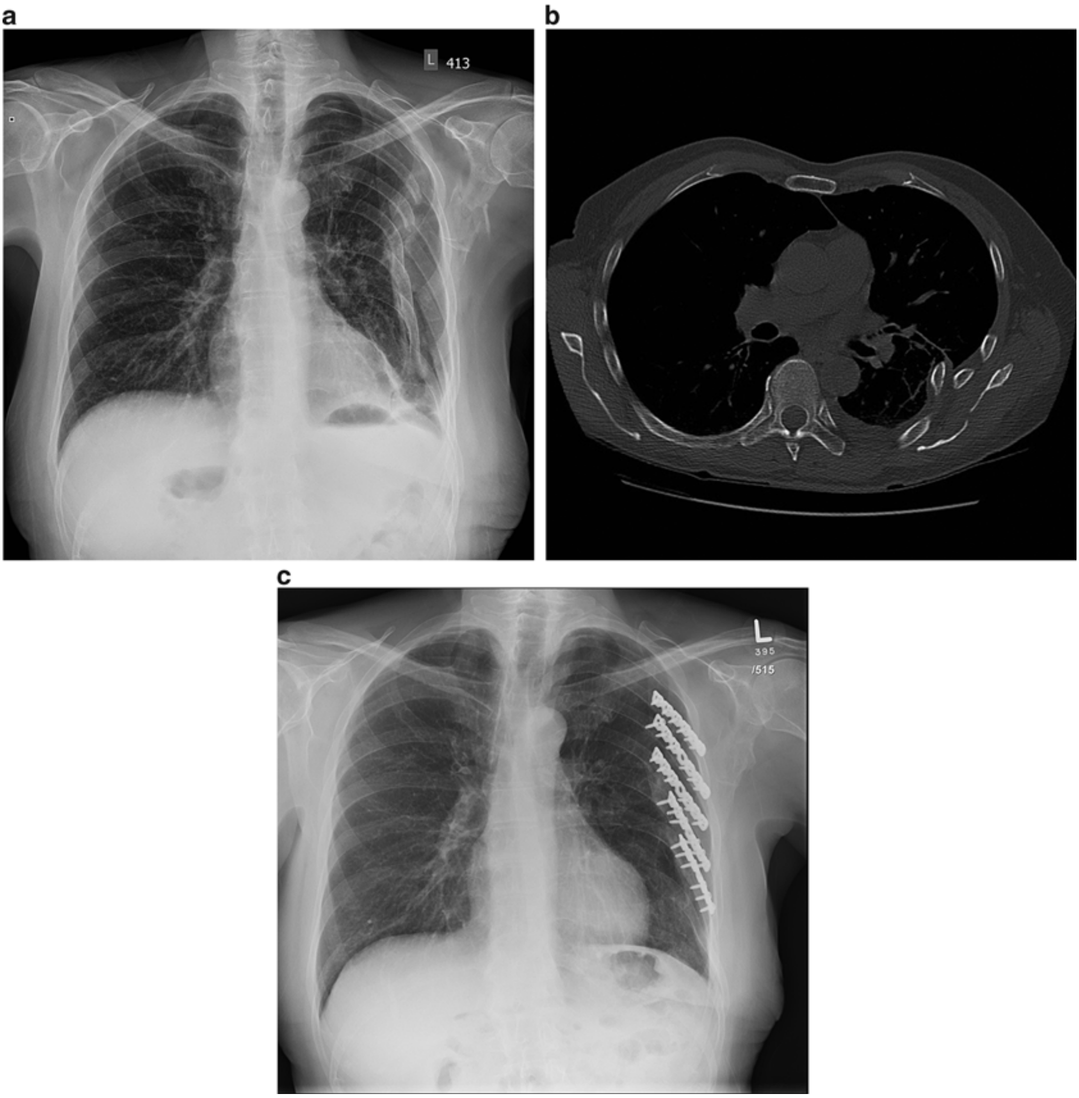

Fig. 9.1 (**a**) A patient sustained multiple rib fractures with a flail segment and deformity. After nonoperative treatment, persistent pain, deformity, and instability resulted. Radiographs (**a**) and a CT scan (**b**) demonstrated rib nonunions. The patient was treated successfully with open reduction, correction of deformity, and plate fixation with conventional 3.5 mm pelvic reconstruction plates (**c**)

chest trauma is gaining renewed attention in recent years. Figure 9.1 demonstrates radiographs and CT scan of a patient with persistent, severe pain with chest wall deformity and nonunion of multiple rib fractures following a flail chest injury who was successfully treated with correction of deformity and plate fixation.

Methods to Achieve Mechanical Stability of Fractures

Basic principles of treatment for fractured bones include realignment of the bone (reduction) and then maintenance of the reduced position. In the extremities, splints, functional braces, and cast immobilization can be used to maintain limb stability in a reduced position without operative stabilization. These external devices, however, are very challenging to use effectively in the chest wall. No splinting method has been shown to have any utility for multiple rib fracture patients.

Nonoperative treatment has long been the standard treatment of rib fractures and remains the most common method of treatment for traumatic chest injury [4]. When using this treatment strategy for chest wall fractures, splinting from neighboring ribs and/or the resilience of muscles and other soft tissues is anticipated to provide adequate stability for bony rib healing. Positive pressure ventilation can also be utilized in the hopes of providing an internal splint to the chest wall [5].

Surgical stabilization options include external or internal fixation. External fixation involves the insertion of pins into the bones with spanning, external connecting rings, or rods to provide support to the injured bone. This is not practical for injuries to the chest wall. Internal fixation involves stabilizing the injured bone with devices placed directly through an open surgical exposure. Pins, plates/screws, and intramedullary implants are the primary options available. Smooth pins have a distinct disadvantage in that they can migrate out of the bone potentially injuring intrathoracic structures [6–8]. Unsecured pins have no role in the modern surgical management of rib fractures. Intramedullary implants have been used successfully in long bones such as the femur and tibia. The rib has an intramedullary canal, and implants have been designed to act as an internal splint. To prevent migration, these devices have a screw and tab to prevent hardware migration [9] (Fig. 9.2).

Many options for stabilizing injured ribs have been described. However, internal fixation with

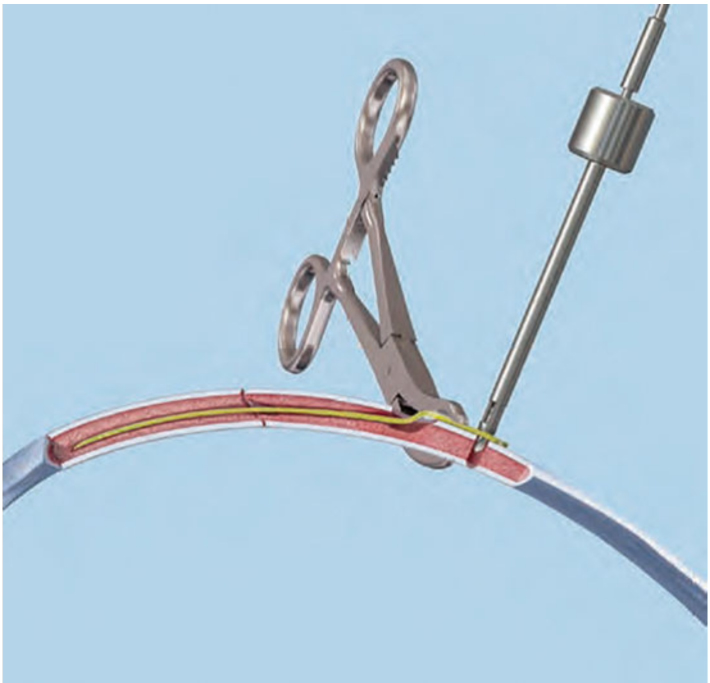

Fig. 9.2 The Matrix IM rib splint highlighting the set screw designed to prevent migration of the implant, as can be seen with smooth intramedullary pins or wires

plating is the most widespread option currently in use to surgically stabilize rib fractures. For the majority of rib fractures requiring surgical stabilization, plates provide the optimal implant to simultaneously provide stability and maintain reduction of the injured rib(s).

Plating System Options

Stabilizing plates have been intermittently used to treat fractured bones as early as the turn of the twentieth century. However, plate fixation of fractures was not popularized until the second half of the twentieth century through the pioneering work of the AO group [10]. Surgical stabilization of ribs with plates was described as early as 1961 [11]; however, early plates differed significantly from modern designs and never gained popularity, probably due to technical limitations which resulted in poor clinical outcomes.

The two main categories of plates that are currently in use today include conventional plates and locked plates. Conventional plates resemble the original plates of the 1960s and have smooth holes cut out to receive smoothed, rounded screw heads (Fig. 9.3). These plates rely on the associated screws to purchase into the underlying bone thus abutting the plate to the bone via friction (Fig. 9.4). Application of multiple screws into the plate splints the injured bone, providing stability to allow successful bone healing in the desired position.

Angular stable "locked plates" have been in use in orthopedics since the 1990s and have the advantage of increased mechanical stability of the screw and plate interphase. This increased stability is obtained by the plate having threaded holes which accept the threaded heads of matched locking screws (Fig. 9.5a, b). Advantages of these plating systems include improved performance in osteoporotic bone and the ability to obtain screw purchase in short segments especially in the extremities in periarticular settings. Modern rib-specific plating systems employ locking plate/screw systems [9, 12]

Fig. 9.3 A conventional 3.5 mm pelvic reconstruction plate. Note the smooth holes for screw insertion and the notches cut into the side of the plate to facilitate contouring in multiple planes

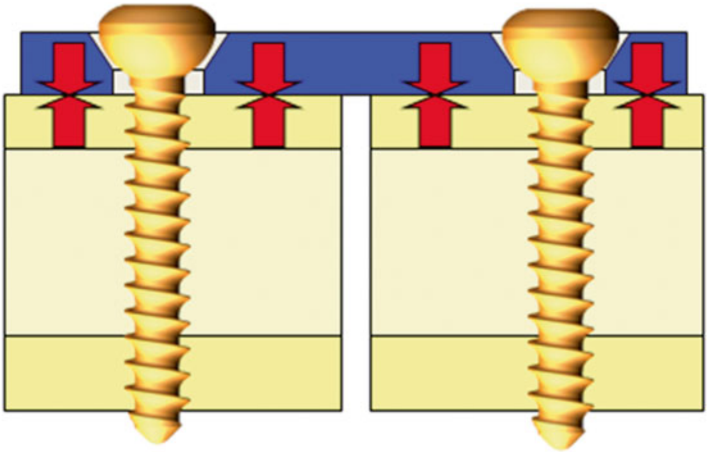

Fig. 9.4 This figure demonstrates screws engaging the holes in a conventional plate: as the screw is tightened to the bone, it creates friction between the bone and plate, ensuring stability in this fashion

(e.g., Depuy-Synthes Matrix rib system™, Acute Innovations Ribloc™).

Successful application of any plating system requires understanding of basic orthopedic trauma techniques. One of the most important requirements for treatment success is ensuring that the injured bone ends are opposed and realigned to near their anatomic position. This is termed "obtaining a good reduction." If the bone ends remain overly distracted and/or displaced, then fracture hematoma and subsequent fracture callus cannot form. Tools for obtaining a proper reduction include various types of reduction clamps (Fig. 9.6). After appropriate surgical exposure, careful placement of bone reduction clamps and manual manipulation will realign the ribs. Care must be taken to avoid injury to the intercostal nerves and vessels while applying the clamps.

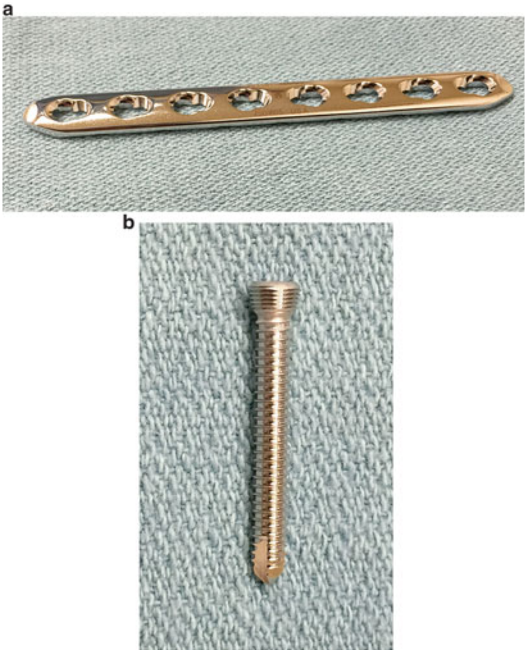

Fig. 9.5 (**a**) In contrast to a conventional plate, a locked plate has threads in one part of the screw hole to engage the corresponding threads in the locking screw head as it is tightened (**b**), creating a tight fit that ensures angular stability between screw, plate, and bone

Conventional Plates

As mentioned above, conventional plates have been in use for several decades with incremental design changes. They can be used with excellent

Fig. 9.6 Small fragment reduction clamps aid in the reduction of the rib fractures and placement of the internal fixation device (plate). These instruments should be an integral part of a rib fracture reduction set

Table 9.2 General categories of plate systems

Plate type	Advantages	Disadvantages
Conventional plates	• Familiar to orthopedic surgeons • Flexible and can be contoured • Low implant cost	• Poor purchase in soft bone • Lack of precontoured rib-specific plates • Difficult to contour over long rib segments • Lack of drill stops to prevent plunging into thorax
Locking plates	• Good purchase in soft bone • Precontoured rib plates • Relatively easy to apply • Protective drill stop • Lower profile implant	• Very high implant cost

results in patients with multiple rib fractures (Fig. 9.4). Conventional plates have several advantages including familiarity of use among orthopedic surgeons, flexibility to allow custom shaping to particular bone configurations, and multiple possible scenarios of use. Disadvantages include their reliance on screw purchase in generally soft rib bones and the lack of availability of pre-manufactured custom plates contoured to human ribs. Contouring conventional plates over long segments of rib is very challenging (Table 9.2). However, conventional plates currently have a distinct advantage in terms of dramatically lower implant costs. In my practice in a Canadian level-one trauma center, conventional plates are the most commonly used implants due primarily to lower operating room budget impact.

Conventional plates come in many shapes and sizes. The conventional plates most commonly used for rib fractures are the relatively light and flexible 3.5 mm plates originally designed for use in the pelvis: the 3.5 mm pelvic reconstruction plate (Fig. 9.3). These plates have a figure of eight style cut out to allow plate contouring in multiple planes including coronal plane and twisting (Fig. 9.7a, b, c). Heavier compression plates are generally too bulky and inflexible to be practical for rib fracture applications.

Conventional plates rely on successful implantation of their associated screws in order to fulfill their stabilizing function. In osteoporotic bones and small bones like the ribs, adequate screw purchase is often a challenge. Understanding the correct technique of screw application is critical to achieve stability in a conventional plating construct. A screw consists of a metallic cylinder with a spiral thread around it. The inner core diameter refers to the solid metal shaft part of the screw and approximates the size of the drill required for insertion. The outer thread diameter refers to the diameter of the screw including the threads. A typical small fragment cortical screw is referred to as a 3.5 mm screw. This measurement refers to the outer thread diameter: proper insertion of this screw utilizes a 2.5 mm drill bit which corresponds to the inner core diameter. This allows the (2.5 mm) shaft of the screw to pass through the path determined by the drill and the (3.5 mm) threads to engage and grip the surrounding bone. If a 3.5 or larger drill bit is used, then the screw will be rendered useless due to the fact that the drilled hole is as large as the outer diameter of the screw, and thus no purchase will be gained. Cortical screws are usually best suited to the ribs. However, in particularly soft bone, a cancellous screw with a wider outer thread diameter and wider thread pitch can be useful. These are known as cancellous screws since they are particularly useful in softer cancellous bone. Their wider thread diameter (4.0 mm) can allow them to achieve purchase when a cortical screw has been unsuccessful. Thus, intraoperatively, if poor purchase is noted with a 3.5 mm cortical screw, the surgeon may switch to a 4.0 mm cancellous screw (without having to redrill the hole) and improve fixation.

Conventional 3.5 mm pelvic reconstruction plates are well suited to rib fracture stabilization.

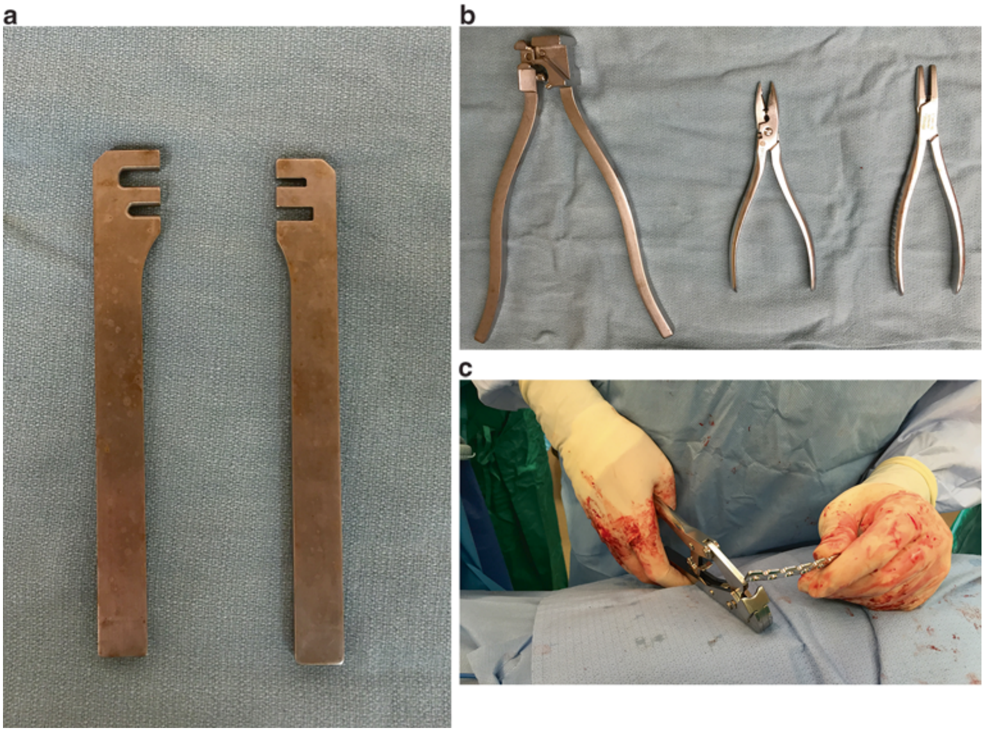

Fig. 9.7 If conventional plates are to be used, it is essential to have contouring tools available including the "handheld" benders (**a**) and various contouring pliers (**b**), shown in use in (**c**)

They usually require minimal contouring to match the rib anatomy. A plate length of six or seven holes is usually appropriate to span a typical transverse fracture of a single rib in a flail chest injury. Three bicortical screws on each side of the fracture are optimal; however, two screws per side may suffice if anatomic space or exposure is limited and screw purchase is good. One screw will not have sufficient stability to withstand the twisting and shear forces of the plate/screw interface and will result in early construct failure. Spanning a single fracture line with a conventional reconstruction plate is technically straightforward. However, if a rib has a flail segment that requires stabilization across two separate fractures, a conventional plate has limitations. Applying a 14-hole reconstruction plate across two fractures is very challenging but can be done with patience and skill (Fig. 9.8). Each rib has a fairly complex three-dimensional shape which is difficult to replicate with manual plate bending. If the plate is contoured incorrectly, the rib will be molded into the incorrect shape of the mal-contoured plate. This will increase the chance of screw application being unsuccessful due to screw pullout. Also, reduction of the subsequent ribs may be difficult if a mal-reduction has been induced early in the procedure. Iatrogenic malunion is to be avoided. In my hands, segmental fractures are stabilized most reliably with a long precontoured rib-specific plate (Fig. 9.9) or by two shorter plates placed in series.

Locking Plates

Locking plates have distinct advantages in softer bone. The threaded heads of the screws engage the plates and produce an angular stable construct that is well suited to the relatively soft bone of the rib. Generic orthopedic locking plates exist and can have some utility in rib fracture cases. Standard orthopedic small fragment (3.5 mm) locking implants are in general too bulky and

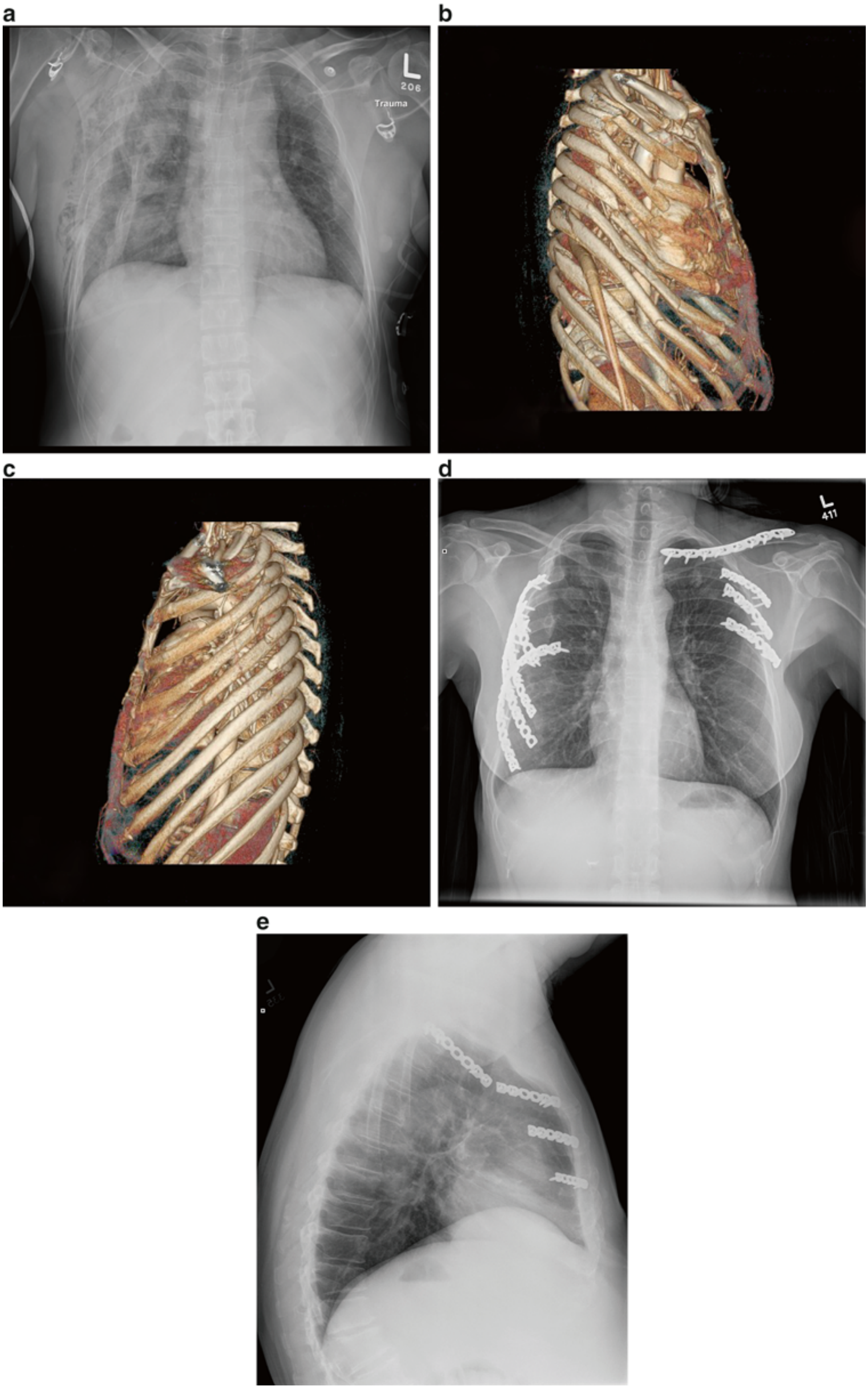

Fig. 9.8 The chest radiograph (**a**) of a 49 year old female pedestrian struck by a vehicle suffering bilateral flail chest injuries and a fractured left clavicle. 3D CT reconstruction films reveal the deformity and fractures of the right (**b**) and left (**c**) sides of the chest wall. Postoperative radiographs (**d**, **e**) following operative fixation of the skeletal injuries

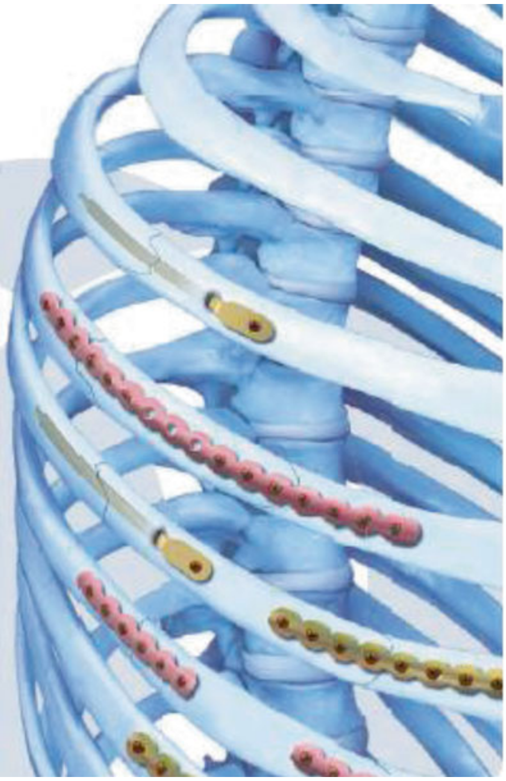

Fig. 9.9 An illustration of a precontoured rib fixation system that includes both plate and intramedullary devices

difficult to contour, making them impractical for rib fracture application. Mini-fragment (2.7 or 2.4 mm) locking plates are well sized to fit rib fractures and can be contoured as required. However, the comparable implant cost and less convenience than rib-specific systems limit the use of generic mini-fragment locking plates.

Modern rib plating systems have been introduced with many specific advantages to rib fracture stabilization. They resemble implants used to stabilize craniomaxillofacial trauma. The small bones of the face and skull have irregular surfaces and relatively thin cortical bone. Thin titanium locking plates offer ease of contouring due to the softer metal while maintaining a good strength profile despite a low plate thickness. Ribs have a complex three-dimensional shape which varies from side to side and rib to rib. Precontoured rib-specific plates are available that match the normal population anatomy [9] (Fig. 9.9). As a result, only minimal contouring is required, even over long segments of rib. Another advantage of a precontoured plate is that it acts as a built-in template to gauge accurate reduction of the injured rib. The commercially available drill systems have built-in stops to prevent plunging into the underlying thoracic viscera. These innovative implants, though likely cost effective in decreasing operative time and possibly intensive care unit stay, suffer from the major disadvantage of a much higher implant cost when compared to conventional plates (Figs. 9.8 and 9.10).

Anterior plating systems such as the Matrix™ system have been gaining in popularity as chest wall stabilization surgery is more commonly performed. Another type of angular stable plating is also available for surgical use. A titanium U-plate system (acute innovations Ribloc™) applies fixation to an injured rib using a superior U-extension over the dorsal and posterior surface of the rib (see Chap. 6, Fig. 9.8). The proximal and distal screw options do not have screw heads that lock into the hole of the plate, rather they achieve angular stability through screw passage from anterior plate, through the cortices of the rib, and then threading into the posterior aspect of the U tab of the plate. These are available in shorter length options and have less precontouring than other available systems. They are promoted as less invasive due to their shorter length and have biomechanical literature support [13]. However, significant soft-tissue dissection is required to insert the U-extension over the dorsal and posterior rib surfaces. Comparative clinical studies between different plating systems are lacking. As a result, surgeons need to exercise caution when applying new technology by employing basic principles to help guide their technique and implant choice.

Conclusion

Operative stabilization of rib fractures is becoming a popular procedure as the limitations and complications of nonoperative treatment become apparent. New techniques and products have been developed and will likely continue to evolve

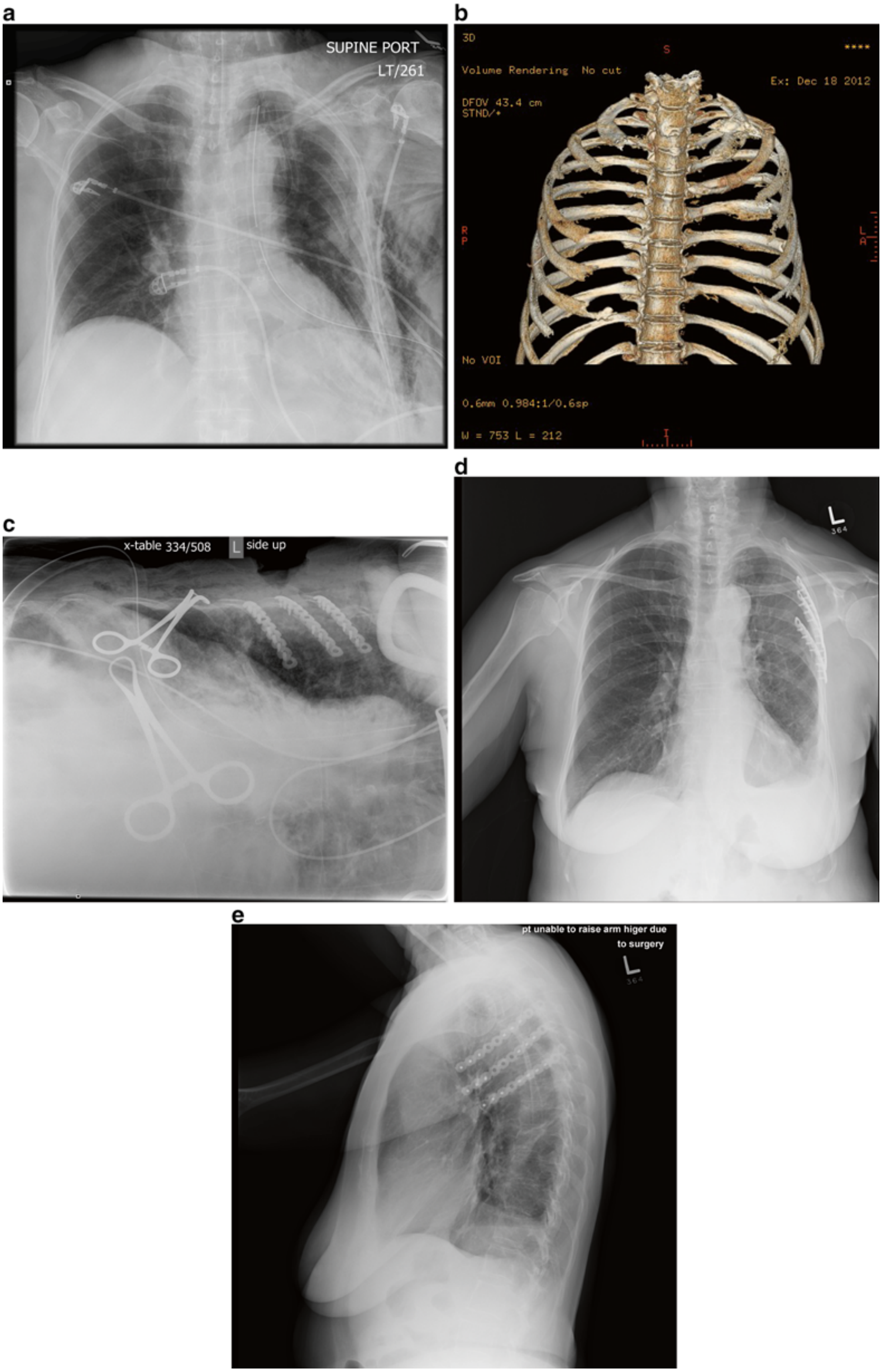

Fig. 9.10 A 65-year-old female sustained multiple rib fractures in a motor vehicle collision demonstrated on chest radiographs (**a**) and a 3D CT scan (**b**). She was intubated and ventilated, but it was not possible to wean her from mechanical ventilation. Fixation of the flail segment was performed: an intraoperative radiograph (**c**) was performed to confirm appropriate plate placement. Postoperative radiographs (**d**, **e**) demonstrating definitive fixation: this facilitated weaning from mechanical ventilation

rapidly in this burgeoning field. Understanding fundamental bone healing principles serves as an important basis when utilizing current implants and evaluating new options as they become available. Understanding basic differences between plate systems is similarly vital information to allow proper utilization of the rib stabilization implants.

The exact indications for rib fracture stabilization continue to be defined. Current literature supports its use in particular situations but remains short of achieving conclusive level-one evidence. Comparative studies examining clinical outcome of different rib fracture stabilization systems are not available to recommend one particular implant over another. Successful stabilization of the chest wall can be achieved with any of the methods described in the preceding chapter. As the field of chest wall stabilization progresses, prospective, clinical studies will be required to determine the optimal stabilization techniques and implants. Until these are available, surgeons undertaking a rib fracture stabilization procedure require a thorough understanding of the plating system(s) available to them and the principles that underpin their successful application.

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Associated Intrathoracic Injuries and Their Treatment

10

S. Morad Hameed, Emilie Joos, and James Bond

Case 1 *A 25-year-old motorcyclist sustains multiple injuries when he is side impacted at high speed by an SUV in a busy downtown intersection. Despite being intubated and mechanically ventilated, he is persistently hypoxemic. A left chest tube is placed and evacuates 1,100 mL of blood and demonstrates a persistent high-volume air leak. Computed tomography of the chest shows multiple displaced left-sided rib fractures, a pulmonary contusion, and a persistent hemothorax.*

Case 2 *A 69-year-old woman is pinned against the wall in her garage by a slowly moving minivan. She is awake and alert, with good oxygen saturations and a blood pressure of 140/90. Chest X-ray demonstrates multiple, displaced, bilateral rib fractures and a widened mediastinum but no other abnormalities. She has a normal ECG, but elevation in her cardiac troponins.*

Introduction

Chest trauma can pose immediate and delayed threats to life by compromising airway patency, breathing function, gas exchange, or the integrity and filling of the circulatory system. In blunt trauma, significant chest wall injury is only an outward manifestation of the potential for significant injury to mediastinal structures, to the lungs, or to the pleural spaces. Surgeons caring for patients with injuries to the chest wall must be aware of the high likelihood of severe associated injuries and delayed complications and should lead the trauma team in a multidisciplinary approach to detecting and treating these injuries.

Initial Approaches to Thoracic Trauma

The Advanced Trauma Life Support (ATLS) course [1] defines a framework for the initial assessment and treatment of trauma patients that prioritizes injuries in the order of their potential threat to life: airway (with cervical spine protection), breathing, circulation, disability (neurologic status), and full exposure and environmental control (avoidance of hypothermia). An initial primary survey of these systems is complemented by diagnostic adjuncts (including chest and pelvic X-rays, portable ultrasound, and arterial blood gases), coupled with injury-specific

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resuscitation, ultimately followed by a more detailed history and physical examination (secondary survey). Many of the initial phases of the ATLS protocol are focused on the management of thoracic injuries.

Six thoracic injuries are considered to be immediate threats to life as a result of airway obstruction, impairment of oxygenation, obstruction of venous return to the heart, or massive blood loss (Table 10.1). Depending on their nature, these injuries are managed with any combination of definitive airway control, mechanical ventilation, aggressive fluid resuscitation and blood product transfusion, placement of chest tubes, and emergent or urgent surgery. The unifying principles of these approaches are to rapidly reestablish oxygen delivery in patients with shock and to stop ongoing hemorrhage. These principles have formed the basis for the emerging concepts of damage control resuscitation and damage control surgery.

The damage control resuscitation concept evolved in response to the recognition of hemorrhage and coagulopathy as a common and potent complication of severe trauma. The strategy encompasses three resuscitation priorities: (1) setting modest blood pressure and perfusion targets until hemostasis is achieved in order to avoid the adverse effects of excess fluid administration, (2) minimization of crystalloid use and early transition of resuscitation to blood component therapy to restore oxygen-carrying capacity and normalize coagulation, and (3) damage control surgery. Surgery emphasizes three key operative priorities: minimization of operative time with early transfer to ICU (for shock resuscitation, correction of coagulopathy, and reversal of hypothermia), rapid control of hemorrhage, and temporizing control of contamination [1–4].

Surgeons caring for patients with severe chest wall trauma will be entering this complex milieu and may be required to adjust their approach based on associated injuries and prevailing priorities. The timing of reconstructive surgery in multiple injured patients will depend on the establishment of effective oxygenation, the reversal of shock, the correction of coagulopathy, and will require coordination with critical care and other surgical services completing other operative interventions. In general, the lateral decubitus positioning required for many chest wall reconstructive procedures does not provide adequate access for damage control procedures and may not be tolerated in patients with pulmonary injuries. Chest wall reconstruction is therefore left until all acute interventions have been completed and homeostasis has been achieved.

Diagnostic Approaches and Advances

Chest Radiograph

The portable chest radiograph (CXR) is one of the first adjuncts to the primary survey advocated by ATLS. In most trauma bays, it is convenient and fast and reveals major early threats to life. There are, however, limitations to this imaging modality. In a blunt trauma patient with a significant mechanism of injury, full spine precautions have to be maintained. The CXR is thus performed supine and anteroposterior, which decreases its accuracy. As a result, the trauma room CXR may miss up to half of pneumothoraces [5, 6]. Up to 65 % of patients with significant blunt chest trauma will have significant chest trauma missed by CXR alone [7]. Despite these limitations, a CXR can diagnose large hemopneumothoraces and lung contusions and should still be part of the initial investigation.

Ultrasound

Ultrasound (US) is increasingly used in the trauma and critical care setting. It has multiple advantages including portability, versatility, steep learning curve, and good accuracy. Smaller probes with greater image quality have made this diagnostic tool an essential in the trauma bay. The addition of the thoracic component to the Focused Assessment with Sonography for Trauma (FAST) has been called the extended FAST (E-FAST). Using a high-frequency probe (10–15 MHz), multiple sonographic signs have

Table 10.1 Associated intrathoracic injuries

Airway obstruction	Patients found to have impending or active airway obstruction are often noted to have alteration of mental status or to exhibit stridorous breathing, dysphonia, tachypnea, indrawing, or accessory muscle use. Urgent placement of a definitive airway is indicated for those patients who are found to be apneic, hypoxemic, or obtunded (GCS < 8) or who are noted to have complex facial injuries, thermal inhalation injuries, penetrating injuries to the neck, or expanding or pulsatile cervical hematomas
Tension pneumothorax	Blunt or penetrating injuries to the thorax may result in airway, lung parenchymal or pleural disruption, and subsequent escape of air to the pleural space. If the injury creates a "one-way valve" with air entering the negative pressure environment of the pleural space, but prevented from returning to the airway, air trapping will occur. Positive pleural pressure creates an extremely dangerous situation of respiratory and hemodynamic compromise due to alterations in respiratory mechanics and venous return. Positive pressure ventilation can hasten this process or convert apparently simple pneumothoraces to tension pneumothoraces (TPs). Patients with diminished air entry and evidence of hemodynamic instability should undergo immediate pleural decompression. TPs require immediate placement of chest tubes on the side of diminished air entry Failure of the lung to re-expand with well-placed chest tubes on 20 cm H_2O suction, persistent air leaks, or the observation of hemoptysis or blood in the endotracheal tube should raise the concern that a more proximal injury to the tracheobronchial tree has occurred. In such instances, a second chest tube may be required, and evaluation for airway injuries by flexible bronchoscopy should be undertaken. Bronchoscopy-guided interventions in the operating room such as selective bronchial intubation or placement of dual-lumen tubes or bronchial blockers may allow protection and selective ventilation of the uninjured lung until definitive measures can be undertaken
Massive hemothorax	Penetrating and sometimes blunt injuries to the chest can cause the accumulation of greater than 1,500 mL of blood in the pleural space. Blood loss of this magnitude in the chest can present with symptoms and signs of respiratory compromise and profound shock. When a chest tube, placed in the setting of hemodynamic instability, evacuates 1,500 mL of blood immediately or continues to drain 200–300 mL/h, ongoing bleeding is likely and preparations for exploratory thoracotomy should be made. Such preparations include reassessment of the patient's airway, breathing, and circulation; thorough evaluation for associated injuries, which may contribute to ongoing hemorrhage; and meticulous efforts to warm the patient and treat transfusion-associated coagulopathy Note: Rapid exsanguinations can occur into the chest without significant chest tube output if the tube is clogged or kinked Physicians attempting to rule out ongoing sources of hemorrhage should not be reassured by low volume chest tube output, and patients must be frequently reexamined and re-X-rayed as necessary
Open pneumothorax	High-velocity weapons or high-speed blunt injury mechanisms can cause full thickness injury to the chest wall. Gaps in the chest wall may permit air entry into the pleural space, especially during spontaneous inspiration when intrapleural pressures are negative. When a chest wall defect reaches roughly two-thirds the diameter of the trachea, pleural ventilation may become the path of least resistance during inspiration, and normal bronchial air flow may become extremely compromised. Patients with this injury present with respiratory distress and a "sucking chest wound" Early therapeutic priorities for these patients include airway management, coverage of the wound, and pleural drainage

(continued)

Table 10.1 (continued)

Cardiac tamponade	Depending on the distensibility of the pericardium as little as 60–100 mL of blood in the pericardial sac can increase pressures around the heart sufficient to limit venous return to the right atrium. Obstructive shock from loss of cardiac preload can initially be compensated by sympathetic measures directed at maintaining cardiac output (tachycardia, vasoconstriction of the venous bed). However, unless mounting pressure is relieved, dramatic decreases in cardiac output and coronary perfusion can ensue. This condition is known as cardiac tamponade
Flail chest	Multiple rib fractures may result in segmental instability of the chest wall. When blunt forces disrupt the continuity of ribs, costal cartilage, or sternum at more than one site, the intervening chest wall can remain stationary or even be drawn inward at inspiration. This phenomenon is known as flail chest (FC). The high-energy transfers required to create a flail segment often result in significant associated injuries such as pulmonary contusion (50 %) and hemopneumothorax (70 %), as well as head, abdominal, pelvic, and extremity injuries. Acute hypoxemia and respiratory failure is seen in those FC patients with associated pulmonary contusions, and flail segments may, in fact, become more evident as more respiratory effort is required with blossoming contusions. The acute and chronic severity of FC is primarily dependent on the magnitude of the underlying pulmonary contusion rather than on abnormalities of the chest wall The diagnosis of FC is clinical—observation of segmental paradoxical chest wall movement with respiration requires adequate exposure and careful examination during all phases of spontaneous breathing. The cornerstones of therapy for FC are close observation and reexamination for signs of deterioration of respiratory function, use of humidified supplemental oxygen and mechanical ventilation as necessary for support of gas exchange, optimization of analgesia, and prompt treatment of associated injuries

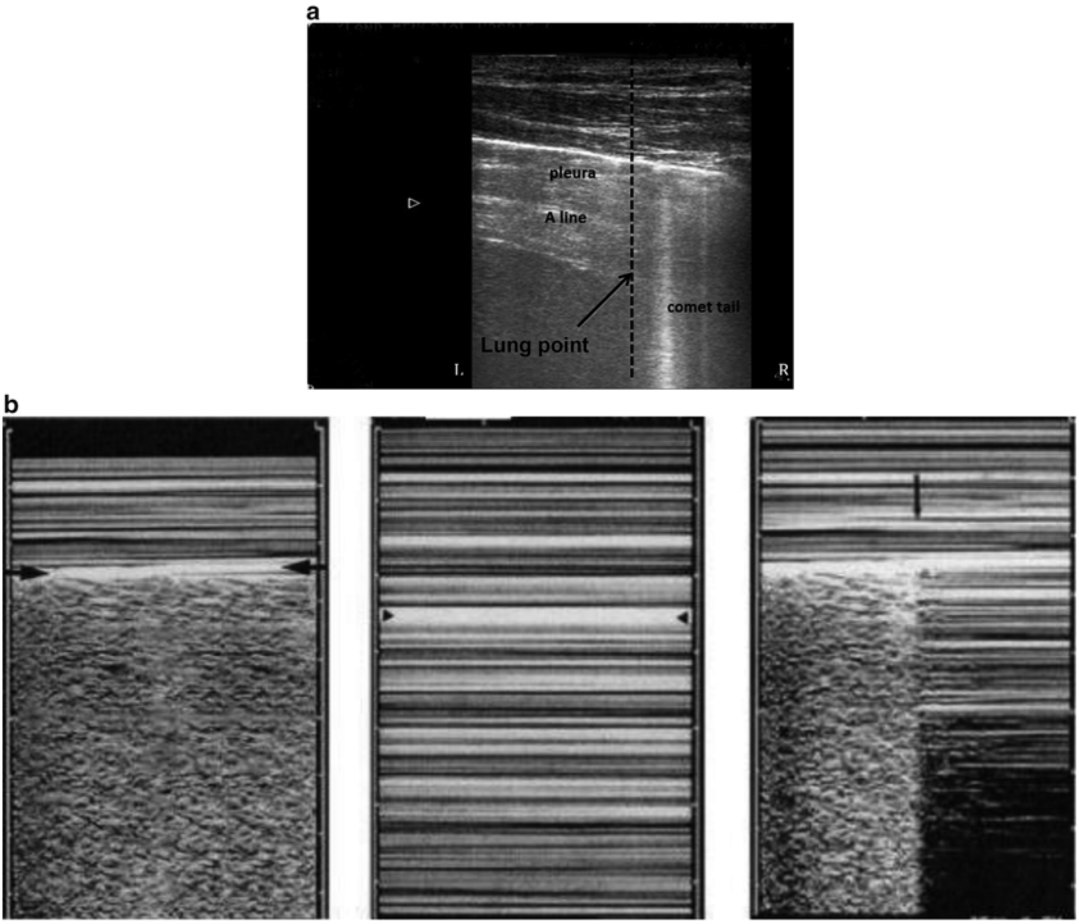

Fig. 10.1 Thoracic ultrasound. (**a**) A 10 MHz probe is used to image the pleural surface in a patient with shortness of breath after blunt chest trauma. The *bright horizontal line* represents the pleura. The horizontal reverberations are referred to as “A” lines, which are a sign of pneumothorax. Similarly, absence of rib shadowing, also called “comet-tail artifact,” is typical of pneumothorax. This image thus depicts the lung point: on the *left side* is a pneumothorax, on the *right side* normal lung. (**b**) The lung point, depicted by the *arrow* in the third image (*right-hand side*), is 100 % specific for pneumothorax. In M-mode, normal lung has a “seashore” appearance (image 1). In a pneumothorax, there is no pleural sliding; thus, the granular pattern created by the pleural movement is absent

been described to detect pneumothoraces: absence of pleural sliding, comet-tail artifact, B lines, and the presence of A lines. The most specific sign is the “lung point,” which defines the border of the pneumothorax (Fig. 10.1). The same findings can be obtained with the standard low-frequency probe (2.5–5 MHz) used for FAST. Multiple studies have shown that US has better sensitivity and specificity than CXR for detection of pneumothorax [8, 9]. A recent systematic review reports a sensitivity ranging from 86 % to 98.2 % and a specificity ranging from 97.2 % to 100 % [10]. Thoracic ultrasound can also detect a hemothorax. This diagnostic modality remains accurate even in the setting of severe chest trauma with multiple rib fractures, as long as there is an adequate window to visualize the pleura.

Another use of the US is the limited transthoracic echocardiography (LTTE), which is gaining popularity in the trauma environment. It allows for a quick assessment of the patient’s volume status, cardiac function, and presence of pericardial effusion. Three views are obtained: the parasternal long and short axis, the apical window, and the subxiphoid window. A recent study by Ferrada et al. reported a 100 % accuracy for pericardial effusion and global heart function [11]. Most patients in this study sustained blunt trauma, and several had a chest tube, previous sternotomy or thoracotomy. All exams were performed in less than 5 min by non-ultrasound trained trauma attendings.

We suggest that US should always be performed in the blunt trauma patient with severe chest injuries, as it is a noninvasive and quick method to diagnose hemopneumothorax and pericardial effusion. An added benefit of this diagnostic test is the assessment of cardiac contractility and volume status.

Computed Tomography

Computed tomography (CT) for chest trauma is the gold standard against which all other imaging modalities are compared. A large retrospective study of more than 1,047 trauma patients showed that a positive CXR was the most significant predictor of finding associated thoracic injuries on CT (OR 15.6; $p<0.001$) [12]. All patients with multiple rib fractures and/or flail chest should have a CT of the chest with intravenous contrast. In patients with significant mechanisms (fall greater than 5 m, pedestrian struck thrown more than 3 m, high-speed motor vehicle crash), a CT angiography of the chest is recommended to rule out blunt thoracic aortic injury. At the Vancouver General Hospital, we perform a rapid imaging protocol in trauma (RIPIT): a whole-body dual-source CT with fast reconstruction time at 40 images per second [13]. After a non-contrast CT of the head, a contiguous whole-body arterial phase from the vertex to the pelvis is performed, which gives good quality images of the thoracic aorta and adjacent structures. With the presence of the CT scanner adjacent to the trauma bay and new advances in technology, the whole-body CT can be completed in 5 min.

Injuries Commonly Associated with Chest Wall Trauma

Mediastinum

Blunt Cerebrovascular Injury

Blunt cerebrovascular injuries (BCVIs) to the extracranial carotid and vertebral arteries, which are thought to result from neck hyperflexion, hyperextension, or rotational mechanisms, occur in about 1 % of hospitalized trauma patients and are associated with increased risk of potentially devastating ischemic strokes, both on admission and within days of injury. Classic studies have shown that certain injury patterns, including traumatic brain injury, complex skull fractures, facial or mandibular fractures, cervical spine fractures, neck soft-tissue injuries, and thoracic or thoracic vascular injuries, are associated with BCVIs and can be used as criteria for screening with CT angiography and/or digital subtraction angiography [14–16]. However, it is estimated that 30 % of patients with BCVIs do not meet any of these screening criteria, and some investigators advocate for more liberal screening, even based on suspicious mechanism alone [17]. Surgeons caring for patients with major thoracic trauma should ensure that their patients have been screened for BCVI, and started on prophylactic antiplatelet or anticoagulant therapy as soon as the risks of stroke (thought to be 21 % in untreated patients) [18] begin to outweigh the risks of anticoagulation-associated hemorrhage.

Blunt Aortic Injury

Blunt thoracic aortic injury (BTAI) is most often caused by rapid deceleration, from motor vehicle or motorcycle crashes. Other common mechanisms include fall from height more than 5 m, crush between two objects, and ejection from a vehicle. Only 20 % of patients with BTAI will survive to the hospital. The injury usually occurs on the descending thoracic aorta, just distal to the takeoff of the left subclavian artery. The diagnosis

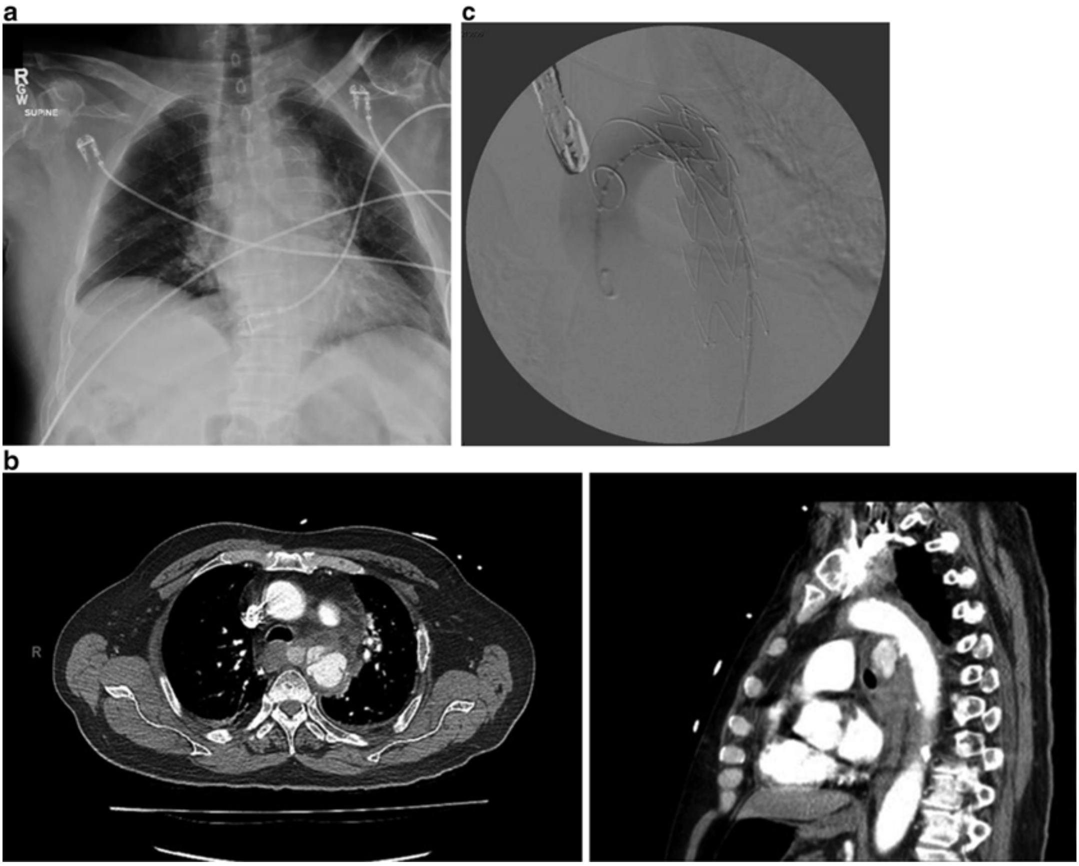

Fig. 10.2 Blunt thoracic aortic injury. An 83-year-old patient was the passenger of a car which crashed into an electric pole, at 70 km/h. He was hemodynamically stable but complained of mild chest pain. The CXR is shown in (**a**). He subsequently underwent a CT scan, shown in (**b**). The patient had a hypoxic arrest shortly after the CT and required emergent intubation and thoracic endovascular repair (**c**)

can be suspected on CXR, with suggestive signs like widened mediastinum, apical cap, loss of aortic knob, or a depressed left main stem bronchus (Fig. 10.2). However, these signs may not be obvious on a supine anteroposterior CXR and are not specific to BTAI. As discussed above, the trauma surgeon should have a low threshold for performing a CT scan in patients with serious mechanism and/or suspicious findings on CXR. Helical CT angiography is the gold standard for diagnosing these injuries. If equivocal, a formal angiogram can be performed. The treatment of BTAI has drastically evolved over the course of the past decades. Two large prospective studies from the American Association for the Surgery of Trauma have redefined the optimal management of this injury [19, 20]. They have shown, first, that delayed repair improves outcomes and, second, that the endovascular stent graft technique has less morbidity and mortality than conventional open repair. A recent study reports 0 % 30-day mortality, no conversion to open repair, and a re-intervention rate of 5.8 % at 3 years with the endovascular approach [21]. In patients with multiple rib fractures and BTAI, priority should be given to patient resuscitation, blood pressure control, and semi-urgent endovascular repair. Rib plating should only be done once the aortic injury has been repaired.

Blunt Cardiac Injury

Patients sustaining motor vehicle crashes, motorcycle crashes, and high-level falls (≥20 feet), as well as pedestrians that are hit by cars, and certainly all patients with significant chest wall trauma, are at risk of blunt cardiac injury (BCI). The clinical manifestations of BCI can be structural, from trauma to the structural elements of the heart, or electrical, from injuries to the heart's electrical conduction system. From a structural standpoint, injuries include transmural rupture (which is usually fatal at the scene), valvular rupture causing acute heart failure and necessitating valve repair or replacement, coronary artery dissection necessitating immediate revascularization procedures, and intramural hematomas, which often resolve with simple expectant management. Electrical disturbances seen in BCI include commotio cordis, a trauma-induced conduction abnormality that is rapidly fatal in the vast majority of cases, as well as atrial and ventricular dysrhythmias and bundle branch block, which often require pharmacological control, cardioversion, or pacing, depending on their severity and hemodynamic effects [22].

BCIs are uncommon, but are of extreme clinical significance. Surgeons caring for patients with significant chest wall trauma should ensure that the possibility of BCI has been considered and ruled out or adequately addressed. A 12-lead ECG (an essential part of the diagnostic workup of chest trauma patients), when normal, has a 95 % negative predictive value for BCI [23], which increases to 100 % when combined with a normal cardiac troponin I [24]. Patients with new ECG abnormalities or troponin elevations require admission to monitored settings and may need additional investigation with echocardiography or cardiac catheterization, depending on the nature of the abnormalities and their hemodynamic status (Fig. 10.3). Such patients can still undergo urgent procedures, provided that their cardiac function can be monitored and optimized.

Esophageal Injury

Blunt esophageal injury is very rare, estimated to be present in 0.1 % of trauma admissions [25], possibly because the esophagus is protected between the aorta and vertebral column in the posterior mediastinum. Blunt esophageal injuries are caused by an increased pressure in the lumen against a closed upper or lower esophageal sphincter, usually secondary to a blow to the epigastrium [26]. A less common cause of esophageal injury in blunt mechanisms is impalement by an adjacent thoracic vertebral osteophyte fracture. Although rare, esophageal injuries cause significant morbidity, especially if diagnosed late. A combination of clinical evaluation (odynophagia, chest pain, hematemesis, sepsis) and multiple imaging modalities is recommended for diagnosis: CXR, CT, water-soluble and barium esophagogram, and esophagoscopy [27]. Pneumomediastinum on CT should prompt consideration of investigation for esophageal trauma, if the clinical circumstances are suggestive. A thoracic esophageal injury should be approached with a posterolateral right or left thoracotomy, depending on the site of perforation. These cases are usually heavily contaminated and the repair is at high risk of dehiscence. If associated rib fractures are present, rib plating should be discouraged because of the high risk of hardware infection.

Lung and Tracheobronchial Tree

Pulmonary Contusion, Acute Respiratory Distress Syndrome, and Other Causes of Respiratory Failure

Respiratory failure in blunt chest trauma results from a combination of injury to the lung parenchyma (pulmonary contusion (PC)) and disruption of the chest wall (flail chest (FC)). Therapeutic efforts are therefore directed at the consequences of both types of injury.

PC is characterized by parenchymal hemorrhage, inflammation, and occlusion of alveoli with blood and pulmonary edema (Fig. 10.4) [28, 29]. Blood or fluid-filled alveoli are unable to participate in gas exchange, and blood shunting past these alveoli will remain deoxygenated. Large lung contusions create large shunt fractions and worse hypoxemia. The extent of pulmonary contusion correlates closely with the severity of hypoxemic respiratory failure, the risk of pneumonia, and the duration of mechanical ventilation. In the long term, patients with PC can

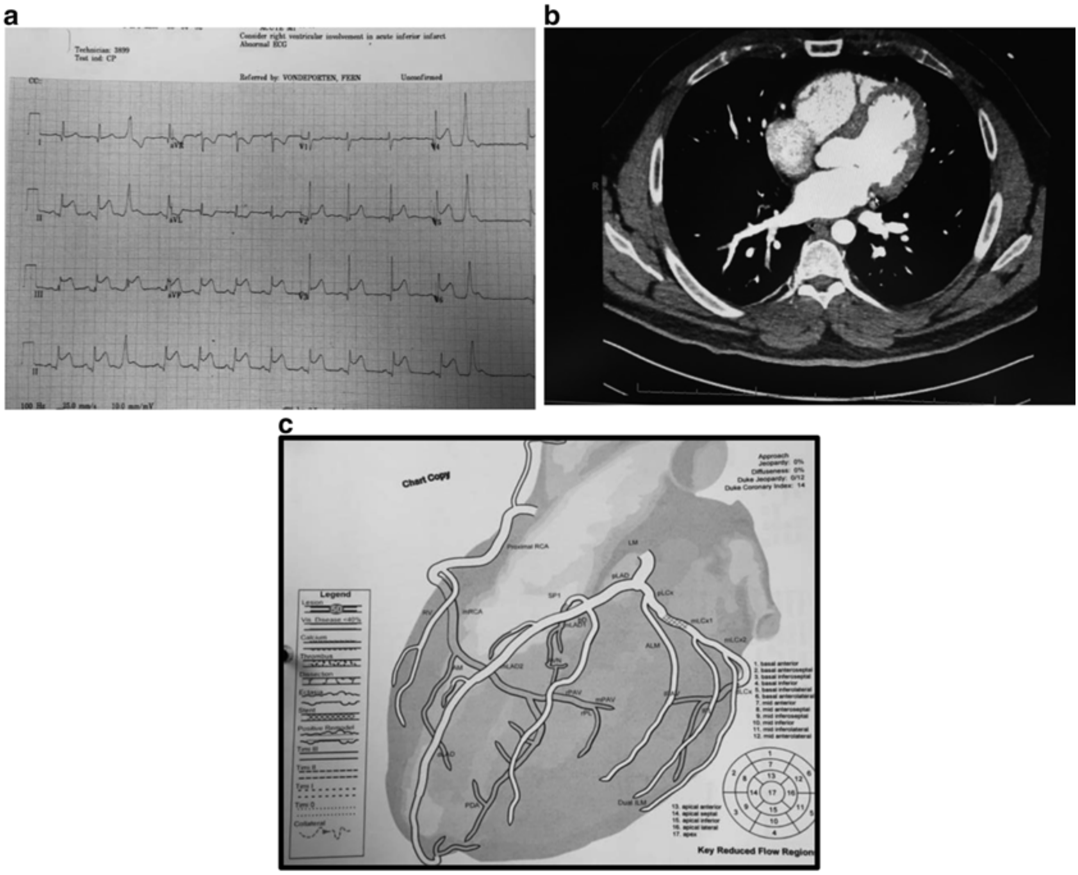

Fig. 10.3 Blunt cardiac injury. A healthy 34-year-old cyclist fell at high speed, striking his chest and sustaining numerous rib fractures. He completed his ride, but soon afterward, felt heavy retrosternal chest pain. (**a**) 12-lead ECG demonstrates inferior ST segment elevation. (**b**) Cardiac CT reveals occlusion of the left circumflex artery, likely as a result of plaque rupture and dissection resulting from impact. (**c**) This segment was revascularized using a stent

develop fibrotic changes in the lung that correlate with worse pulmonary function.

Supportive care with supplemental oxygen, adequate analgesia (including thoracic epidural analgesia) [30], chest physiotherapy, and the judicious use of intravenous fluids helps the hypoxemic effects of PC resolve in most cases. Positive pressure ventilation with positive end-expiratory pressure (PEEP) reduces shunt fraction and improves rib fracture apposition. However, invasive mechanical ventilation is associated with significant complications and high cost. In recent years, the practice of intubating all patients with significant pulmonary contusion has given way to the more selective use of intubation and mechanical ventilation as a safety net for PC patients who develop respiratory failure despite aggressive supportive care. In recent years, well-designed studies have shown that the liberal use of noninvasive modes of positive pressure ventilation, such as continuous positive airway pressure (CPAP), is effective in reducing atelectasis, pneumonia, respiratory failure, and the need for invasive mechanical ventilation [29]. A multidisciplinary approach to PC, which includes the use of noninvasive positive pressure ventilation as needed, along with bronchial hygiene, chest physiotherapy, early mobilization, and conscientious pain control has been shown to drastically reduce the need for invasive mechanical

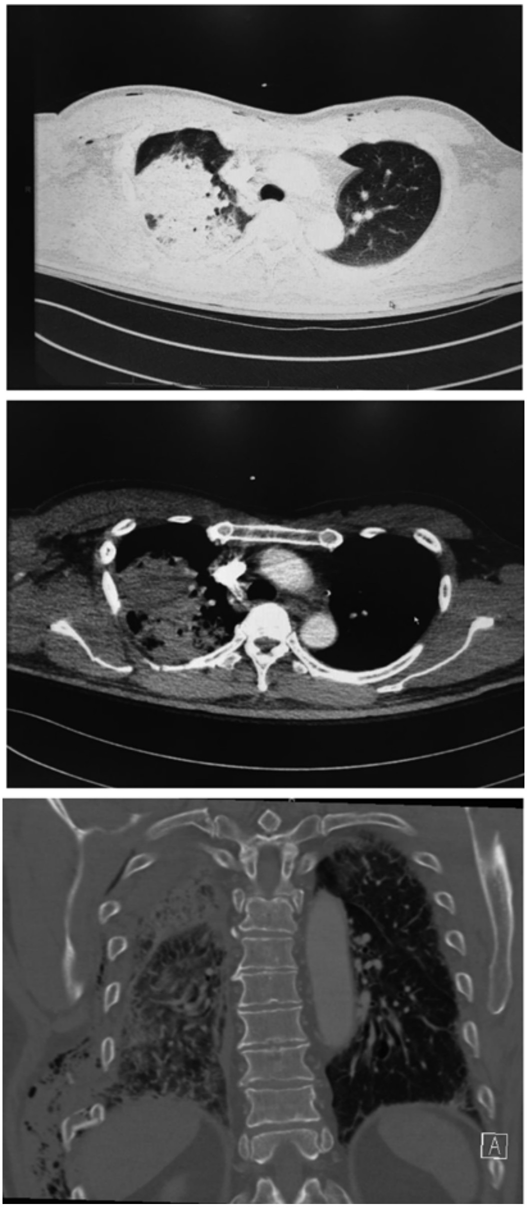

Fig. 10.4 Pulmonary contusion. A 43-year-old male was involved in a head on motor vehicle crash. In addition to a mild traumatic brain injury, he sustained rib fractures and a right upper lobe pulmonary contusion. He was intubated for airway protection and placed on positive pressure ventilation to maintain cerebral oxygenation in the context of hypoxemic respiratory failure from his pulmonary contusion. Chest wall reconstruction was deferred until the severity and course of the pulmonary contusion are determined

ventilation [31]. When a flail chest is present, rib fracture fixation may be an important adjunct in a multidisciplinary strategy, although the indications and timing of the intervention should be tailored to the specific injury patterns and clinical circumstances.

Heightened vigilance and care must be applied to elderly patients with chest wall injuries, even from low-velocity mechanisms, such as ground-level falls, that may not normally be associated with substantial pulmonary contusions. These patients sustain their injuries on a background of poor pulmonary reserve, or even chronic lung disease, or other significant comorbidities such as ischemic heart disease, liver failure, renal failure, or type 2 diabetes. Under these circumstances, even small volumes of pulmonary contusion or atelectasis with associated increases in shunt fraction are poorly tolerated and can severely compromise respiratory function in patients who had previously been compensating well. Elderly patients with rib fractures are at greater risk of pneumonia, prolonged mechanical ventilation, prolonged ICU stays, loss of functional independence, and mortality, in comparison to younger, matched control patients, and some of these risks increase nearly 20 % with each additional rib fracture [32]. The aggressive multidisciplinary approach to pulmonary contusion and flail chest outlined above is especially relevant in the care of elderly patients—these patients should be admitted to high acuity units, followed closely, and treated aggressively in order to avoid the complications that often lead to permanent loss of function and independence and even death.

Pulmonary Lacerations (Surgical Considerations)

Pulmonary lacerations secondary to blunt trauma are rare and usually the result of displaced rib fractures puncturing the lung parenchyma. They can be associated with bleeding or persistent air leaks. The natural history of these injuries is usually spontaneous resolution, as most are small and superficial and heal without any intervention. The vast majority of lung injuries requiring surgery are caused by penetrating trauma. However, when patients with blunt trauma require surgery, the injury is usually more extensive and more difficult to treat. Up to 20 % of patients requiring thoracotomy for blunt trauma will need a lung resection [33]. The most common procedures required are primary suture repair, tractotomy, or stapled wedge resection. If the injury is perihilar, a lobectomy may be required. Proximal control with hilar clamping may be needed if extensive bleeding is encountered.

If a surgeon encounters a pulmonary laceration during rib fracture fixation, several options are available. Persisting impalement by a rib should be promptly addressed by reduction of the rib fracture. Hemorrhage at the laceration site can be controlled by the use of absorbable sutures or, preferably, by stapled nonanatomic wedge resection of the lacerated lung tissue. Compared to oversewing of a laceration, wedge resection reduces the likelihood of leaving behind occult, ongoing intraparenchymal hemorrhage, which can result in dense pulmonary consolidation or even hemoptysis and airway compromise. An air leak from a laceration site can often be managed simply by the placement of chest tubes and confirmation that the lung expands fully to bring the visceral and parietal pleural surfaces in contact. Larger lacerations with air leaks may need to be oversewn or resected. In general, the mortality of lung injuries increases as more extensive procedures (chest tube drainage, direct suture, wedge resection, stapled tractotomy, lobectomy, pneumonectomy) are required, and the least aggressive procedure that adequately addresses air leak or hemorrhage is preferred [33, 34].

Tracheobronchial Injury

Tracheobronchial injuries result from acceleration–deceleration mechanisms. The injuries are often located within a centimeter of the carina and create a pneumothorax with a massive air leak and fallen lung sign on a chest radiograph (Fig. 10.5). Placement of additional chest drains may not result in any appreciable lung expansion, and air loss from the tracheobronchial tree makes positive pressure ventilation ineffective. Efforts should be directed toward selective intubation of the contralateral bronchus, early tracheobronchial repair, and the use of adjunctive strategies, including extracorporeal life support, if oxygenation remains severely impaired.

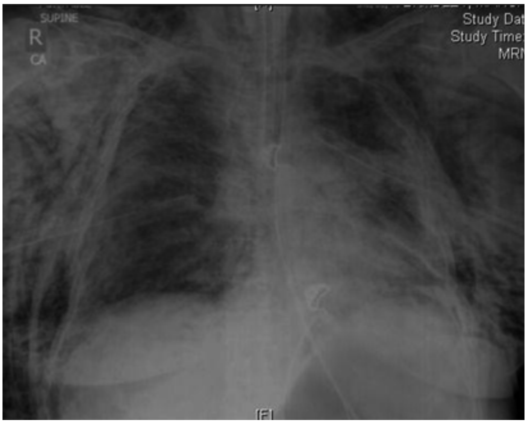

Fig. 10.5 Tracheobronchial injury. A 52-year-old truck driver was crushed by falling logs while unloading his truck. He sustained multiple bilateral rib fractures, with bilateral pneumothoraces and massive subcutaneous emphysema. Two chest tubes were placed and he was intubated for oxygenation and ventilation support. Blowing air leaks were seen from the chest tubes, and the subcutaneous emphysema progressed, indicating a tracheobronchial rupture

Pleural Spaces

Pneumothorax

Pneumothoraces are a frequent manifestation of chest trauma, particularly in the setting of rib fractures. A simple pneumothorax can easily be missed by a supine CXR (see section above). It is critical to rule out a tension pneumothorax, which should manifest clinically with shortness of breath, desaturation, hypotension, absence of breath sounds ipsilaterally, and a deviation of the trachea contralaterally (Fig. 10.6). A radiographic or even CT image of a tension pneumothorax should be seen as a missed diagnosis. A tension pneumothorax should be immediately decompressed with a needle followed by a chest tube. Tension pneumothoraces can have a delayed

Fig. 10.6 Tension pneumothorax. A radiograph of a tension pneumothorax (**a**) compared to a non-tension pneumothorax, pointed by the *arrow* (**b**). Note the mediastinal deviation, tracheal deviation, and complete lung collapse in (**a**). A 33-year-old man was thrown out of a moving car and sustained major right-sided crush injuries. The scout of the CT scan reveals a tension pneumothorax, with a characteristic deep sulcus sign (**c**). The CT shows a right pulmonary contusion and hemothorax (**d**) as well as tension pneumothorax with dramatic mediastinal deviation and moderate subcutaneous emphysema (**e**). This patient was considered for rib fixation, but he unfortunately developed acute respiratory distress syndrome secondary to the lung contusions

presentation, following the institution of positive pressure ventilation. Surgeons caring for ventilated chest trauma patients with unexpected instability in the emergency department, operating room, or intensive care unit should consider tension pneumothorax and take systematic and decisive action to diagnose and treat it.

Most pneumothoraces can be treated with tube thoracostomy. Two exceptions exist: the small asymptomatic pneumothorax and the occult pneumothorax. Trauma surgeons may feel comfortable observing a stable, asymptomatic patient with a pneumothorax of less than 1.5 cm apically if there is no progression on serial CXR. The occult pneumothorax is defined as a pneumothorax seen on CT scan but not on CXR. A Canadian multicenter study randomized patients with occult pneumothoraces undergoing positive pressure ventilation (PPV) to chest drainage versus observation [35]. Twenty percent of patients in the observation group required subsequent tube thoracostomy for pneumothorax progression, pleural fluid, or hemodynamic instability. None of these patients developed a tension pneumothorax, and there was no increase in ventilator days or mortality in the group observation. These results are corroborated by the American Association for the Surgery of Trauma (AAST) prospective observational trial, which showed that 14 % of patients with occult pneumothoraces in the group PPV required a chest tube versus 6 % in the non-ventilated group [36]. The Eastern Association for the Surgery of Trauma (EAST) recommends observation for all occult pneumothoraces, regardless of positive pressure ventilation (level 3) [37].

Hemothorax and Retained Hemothorax

Hemothorax is a common complication of rib fractures. It is usually caused by bleeding from intercostal vessels or, more rarely, from the lung parenchyma itself. Any hemothorax visible on CXR or more than 300 cc in volume should be drained with a large bore thoracostomy tube, at least 28F (Fig. 10.7). A prospective observational study from Los Angeles County Level 1 Trauma Center showed that there was no benefit in placing a chest tube larger than 32F for the drainage of a hemothorax [38]. Fresh blood can be autotransfused back to the patient. Most hemothoraces are successfully managed with a chest drain. The role of prophylactic antibiotics at the time of chest tube placement is controversial. A systematic review showed that it reduces the risk of empyema but only in patients with penetrating trauma [39].

If the initial drainage is more than 1.5 l or if the drainage persists at a rate of 200 cc/h, there is an indication for urgent thoracotomy for hemostasis. We favor a surgical approach to massive hemothorax over interventional radiology with angioembolization of intercostal arteries. In our experience, intercostal embolization for hemorrhage control has not been reliable and still often requires follow-up surgical intervention for hematoma evacuation and treatment of associated injuries.

It is important to repeat a CXR 24 h post drainage, to rule out a retained hemothorax, which has been associated with numerous complications, including pneumonia, empyema (up to 33 % of patients) [40], and trapped lung. Abnormal repeat CXRs can be followed up with computed tomography to confirm and quantify the presence of pleural fluid and to assist with operative planning. Early evacuation of retained hemothoraces, within days and before the onset of coagulation, loculation, inflammation, and sepsis, is a high priority in the management of chest trauma patients.

Multiple algorithms have been proposed for the management of retained hemothoraces. One randomized controlled study favored early video-assisted thoracoscopic surgery for definitive hemothorax drainage and decortication over the placement of a second chest tube [41]. Other approaches include placing a second chest tube, using image guidance to insert a pigtail catheter, intrapleural fibrinolysis, and thoracotomy. The increasingly operative approaches to retained hemothoraces may create an opportunity for concomitant rib fracture fixation. Surgeons considering operative evacuation of retained hemothorax should include the possibility of rib fracture stabilization in their preoperative planning and discussions.

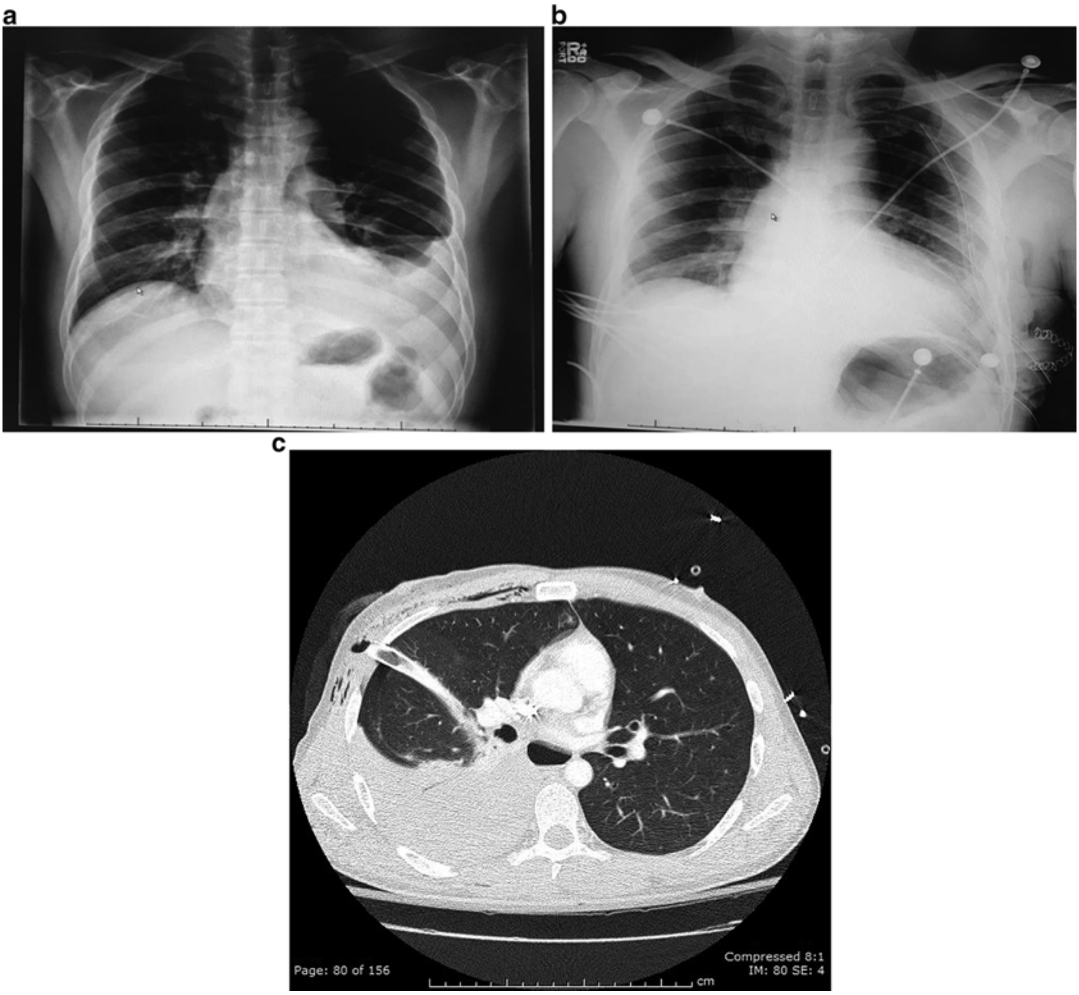

Fig. 10.7 Retained hemothorax. A 58-year-old skier sustained rib fractures in a collision with a tree. He presented to hospital 48 h later with chest wall pain, exertional dyspnea, and the X-ray shown in (**a**), demonstrating a large left retained hemothorax. (**b**) The hemothorax was successfully drained with a large diameter chest tube. (**c**) A 35-year-old man sustained a flail chest with a large hemopneumothorax secondary to a fall while biking. Forty-eight hours after admission, his CT scan shows a chest tube in right position with a large retained hemothorax

Open Pneumothorax

Open pneumothorax is a chest wall defect that is severe enough that the air is drawn into the wound during negative pressure inspiration, causing a large pneumothorax and subsequent lung collapse. It is also called a “sucking chest wound.” The ATLS recommends placing a three-sided dressing, which creates a valve-like effect and convert the open pneumothorax to a closed one. A chest tube should subsequently be placed. In the military setting, these injuries can be highly lethal in the field. The use of a vented chest seal or a nonvented chest seal with a low threshold to place a chest tube has drastically improved the management of these patients [42]. These injuries almost always require definitive management of associated injuries and surgical reconstruction.

Diaphragm

To rupture the strong musculotendinous structure that is the diaphragm requires a tremendous amount of force applied to the torso. The most common mechanisms of injury are similar to the ones causing BTAI: high-speed decelerating injuries such as motor vehicle crashes or fall from more than 5 m and pedestrian struck. The incidence ranges from 0.5 % to 8 % of all patients admitted for major chest and abdominal trauma [43]. The diagnosis of diaphragmatic injury can be difficult to make in the trauma bay, since these patients have severe associated injuries. In a series from Shock Trauma in Baltimore, the most common associated injury was lung (77 %), followed by liver (52 %), and spleen (32 %). Rib fractures were present in 33 % of patients [44]. Left diaphragmatic rupture is more common than right, because of the protection from the liver. Radiographic signs include elevated hemidiaphragm, presence of the nasogastric tube in the chest, and bowel evisceration into the chest. A CT scan is the optimal diagnostic modality, although not perfectly accurate. A recent retrospective study from Texas reported a sensitivity of only 57 % [45]. If nondiagnostic, a thoracoscopy or laparoscopy can be performed. The index of suspicion should be high, since missed injuries have a high rate of morbidity and mortality [46]. The treatment of diaphragmatic rupture is always surgical fixation, and there is no role for nonoperative management. While most of these injuries can be approached by laparotomy (up to 80 % in one series), other approaches include thoracotomy, laparoscopy, and thoracoscopy [47]. Surgical techniques include suture repair, preferably with nonabsorbable sutures, and mesh fixation if the defect is too large.

Abdominal Injuries

When caring for patients with chest wall injuries, surgeons must be vigilant about the possibility of associated intra-abdominal injuries. Lower rib fractures are associated with liver injuries (7 %) and splenic injuries (9 %) [48, 49]. The diagnostic workup of patients with severe chest wall trauma should include serial abdominal exams, FAST ultrasound, computed tomography, or any combination of these, depending on patients' hemodynamic stability and on the overall clinical context. CT provides the most information and is a powerful tool in the assessment of stable patients.

Conclusions

The cases presented at the beginning of this chapter, a young patient with a high speed mechanism and an elderly patient with a low-velocity injury, both involve major injuries to the chest wall. Both patients are at high risk for morbidity and mortality but along markedly different pathways.

The motorcycle crash is associated with high-energy transfer and tremendous force, with tissue disruption and acute hemorrhage. This patient will require immediate resuscitation and surgical interventions aimed at reversing shock, correcting coagulopathy, and controlling ongoing hemorrhage, if he is to survive the initial post-injury period. Once bleeding is controlled, his ongoing care will require a systematic survey for other potentially life-threatening injuries and a nuanced understanding of the pathophysiology and treatment of pulmonary contusion, as well as the consequences of and approaches to retained hemothorax. If rib fracture fixation is considered, it will have to be coordinated with and balanced against other competing priorities in a complex and rapidly evolving physiologic picture.

The injury pattern in the elderly patient pinned by a minivan is no less alarming. A low-velocity mechanism resulted in a dramatic fracture pattern because of her underlying osteopenia. Impairments in her chest wall mechanics from the fractures and from the resulting pain will be superimposed on age and chronic disease-related depletions of physiologic reserve across her respiratory, cardiovascular, gastrointestinal, renal, immune, and central nervous systems. Any complications in her care such as pneumonia, respiratory failure, acute coronary syndrome, or renal failure will, even if she survives them, result in potentially irreversible losses in her functional capacity and independence. Surgical and medical teams have an opportunity to circumvent these pitfalls by close attention to analgesia, judicious fluid management, selective use of noninvasive positive pressure ventilation, and careful consideration of operative approaches, including rib fracture or sternal fixation. Early mobilization, physiotherapy, and adequate nutrition are essential to this patient's functional recovery and even long-term survival.

Operative approaches to chest wall trauma have vastly improved the armamentarium of surgeons, as they confront a common and life-threatening problem. These approaches will likely be most effective when they are carefully timed and seamlessly integrated into a comprehensive overall effort to identify and treat associated multidisciplinary injuries and prevent avoidable complications.

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Clinical Outcomes Following Operative Fixation of Flail Chest Injury

11

Justin A. Walker and Peter L. Althausen

Introduction

Flail chest injuries, typically defined as fractures of four or more consecutive ribs at two or more sites, represent a more severe subset of chest wall injuries. In this biomechanically unstable condition, paradoxical chest wall motion and rib fracture pain can result in low tidal volumes, significant alveolar collapse, arteriovenous shunting, and hypoxemia [1]. Flail chest injuries are therefore associated with high morbidity and mortality and can result in longer intensive care unit (ICU) stays than trauma patients without rib fractures, leading to increased hospital costs and length of stay [2, 3]. Flail chest injuries have traditionally been managed nonoperatively; however, operative management has been performed in certain trauma centers in light of recent favorable research publications (Fig. 11.1) [4]. Although ongoing studies seek to better define outcomes of both operative care and nonoperative care, there is no consensus at this time as to which treatment is superior. This chapter will review the outcomes of flail chest injuries treated both nonoperatively and operatively with a focus on commonly reported outcome measures.

Ventilator Days

Patients suffering from flail chest injuries have a high likelihood of requiring mechanical ventilation. A recent review of data from the National Trauma Data Bank revealed that of 3,467 patients with flail chest injuries, 59 % required mechanical ventilation for a mean of 12.1 days [2]. These numbers increased in patients with concomitant head injuries.

Results of studies comparing rib fixation using modern techniques and implants to nonoperative management of flail chest injuries consistently demonstrate shorter mechanical ventilation times in patients treated operatively. A recent meta-analysis pooling the results of 11 clinical studies of operative treatment of flail chest injuries demonstrated a mean 7.5-day reduction in ventilator days in patients treated operatively compared with those managed nonoperatively. A similar result was seen (mean 8.3-day decrease) when the data from the randomized controlled trials alone were reviewed [3]. In the study of Ahmed et al., 21/26 patients with flail chest injuries treated with open reduction and internal fixation (ORIF) of their rib fractures were weaned from the ventilator in 1.3 days, with a mean

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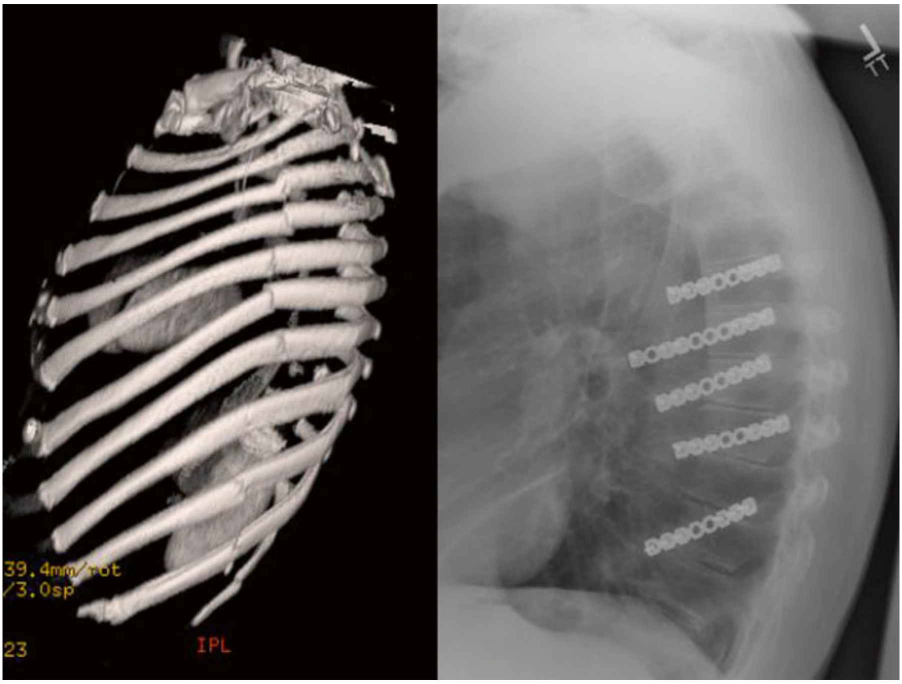

Fig. 11.1 A 3D CT scan revealing multiple ipsilateral displaced rib fractures and a postoperative radiograph following open reduction and plate fixation. This fixation rapidly restored chest wall integrity and facilitated rapid weaning from mechanical ventilation

ventilator time of 3.9 days, compared with a mean of 15 ventilator days in patients managed nonoperatively [1]. Even more dramatic results were seen by Kim et al., who demonstrated a 17-day mean difference in ventilator times of those treated operatively compared with those treated nonoperatively [5]. Lardinois et al. reported that immediate postoperative extubation following surgical fixation of flail chest injuries was possible in 47 % of patients, and the median length of postoperative intubation was only 2.1 days; no nonoperative control group was available for this study [6, 7]. Voggenreiter showed that early operative intervention (<48 h after injury) resulted in a mean ventilator time of 6.5 days and that operative treatment reduced ventilator days by a mean of 16.4 days [8]. The results of Althausen et al. support the decreased ventilator time in patients treated operatively [9]. In that series, patients treated operatively required a mean of 4.1 ventilator days, compared with 9.7 days in patients treated nonoperatively, with immediate postoperative extubation possible in 18 % of operatively treated patients (Table 11.1). In another series with matched cohorts of operatively and nonoperatively treated patients, Doben et al. demonstrated a decrease in mean ventilator days in patients that underwent surgical rib fixation (4.5 days vs. 16 days) compared with those treated nonoperatively [10].

A recent prospective, randomized, controlled trial by Marasco et al. demonstrated a less dramatic reduction in ventilator support following rib fixation than many other studies. In this study, no significant difference was found in ventilator time between operative and nonoperative patients. The authors did, however, find a significant decrease in the duration of noninvasive ventilatory support and in ICU length of stay in patients treated operatively. There are a few potential explanations for this lack of improvement in ventilator time in operatively treated patients. First, the inclusion criteria for enrollment into the study were vague and, more importantly,

Table 11.1 These data from Althausen et al. where 2.7 mm locking plates were utilized for operative fixation of flail chest injuries, summarizes the potential benefits of operative treatment of flail chest injuries

	Operative patients (mean)	Nonoperative patients (mean)	*p*-Value
ICU LOS	7.6 (7.43)	9.7 (9.18)	0.018
Hospital LOS	11.9 (7.79)	19.0 (12.64)	0.006
Days on vent	4.1 (6.66)	9.7 (9.18)	0.007
Tracheostomy	13.6 % (3/22)	39.3 % (11/28)	0.042
Pneumonia	4.6 % (1/22)	25 % (7/28)	0.047
Re-intubation	4.6 % (1/22)	17.9 % (5/28)	0.034
Home O_2	4.6 % (1/22)	17.9 % (5/28)	0.034

subjective. In this study, patients were enrolled if they had a flail chest injury, were ventilator dependent, and had "no prospect of successful weaning within the next 48 h." There were numerous exclusion criteria, which, when combined with subjective enrollment criteria, may have limited the patient population available for study to a greater extent than in prior studies. Additionally, the duration of ICU time prior to enrollment for patients in this study varied greatly. Operatively managed patients were enrolled at a mean ICU time of 61.6 h, with a standard deviation of 36.1 h, and nonoperatively managed patients were enrolled at a mean of 81.3 h, with a standard deviation of 84.2 h. Patients treated operatively remained in the ICU for a mean of 49.4 h after randomization until surgery or a mean ICU time prior to surgery of 111 h. Finally, while no significant difference in the time of mechanical ventilation was found between the two groups, a huge amount of variance within the data was noted. This great degree of variance, especially within the nonoperative group's mechanical ventilation times, could potentially mask a true difference, particularly with a small sample size.

These studies demonstrate the need for further large-scale randomized trials with clear, objective inclusion and exclusion criteria.

Pneumonia and Septicemia

Although researchers have grappled with the exact definition, ventilator-associated pneumonia (VAP) is a well-described, dreaded, and potentially fatal complication of rib fractures and flail chest injuries. Reported rates of pneumonia in flail chest injuries vary and approach 100 % in some series when time of mechanical ventilation exceeds 8 days [11]. Dehghan et al. recently reported that the rate of pneumonia in 3,467 patients with flail chest injuries identified from the National Trauma Data Bank was 21 % [2]. Consequences of pneumonia secondary to flail chest injury can include increased antibiotic usage, increased need for mechanical ventilation, increased ICU length of stay (LOS), increased cost, sepsis, and death.

Some studies have demonstrated a reduction in the rate of pneumonia with operative treatment of flail chest injuries or rib fractures. In their meta-analysis, Slobogean et al. reported an odds ratio of 0.18 for the development of pneumonia in patients treated operatively compared with those treated nonoperatively. The number needed to treat reported in their study was three. This implies that for every three flail chest patients treated with rib ORIF, one case of pneumonia will be prevented. In seven of the eight studies reporting pneumonia as an endpoint included in the meta-analysis, the odds ratio for operative versus nonoperative treatment was found to significantly favor ORIF (odds ratio range 0.034–0.714). In the remaining study, although the rate of pneumonia was lower in the operative group, the odds ratio did not reach statistical significance. When the results of the randomized controlled trials alone were analyzed, an odds ratio of 0.06 (i.e. a patient treated with ORIF was almost 17 times less likely to develop pneumonia) was found [3]. Supporting these findings, Althausen et al. recently reported that 4.5 % of patients treated operatively developed pneumonia compared with 25 % of patients managed nonoperatively [9]. Even more dramatic results were demonstrated by Ahmed et al., with 50 % of nonoperatively managed patients developing "chest infection" compared with 15 % of those treated operatively. This reduction in pneumonia rates is likely in part due to the reduction in the mean number of ventilator days and likely contributes to a decrease in mean ICU LOS.

Septicemia is a dreaded complication of flail chest injuries and may occur secondary to the development of pneumonia. The meta-analysis of Slobogean et al. also reviewed the results of four studies reporting septicemia as an outcome and discovered an odds ratio of 0.36 favoring operative management (i.e. operatively treated patients had roughly one third the chance of developing septicemia than nonoperatively treated patients did), with a number needed to treat of 7 [3].

Tracheostomy

Tracheostomy is a procedure commonly associated with the long-term need for mechanical ventilation. Complications of tracheostomy include bleeding at the time of insertion, obstruction of the tracheostomy tube, and stomal infection [12]. The rate of tracheostomy for all patients with flail chest injuries was reported by Dehghan et al. to be 21 % from 2007 to 2009 [2]. Likely due to the fact that operative treatment of flail chest injuries has been shown to lead to shorter mean mechanical ventilation times, surgical fixation of rib fractures in flail chest injuries has been shown to reduce the rate of tracheostomy. Slobogean reported an odds ratio for tracheostomy of 0.12 for patients treated operatively compared with those treated nonoperatively [3]. In the series by Althausen et al., operative intervention reduced the need for tracheostomy from 39 % in patients treated nonoperatively to 13.6 % in those treated with chest wall ORIF (Figs. 11.2 and 11.3) [9]. Ahmed et al. demonstrated similar results, with 11 % of patients treated operatively requiring tracheostomy, compared with 37 % of patients treated nonoperatively [1]. Reduction in the need for tracheostomy not only helps avoid a secondary surgical procedure but also helps avoid its associated complications.

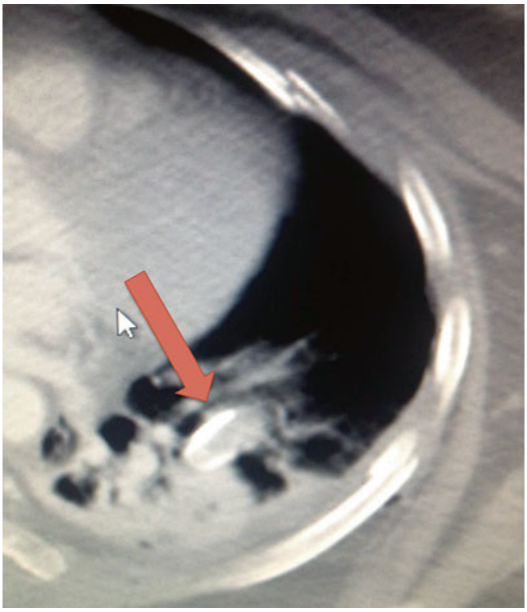

Fig. 11.2 This CT scan demonstrates impalement of the lung by a displaced posterior rib fracture (*red arrow*). This degree of visceral injury by a rib fracture represents, in itself, an indication for surgical extrication, fracture reduction, and fixation, irrespective of the overall injury pattern of the chest wall

Pulmonary Contusion

Longer periods of mechanical ventilation and a higher rate of pulmonary complications have been noted by several authors when flail chest injury occurs with concomitant pulmonary contusion [8, 11, 13]. Voggenreiter et al. compared ventilator days in patients with flail chest injuries with and without pulmonary contusions managed nonoperatively. Patients with pulmonary contusions required a mean ventilator time of 30.8 days, compared with 6.5 days in patients without pulmonary contusions. Additionally, pulmonary contusion increased the mortality rate in operatively treated patients from 0 % to 30 % [8]. The direct effect of surgical fixation of flail chest

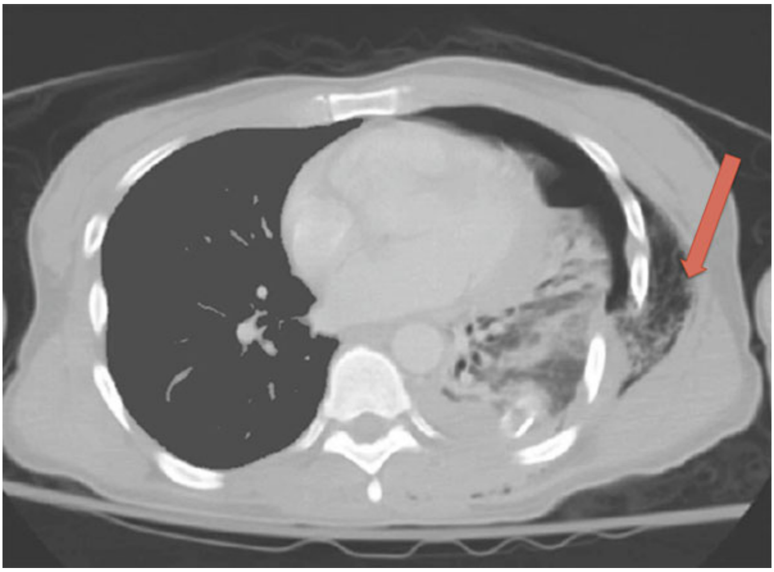

Fig. 11.3 Another operative indication is seen on this CT scan that demonstrates lung tissue (*red arrow*) outside the chest wall. Again, lung herniation of this nature represents a specific indication for operative repair irrespective of the overall chest wall injury pattern

injuries in patients with concomitant pulmonary contusions on duration of mechanical ventilation remains controversial, but current evidence would suggest a similar reduction in ventilator days with surgical stabilization.

Results of rib fixation for flail chest injuries in the setting of pulmonary contusion have been variable, and current data does not show the same success in improving ventilator and ICU times when compared with ORIF in patients without pulmonary contusion (Fig. 11.4). To date, the studies that have investigated the effect of pulmonary contusions in surgical treatment of flail chest injuries—most notably the Voggenreiter study—have been limited by small sample sizes, particularly in the groups with pulmonary contusions. Additionally, small retrospective studies such as the Voggenreiter study can be limited by selection bias with regard to how patients with pulmonary contusions are treated (operative vs. nonoperative).

Ultimately, in these cases, the pulmonary contusion may be the rate-limiting factor for liberation from the ventilator, and ORIF may not be of substantial benefit. Further investigation into the effect of pulmonary contusions on the outcome of flail chest injuries is certainly warranted.

Mortality

Mortality in trauma patients is a multifactorial entity, and it can be very difficult clinically and statistically to demonstrate differences in mortality with specific interventions. Regardless of treatment modality, flail chest injuries are life-threatening injuries irrespective of associated injuries. Dehghan et al. reported the overall mortality rate of patients with flail chest injuries to be 16 % based on data from 2007 to 2009 in the National Trauma Data Bank [2]. The difference in mortality between nonoperatively and operatively managed patients is difficult to determine as most retrospective studies lack a comparative or control group. However, current data indicates that there may be a reduction in mortality for operatively treated flail chest patients.

The mortality rates of patients with flail chest injuries treated nonoperatively reported in the

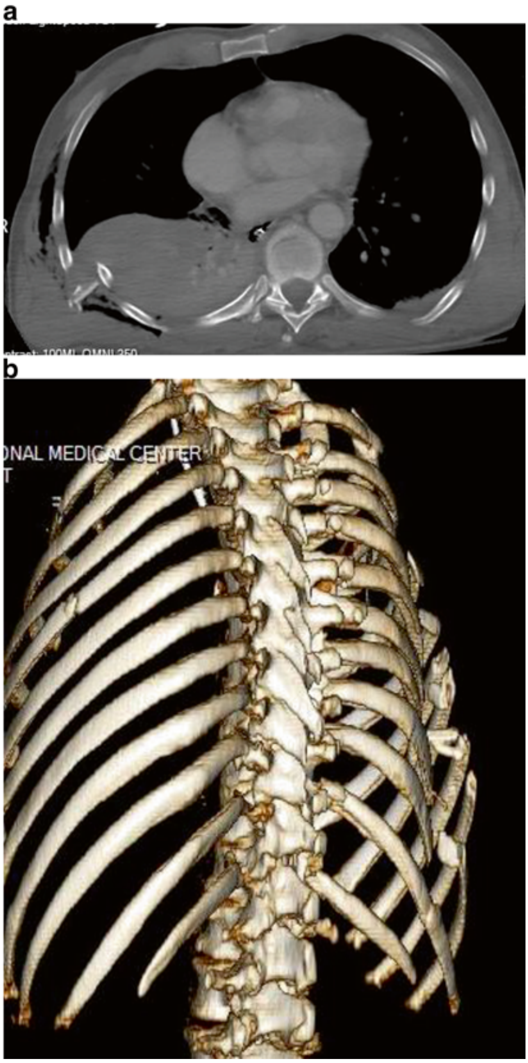

Fig. 11.4 A CT scan (**a**) demonstrates severe displacement of multiple posterior rib fractures with significant underlying soft tissue injury including hemothorax and pulmonary injury. A 3D CT scan (**b**) confirms the injury pattern and assists in the surgical planning: this pattern of injury (multiple ipsilateral segmental rib fractures with displacement) represents the most common current indication for operative fixation of the chest wall

current literature are alarmingly high. Ahmed et al. reported a mortality rate of 29 % in nonoperatively managed patients [1]. Voggenreiter et al. reported a 39 % mortality rate in patients with flail chest injuries and without pulmonary contusions managed nonoperatively [8]. Balci et al. noted similarly poor results, with 21–33 % mortality in nonoperatively treated patients [14]. Landercasper et al. noted a lower rate of mortality, with 13 % of patients expiring during the initial hospitalization and an additional 8 % expiring between 1 month and 9 years of the injury [15]. Rib fractures alone imparted a 5.7 % mortality rate in the report by Sirmali et al., with a 3.3 % mortality rate due to pulmonary causes. In the subgroup of patients with rib fracture who expired due to pulmonary causes, patients with >6 rib fractures accounted for 85 % of deaths [16].

Most studies that report mortality data in patients with flail chest injuries treated operatively report lower mortality rates than patients treated nonoperatively. Pooling the data from 7 studies and 582 patients, Slobogean found an odds ratio for mortality of 0.31 in patients treated operatively versus those treated nonoperatively and a number needed to treat of only five (treating five patients operatively prevented one death) [3]. Ahmed et al. report an 8 % mortality rate in patients treated operatively compared with a 29 % mortality rate in those treated nonoperatively [1]. Similarly, Mouton et al. reported an 8.7 % mortality rate in patients treated operatively (there was no nonoperative cohort in this study) [7], and Lardinois et al. report an 11 % mortality rate in patients undergoing surgical stabilization (no nonoperative cohort) [6]. Despite demonstrating 21–33 % mortality in nonoperative patients, Balci et al. reported a substantial improvement in operative patients, who had a 10 % mortality rate [14]. Although limited by small numbers in each group, Voggenreiter et al. reported 100 % survival in patients with flail chest injuries (without pulmonary contusions) treated operatively [8]. In this series, operatively treated patients with pulmonary contusions fared significantly worse, with a mortality rate of 30 %. Despite the notable increase in mortality rate associated with pulmonary contusion, these patients still showed a lower mortality rate than nonoperatively treated patients without pulmonary contusions, who suffered an extremely high 39 % mortality rate.

With the limits of the available data, it appears that operative fixation of rib fractures may reduce the mortality rate of patients with flail chest injuries. However, further prospective trials and/or larger retrospective trials are needed to determine the true effect of surgical stabilization on mortality.

ICU Days

Flail chest injuries often require extended stays in intensive care units (ICUs). In their review of the National Trauma Data Bank data from 2007 to 2009, Dehghan et al. noted that ICU admission was required in 82 % of cases, with a mean stay of 11.7 days [2]. Sirmali et al. reported a mean ICU stay of 11.8 days for patients with rib fractures not meeting criteria for flail chest injuries, which increased to 16.8 days for patients with flail chest injuries [16]. Clearly, patients with flail chest injuries require a higher level of care and often for much longer durations than would be required in the absence of such an injury.

Several studies demonstrate a reduction in ICU length of stay (LOS) when flail chest injuries are surgically stabilized [1, 6, 7, 9, 17, 18]. Ahmed et al. demonstrated a reduction in the ICU stay of 12 days, with operative patients requiring a mean of 9 ICU days compared with 21 days in nonoperative patients [1]. Lardinois et al. reported a mean ICU stay of 6.8 days for patients treated operatively [6]; notably lower than the 11.7-day average stay was noted by Dehghan et al. [2]. Although of smaller magnitude, Althausen et al. reported a statistically significant decrease in ICU LOS, with operatively managed patients averaging 7.6 days in the ICU and nonoperatively managed patients requiring a mean 9.7 days [9]. Granetzny et al. reported a similar decrease in ICU LOS of 5 days in patients treated operatively [18]. In a prospective, randomized trial, rib fracture patients (not limited to flail chest injuries) treated with surgical rib stabilization had a similarly reduced ICU LOS, with operatively managed patients requiring a mean of 285 h compared with 359 h in nonoperatively managed patients [17]. Current data demonstrates that surgical fixation of flail chest injuries can be beneficial in reducing ICU days, resulting in cost reduction, as well as increased ICU bed availability.

Hospital Length of Stay

Patients with flail chest injuries, regardless of whether operative intervention is undertaken, typically require a longer period of hospitalization. Great variability exists in the current literature with regard to average hospital length of stay for patients with flail chest injuries. This is likely due to numerous factors, including cultural differences between study sites/populations, variation in concomitant injuries (especially head injuries), and the high incidence of major medical complications, such as adult respiratory distress syndrome, pneumonia, sepsis, and death, which may greatly alter the hospital LOS. A recent review of the National Trauma Data Bank revealed a mean hospital LOS of 16.6 days for patients with flail chest injuries [2], the overwhelming majority of whom were treated nonoperatively. Data from studies performed in other countries varies: for instance, Borrelly et al. found a mean hospital LOS of 44 days in patients treated nonoperatively [19], and Granetzny reported a mean LOS of 23.1 days in nonoperatively treated patients [18].

There is some data to suggest that patients treated operatively may have a subsequent decrease in hospital LOS. While some studies note no difference in hospital LOS [10, 20], and other studies do not report hospital LOS at all, there are studies demonstrating a dramatic reduction in hospital LOS in operatively managed patients [18, 19]. Pooling the results of 4 studies (400 patients), a recent meta-analysis demonstrated a mean reduction in hospital LOS of 4 days in operatively treated patients [3]. Some individual studies demonstrate more dramatic results; for instance, Borrelly et al. demonstrated a mean decrease in hospital LOS of 14 days between operatively managed patients and those treated nonoperatively [19]. In their randomized controlled trial, Granetzny and colleagues found a mean reduction in hospital LOS of 11.4 days for patients treated operatively [18]. Althausen et al. report a mean hospital LOS of 11.9 days in operatively managed patients compared with 19 days in nonoperatively managed patients [9]. While hospital LOS is certainly influenced by many other factors, there is data to suggest that surgical stabilization of flail chest injuries does not lengthen, and more likely shortens, hospital LOS.

Hospital Costs

Overall cost of treatment of flail chest injuries has not been well investigated or reported. This is a difficult task, as these patients are often multiply injured and other associated injuries confound the quantification of cost. Given the high proportion of these patients who require extended periods of ICU care and mechanical ventilation as well as high complication rates, one can infer that the cost of flail chest injuries to the hospital and health-care system is quite substantial.

The surgical costs of rib fixation are variable depending on the implant preferences of the operative surgeon. The cost of an average operative case can range from $8,000 to $20,000: the operative cost of flail chest fixation averages $9,800 at our institution. This includes anesthesia costs, supply costs, implant costs and surgical charges. Simple 2.7 mm locking plates are contoured and placed by the operative surgeon with three bicortical screws on either side of the construct. An average of four ribs are plated in each of our cases.

There have been some studies that have examined the relative difference in cost between patients managed operatively and those managed nonoperatively. Althausen et al. noted a decrease in hospital room and board costs of $2,811 in patients treated operatively [9]. This figure did not include cost of treatment, treatment of complications, or secondary procedures. In a prospective randomized trial, Tanaka et al. evaluated the total medical cost of operatively managed patients compared with nonoperatively managed patients in the Japanese public health-care system and found a cost savings of $17,583 for patients treated operatively [21]. This difference represented a nearly fourfold increase in cost for patients treated nonoperatively. Another prospective randomized trial of operative fixation using bioabsorbable implants demonstrated a cost savings of $14,443 per patient undergoing operative fixation [17]. While relatively little data exists for the relative cost of nonoperative versus operative management, the existing data certainly favors operative management.

Surgical Complications

There are several complications of the fixation of flail chest injuries that are unique to surgical treatment. These include hardware loosening, implant migration, loss of reduction, malunion, nonunion, and infection.

Hardware loosening is clearly a complication unique to operative management of rib fractures. It has been reported with varying frequency, most likely in part due to variation in the type of implants used. Multiple methods of rib fixation have been described ranging from K-wire fixation to locking plates or bioabsorbable methods of osteosynthesis. Data is lacking regarding the exact hardware failure rate of every method of fixation, as many studies describe the technique and/or report short-term results (hospital LOS, ICU LOS, ventilator days, etc.) but do not report on hardware-related complications. However, several studies have mentioned complication rates associated with hardware type.

The use of K-wires for rib fixation has been associated with pin migration, requiring removal in 4 % in the series by Ahmed et al. [1]. Fortunately, these pins migrated to a subcutaneous location rather than intrathoracic, as this could have catastrophic consequences. Due to the potential issues associated with this hardware loosening and migration, K-wire fixation has been abandoned at most centers.

Prior to the introduction of locking fixation, Lardinois et al. utilized 3.5 mm reconstruction plates and cancellous screws. They noted asymptomatic loosening and migration of screws in two patients on 6-month radiographic follow-up [6]. In that series, 11 % of patients also reported symptomatic hardware, requiring removal in half of these patients. Doben et al. report on ten patients that underwent osteosynthesis with an unspecified plating technique or intramedullary nails (numbers per group not reported) and report no patients requiring hardware removal [10].

The use of locking fixation is a relatively recent trend, and sparse results are published demonstrating the results of locked plating techniques. Althausen et al. demonstrated no cases of hardware failure or nonunion/malunion in their series of 22 patients with flail chest injuries treated by open reduction internal fixation with 2.7 mm locking reconstruction plates [9]. Majercik et al. reported no cases of hardware failure in their series of 101 rib fracture patients treated with surgical stabilization, with only one patient requiring hardware removal for symptomatic hardware [22].

Bioabsorbable plates have the highest reported failure rate in the literature, with Mayberry et al. reporting a 20% implant failure and loss of reduction. A similar rate of loss of reduction was reported by Vu in a study of bioabsorbable plating of rib fractures in an animal model [23]. Results of the use of bioabsorbable plates have been reported in a randomized prospective trial comparing nonoperative with operative management [17]. While the authors did not report any hardware failures, results of 3D CT scans 3 months post-injury demonstrate improvement of fracture displacement in only 5/9 patients operatively treated patients, improvement of fracture angulation in only 6/9 patients, and complete healing in only 11/21. In fact, no significant difference was found between the nonoperative and operative groups for improvement in angulation, displacement, or overlap of rib ends. Early results of bioabsorbable plating systems raise concern due to the high risk of hardware failure, and at the present time, this technique appears to be inferior to standard plating with metallic implants.

Wound infection is another surgical complication associated with any form of surgical intervention. Although there is sparse information regarding the risk of infection following ORIF of rib fractures, what evidence does exist would suggest that the rate is low. Althausen et al. reported no infections in their series of 22 patients [9], and similarly Doben et al. reported no infectious complications in their series of ten patients [10]. In their prospective randomized study of rib fracture plating in 101 patients, Majercik et al. report a 2 % surgical site infection rate [22]. Similarly, Lardinois et al. report a 3 % infection rate [6]. Compared to areas that traditionally have had high infection rates following ORIF for severe injuries (such as the ankle or knee), the chest wall is very well vascularized and the soft tissue envelope particularly robust. Although a real risk, it appears that postoperative infection rates (and soft tissue complications in general) are low and should not be considered a deterrent to surgical intervention if operative stabilization is warranted.

Benefit of Early Versus Late Operative Intervention

To our knowledge, only one study has directly investigated the effect of timing of surgery on outcomes. In the study by Althausen et al., regression analysis demonstrated a positive correlation between hospital LOS, ICU LOS, ventilator days, and time to surgery [9]. This would suggest that early intervention would maximize the reduction of hospital LOS, ICU LOS, and ventilator days, whereas delayed fixation may increase the risk of pneumonia or prolong hospital LOS, ICU LOS, or ventilator time. Future studies, including randomized controlled clinical trials, will further elucidate this point.

Long-Term Clinical Outcomes

While much of the outcome reporting for flail chest injuries focuses on short-term and in-hospital outcomes, some data exist detailing the long-term sequelae of rib fractures and flail chest injuries. Problems such as prolonged disability, inability to return to work or an increased number of days of work lost, persistent chest wall pain or deformity, and altered pulmonary function testing have been described.

Nonoperatively treated patients with rib fractures (even in the absence of a flail chest injury) are more disabled at 30 days post-injury than patients with chronic medical illnesses [24]. Rib fracture patients have also been found to lose a mean of 70 days of work or typical activity during their initial recovery [24]. Studies investigating the long-term outcomes of flail chest injuries have found that 50–60 % of patients develop long-term morbidity, most commonly pain or chest wall deformity [15, 25]. Approximately 20–60 % of patients did not return to full-time employment [15, 25]. However, a more recent prospective, randomized trial of surgically and nonsurgically treated flail chest patients has challenged these results [17]. In this study, approximately 60 % of rib fracture patients (across both operative and nonoperative groups) reported ongoing problems in their daily work or home lives, but the majority attributed these difficulties to injuries other than their rib fractures. Additionally, only two of 34 patients (one operative, one nonoperative) complained of chest wall deformity. However, the same authors reported in a separate study that nonoperatively treated rib fracture patients had a significantly lower quality of life 24 months post-injury than population norms, with only 71 % of patients returning to any work by 24 months post-injury [26]. Despite the somewhat inconsistent results in the literature, nonoperative treatment of rib fractures does appear to put the patient at high risk for long-term morbidity related to chest wall deformity and pulmonary dysfunction.

Long-term outcomes of surgical stabilization of flail chest injuries are sparsely reported, and varying results are seen. Majercik et al. reported the absence of pain in 50 operatively treated rib fracture patients at a mean of 5.4 weeks post discharge and a satisfaction rating of 9.2 on a 1–10 visual analogue scale [22]. In that study, 90 % of patients returned to work at a mean 8.5 weeks. Mayberry reported low long-term morbidity and health status equivalent to the general population after surgical repair of flail chest injuries [24]. In slight contrast, another study demonstrated no difference in general health status (as measured by SF-36 scores) between operatively and nonoperatively treated patients 6 months post-injury [26]. In their meta-analysis, Slobogean et al. analyzed data from 2 studies (71 patients) and found no significant difference in the presence of chest pain between operatively and nonoperatively treated patients [3].

Pulmonary function testing at 6 months demonstrated normal results in greater than 50 % of patients undergoing operative management [6], and at 2 months postfixation, Granetzny et al. noted improvement in forced vital capacity (FVC) and total lung capacity (TLC) in operatively treated patients compared with nonoperatively treated patients [18]. However, a study in rib fracture patients has demonstrated no difference in spirometry at 3 months between operative and nonoperative patients [17]. While long-term outcomes of operative treatment of rib fractures and flail chest injuries are not well reported, the current literature suggests reduced morbidity in patients treated operatively.

Conclusions

Flail chest injuries are both life-changing and life-threatening injuries. The clinical outcomes of these injuries can be dismal and fraught with complications. Based on current evidence, operative management of these injuries appears to impart a clinical benefit with regard to decreasing ICU and hospital LOS, decreasing ventilator days, decreasing tracheostomy rate, and decreasing mortality rates. Complications of operative management appear to be infrequent and relatively minor; however, reporting of complications in the current literature is inconsistent.

When operative intervention is undertaken, we believe that outcomes are maximized when a team approach to rib fracture stabilization is employed, with the surgical approach/thoracotomy, lung decortications, and chest tube placement performed by a general or trauma surgeon and fixation of the rib fractures performed by an orthopedic trauma surgeon. In the authors' experience, utilizing a team approach leads to shorter operative times, minimizes blood loss, and results in fewer complications. The presence of a general or trauma surgeon allows unexpected intrathoracic findings to be dealt with promptly and appropriately.

Despite its potential benefits, at present, relatively few patients with flail chest injuries receive operative fixation of their rib fractures, and nonoperative management remains by far the most common treatment method and should be considered the current standard of care [2, 4]. Certainly, the relatively small number of studies describing the outcomes of such operations contributes to the general lack of acceptance of rib ORIF in this setting. Current literature on the operative management of flail chest injuries consists predominantly of small retrospective studies, with only three prospective randomized trials dedicated to treatment of flail chest injuries [17, 18, 21]. These studies demonstrate notable heterogeneity in their reporting of outcomes, standards of nonoperative care, and types of operative fixation and span a wide time range. Additionally, these studies were performed in widely disparate health-care environments (Iran, Egypt, Australia). Despite the positive outcomes demonstrated, the small number of studies with relatively few participants, the utilization of varying means of fixation, and the reporting of varying outcomes should induce caution. As such, further investigation involving large prospective cohorts with detailed reporting of all outcomes and complications is warranted to document the outcomes of both the operative management and nonoperative management of flail chest injuries.

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12 Complications of Surgical Treatment and Their Management

Ryan Martin, Bernard Lawless, Patrick D. Henry, and Aaron Nauth

Introduction

There has been a dramatic increase in the rate of surgical intervention and treatment for the management of flail chest and unstable chest wall injuries over the last decade. Concomitant with the introduction of any novel surgical procedure is the occurrence of surgical complications. This chapter will describe in detail the identification and management of the surgical complications that have been reported following surgical intervention for the operative stabilization of flail chest injuries. The relative benefits of surgical intervention for flail chest injuries and surgical indications are addressed elsewhere in this book.

Current Literature

Unfortunately, there is a paucity of published literature on surgical complications following operative interventions for flail chest injuries. Two meta-analyses have been recently published comparing surgical management versus nonoperative treatment for the treatment of flail chest injuries [1, 2]. Both studies found significant benefits from surgical treatment including decreased days on mechanical ventilation and decreased length of hospital and intensive care unit (ICU) stay. In addition, both studies found that surgery led to significantly lower rates of general complications such as pneumonia, the need for a tracheostomy, sepsis, and mortality. The decrease in mortality is particularly important, as part of the apprehension regarding surgical intervention in the past has include concerns related to high rates of perioperative mortality in this critically ill patient population. Neither of these two meta-analyses examined rates of specific surgical complications such as hardware failure, nonunion, empyema, wound infection, retained hemothorax, or recurrent pneumothorax.

There have been three prospective randomized trials published comparing surgical fixation to nonoperative management of rib fractures [3–5]. All three studies found significant benefits with surgical intervention including decreased ventilator time, decreased ICU length of stay, and decreased rates of pneumonia and tracheostomy. Unfortunately, all three studies had small sample sizes (less than 25 patients per treatment group),

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variable methods of surgical fixation were used for rib fracture stabilization, and the studies lacked standardized outcomes or measures for reporting surgical complications. In fact, only the Granetzny et al. [4] trial provides specific reporting of surgical complications in their publication. The authors report a 10 % rate of pneumonia (vs. 50 % in the nonoperative group), a 5 % rate of empyema (vs. 10 % in the nonoperative group), a 10 % rate of mediastinitis (vs. 0 % in the nonoperative group), and a 10 % rate of wound infection (vs. 0 % in the nonoperative group).

In 2009, Nirula et al. reported on a review of surgical complications of the "650 rib fracture repairs described since 1975" [6]. The authors reported that from the 650 surgical cases, there were eight superficial wound infections (1.2 %), four cases of wound drainage without infection (0.6 %), two pleural empyemas (0.3 %), one wound hematoma (0.15 %), and one persistent pleural effusion (0.15 %) reported. Fixation failure, including plate loosening or wire migration, occurred in eight patients (1.2 %), and postoperative chest wall "stiffness," "rigidity," or "pain" necessitating plate removal was reported in nine patients (1.4 %). A single case of rib osteomyelitis (0.15 %) requiring secondary surgery was reported. The cumulative complication rate of 5.15 % reported in this review is exceedingly low for a surgical procedure of this nature and magnitude: the accuracy and complete inclusion of all complications in these series must be questioned.

Overall, the literature on surgical intervention for flail chest injuries is relatively novel, and there has been very little published specifically on complications of surgery. It is likely that the current literature on surgery for flail chest injuries and rib fracture fixation suffers from a bias towards underreporting of surgical complications. Future trials on surgery for flail chest injuries need to address this gap in the evidence and identify surgical complications in a rigorous and standardized fashion with comparison to nonoperative treatment, so that those complications truly attributable to the surgical intervention can be identified and quantified. In addition, post-market surveillance on rib-specific implants should be performed to allow for collection of prospective data on surgical complications.

Systematic Review

We conducted a systematic review of the literature to identify reported rates of complications following the surgical management of flail chest or unstable chest wall injuries, as well as to compare those rates with the complication rates associated with nonoperative treatment. The results are presented in Table 12.1. It is important to note that although this review takes into account essentially all of the available literature on the surgical management of flail chest injuries, the review relies upon the reporting of surgical complications by the authors of the published studies included. In many cases, surgical complications were not specifically reported or referenced. For the purposes of the review, if no complications were reported in the study, it was assumed the complication rate was zero. As alluded to previously, this is likely to bias the results substantially towards underestimation of complication rates.

While recognizing these limitations, several important observations can be made. First, consistent with previous systematic reviews, we found that the surgical stabilization of flail chest injuries led to significantly reduced rates of general complications including pneumonia (8.0 % operative vs. 28.86 % nonoperative), sepsis (0.48 % operative vs. 4.47 % nonoperative), tracheostomy (5.37 % operative vs. 10.51 % nonoperative), and death (7.16 % operative vs. 20.58 % nonoperative). Second, the rates of local complications such as empyema (0.12 % operative vs. 0.45 % nonoperative), retained hemothorax (0.12 % operative vs. 0 % nonoperative), and recurrent pneumothorax (none reported) are relatively low and generally compare favorably to the rates seen with nonoperative management. Finally, the rates of surgery-specific complications such as surgical wound infections (3.10 %), hardware failur e (0.95 %), and symptomatic hardware requiring removal (1.91 %) appear to be relatively low. In addition, the cumulative complication rate was 38.78 % in the surgical group vs. 81.21 % in the nonoperative group. Once again, it is important to view these rates in the context of what has likely been a substantial underreporting of surgical complications in the previous literature.

Table 12.1 Results of systematic review of the literature on rates of complication for operative stabilization of rib fractures versus nonoperative management

	Operative		Nonoperative	
Complication	Overall rate (%)	Range (%)	Overall rate (%)	Range (%)
Wound complications	3.10	(0–20)	N/A	N/A
Empyema	0.12	(0–5)	0.45	(0–20)
Pleural effusion	0.12	(0–2)	0	(0)
Nonunion	0.84	(0–15)	0.22	(0–4.5)
Chest wall numbness	0.6	(0–16)	0	(0)
Hardware pain	1.91	(0–33)	N/A	N/A
Hardware removal	1.91	(0–33)	N/A	N/A
Loose hardware	0.95	(0–20)	N/A	N/A
Chest wall rigidity	2.39	(0–60)	3.58	(0–84)
Tracheostomy	5.37	(0–20)	10.51	(0–79)
Sepsis	0.48	(0–4)	4.47	(0–50)
Death	7.16	(0–23)	20.58	(0–46)
Pneumonia	8.00	(0–42)	28.86	(0–90)
Chest wall deformity	0.84	(0–12)	8.50	(0–64)
Atelectasis	1.91	(0–21)	0.22	(0–3)
Chest wall pain	2.98	(0–39)	3.80	(0–89)
Retained hemothorax	0.12	(0–0.5)	0	(0)
Cumulative complication rate	38.8		80.52	

Data for the nonoperative cohort was only retrieved from comparative studies that included a surgical cohort

Specific Surgical Complications and Their Treatment

Infection

Infection can occur in the lung parenchyma (pneumonia), in the pleural space (empyema), superficially in the surgical wound, or systemically (sepsis). In the setting of operative intervention, any infection of the surgical site or pleural space is complicated by the presence of surgical implants, which are typically metallic and prone to biofilm formation. Rates of pneumonia following surgical stabilization of flail chest injuries range from 0 to 42 % with an average rate of 8.0 %. While this may appear to be an elevated rate, it must be remembered that this is a high-risk patient group: these rates are significantly lower than the rates observed in patients with similar injuries treated nonsurgically, which may be due to decreased time spent on mechanical ventilation in the surgical group. Pneumonia in the setting of surgical stabilization is reliably treated with targeted antibiotic therapy and appropriate pulmonary toilet practices. There have been no reports in the literature of the need for secondary surgery in the setting of pneumonia following surgical stabilization of flail chest injuries.

Rates of pleural empyema in the literature have varied widely, with rates 0–20 % reported. The overall rate in our systematic review was 0.12 % with surgical management versus 0.45 % with nonoperative management. These rates seem low, given the fact that previous literature had documented an empyema rate of 3 % among all patients with blunt chest trauma [7]. Diagnosis is generally based on physical exam findings, culture of chest tube drainage, routine blood work (white blood cell count, c-reactive protein, and erythrocyte sedimentation rate), and radiographic imaging including a chest radiograph and contrast computed tomography (CT) of the chest to assess for pleural collections. Given the presence of hardware (typically plates and screws) traversing both the deep wound and the pleural space, distinguishing between a deep wound infection and empyema can often be difficult. Rates of wound infection following surgical stabilization of flail chest injuries range from 0 to

20 %. Mayberry et al. reported two deep infections in their cohort of 46 patients (4.3 %) treated with a combination of implants for rib fracture fixation [8]. Both cases of infection required secondary surgery for drainage of infection.

Superficial wound infections can generally be treated with antibiotics alone and close surveillance. However, the treatment of both deep wound infections and pleural empyemas requires surgical intervention given the presence of hardware. There are no published guidelines on the management of empyema or deep wound infections in the setting of rib fixation. However, treatment recommendations can be extrapolated from the existing orthopedic literature on implant-related infections [9]. Acute infections (less than 6 weeks post-rib fixation) can be managed with irrigation and debridement, retention of stable hardware, and culture-specific intravenous antibiotics. Chronic infections (greater than 6 weeks post-rib fixation) require a similar approach as outlined above plus removal of hardware and necrotic/infected bone. In both the acute and chronic setting, any suggestion of infection of the pleural space requires additional irrigation and debridement of the pleural space +/− decortication, by either a formal thoracotomy or video-assisted thoracoscopic surgery (VATS) (see Fig. 12.1) [7].

There are several steps that can be taken to reduce the risk of deep infection and pleural empyema in the setting of rib fracture fixation for flail chest injuries. First, chest tubes that have been placed prior to surgery should be removed, as these tubes are frequently placed under semi-sterile conditions and have often been in place for several days prior to surgery. The authors generally perform our sterile preparation of the surgical field with the old chest tube in situ and then remove the tube once we have dissected down to the fractured ribs (this is done to reduce the risk of developing a tension pneumothorax during induction of anesthesia). Second, we position our new chest tube through an incision caudal to the surgical incision with tunneling of the chest tube in the subcutaneous tissues in order to maximize the distance between the chest tube incision and rib fixation hardware (see Fig. 12.2). Finally, we are aggressive in treating retained hemothoraces in patients who have undergone rib fracture fixation (see following section).

Retained Hemothorax

A retained hemothorax is defined as a radiographically apparent hemothorax 72 h after appropriate chest tube placement. There has only been a single case of retained hemothorax reported in the literature following rib fixation surgery (rate of 0.12 %). This is surprising, since previous trauma literature has suggested an 18–20 % rate of retained hemothorax in all patients who require chest tube placement for traumatic hemothoraces [10, 11]. It is possible that performing rib fracture fixation allows the surgeon the opportunity to surgically evacuate any hemothorax through the chest wall defect typically seen at the fracture site (Fig. 12.3), decreasing the risk of this complication. However, it is also possible that this complication is substantially underreported in the current literature on surgical fixation for flail chest injuries. The authors of this chapter routinely perform evacuation of any retained hemothorax at the time of rib fracture fixation (Fig. 12.3). In addition, we always place a large-bore (32–36 F) chest tube at the conclusion of the procedure in order to mitigate the risk of retained hemothorax or persistent pneumothorax.

The diagnosis of retained hemothorax is made on the basis of screening radiographs of the chest followed by CT scanning if suspicion is raised on plain films. Treatment is initiated for retained hemothoraces estimated to be greater than 500 mL or 1/3 of the chest cavity 72 h after adequate chest tube placement [7]. On the basis of recent literature showing improved outcomes with early VATS and concerns over the development of empyema in the presence of hardware, the authors of this chapter are relatively aggressive in managing retained hemothoraces following rib fracture fixation with surgical intervention [7, 12]. We will generally perform a VATS procedure within 5–7 days post-rib fracture fixation if a retained hemothorax has been diagnosed in the presence of a

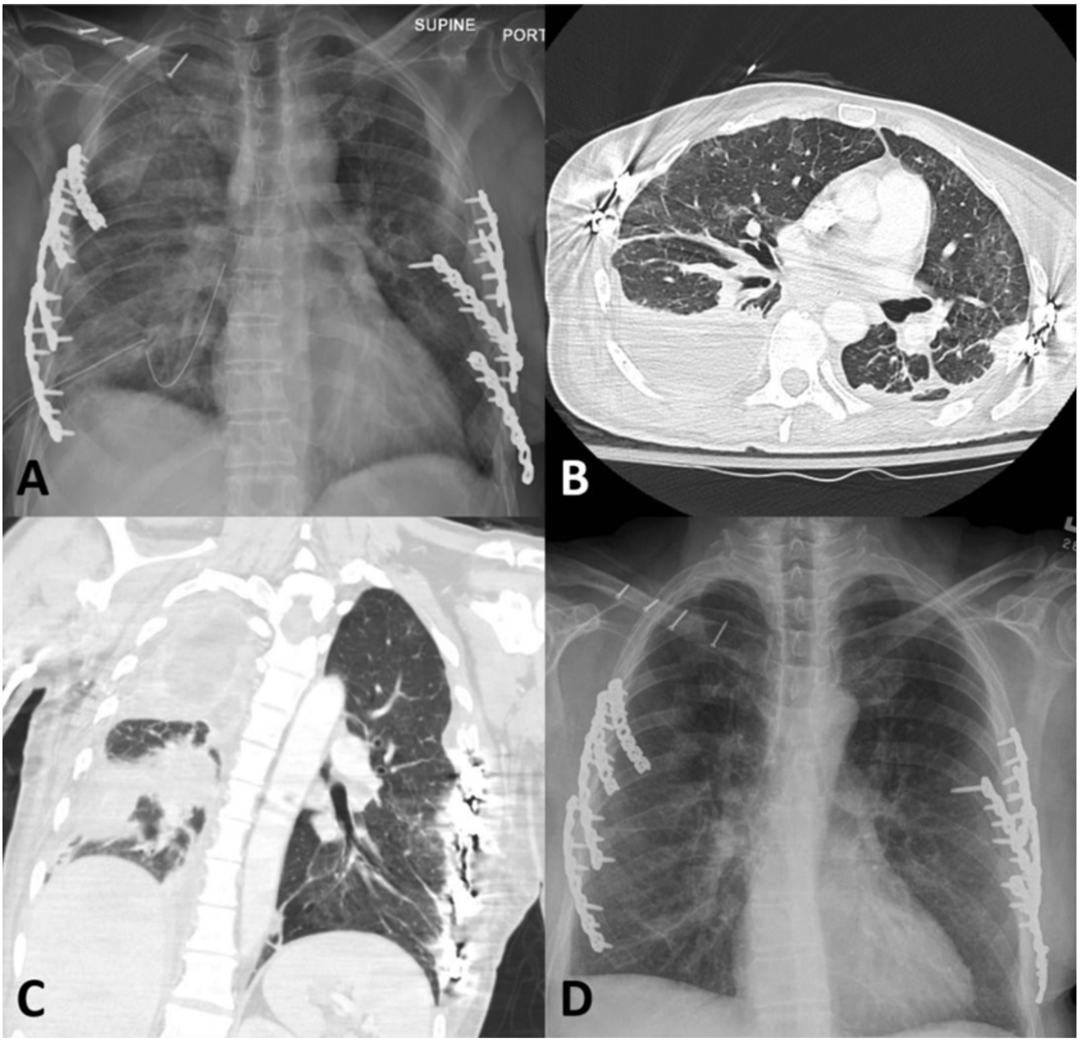

Fig. 12.1 A 50-year-old female patient was treated with bilateral rib fixation for bilateral flail chest injuries. (**a**, **b**, and **c**) AP chest radiograph and axial and coronal CT slices on postoperative day 21 showing complex fluid collection in right lung cavity. The patient was febrile, with purulent drainage from her chest tube. (**d**) AP chest radiograph 1 week post-thoracotomy and decortication of the right lung and antibiotic treatment demonstrating resolution of the patient's empyema

correctly placed chest tube. We will occasionally use intrapleural fibrinolytics as an alternative to VATS in select patients (see Fig. 12.4) [13].

Recurrent Pneumothorax

In our systematic review of the literature, we were unable to identify a single case of persistent/recurrent pneumothorax in the setting of rib fracture fixation for flail chest injuries, which is surprising given that rates in the trauma literature range from 4 to 23 % [12]. The cause is usually a persistent air leak from the tracheobronchial tree that does not close or seal with time and often requires surgical management. The senior author (A.N.) has observed one case of persistent/recurrent pneumothorax in a patient treated with surgical stabilization of multiple rib fractures and a displaced sternal fracture (see Fig. 12.5). This patient was successfully treated with a VATS procedure.

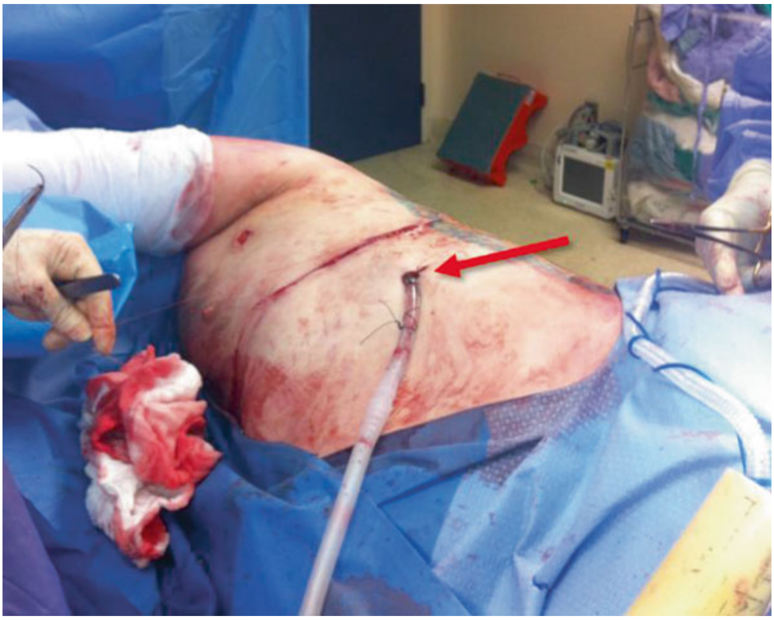

Fig. 12.2 Intraoperative photograph demonstrating positioning of the chest tube (*red arrow*) caudal to the surgical incision following rib fracture fixation for a flail chest injury

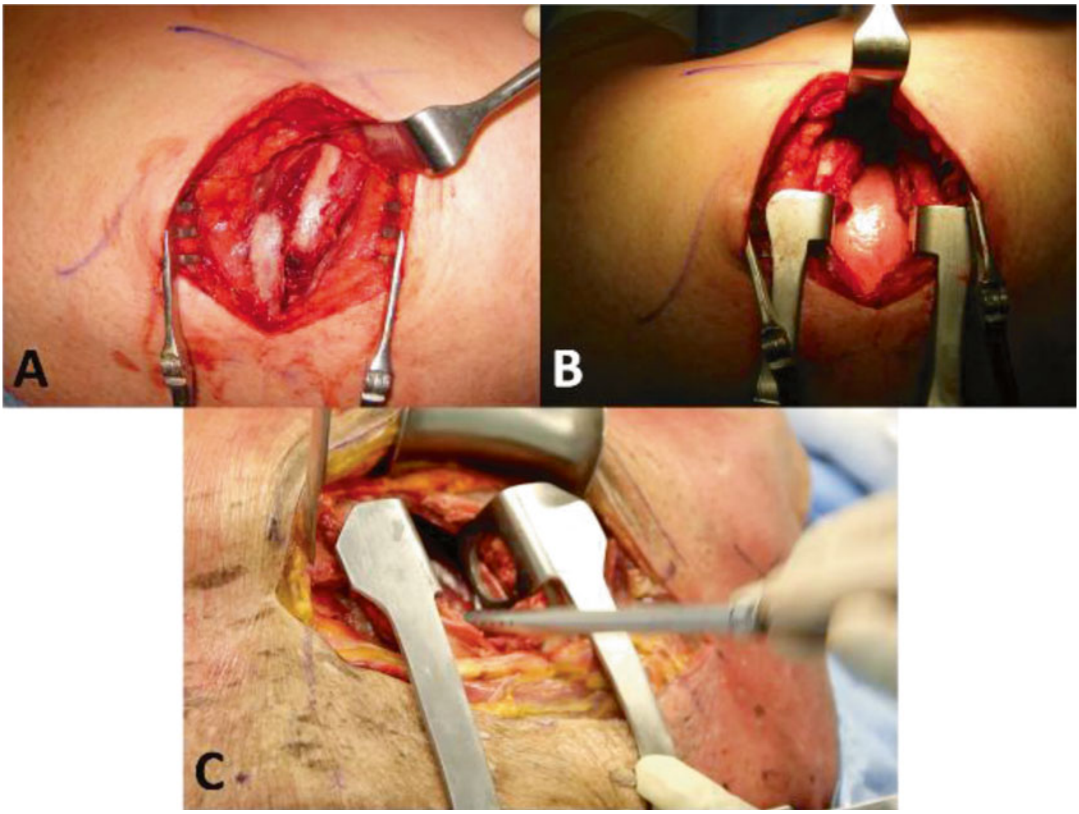

Fig. 12.3 (**a** and **b**) Intraoperative photographs of a patient undergoing rib fracture fixation surgery demonstrating displaced and overlapped rib fractures with subsequent placement of a miniature rib spreader to gain access to the pleural cavity for evacuation of hemothorax. (**c**) Photograph of a cadaver demonstrating suction of the pleural cavity using a pool sucker following placement of rib spreader

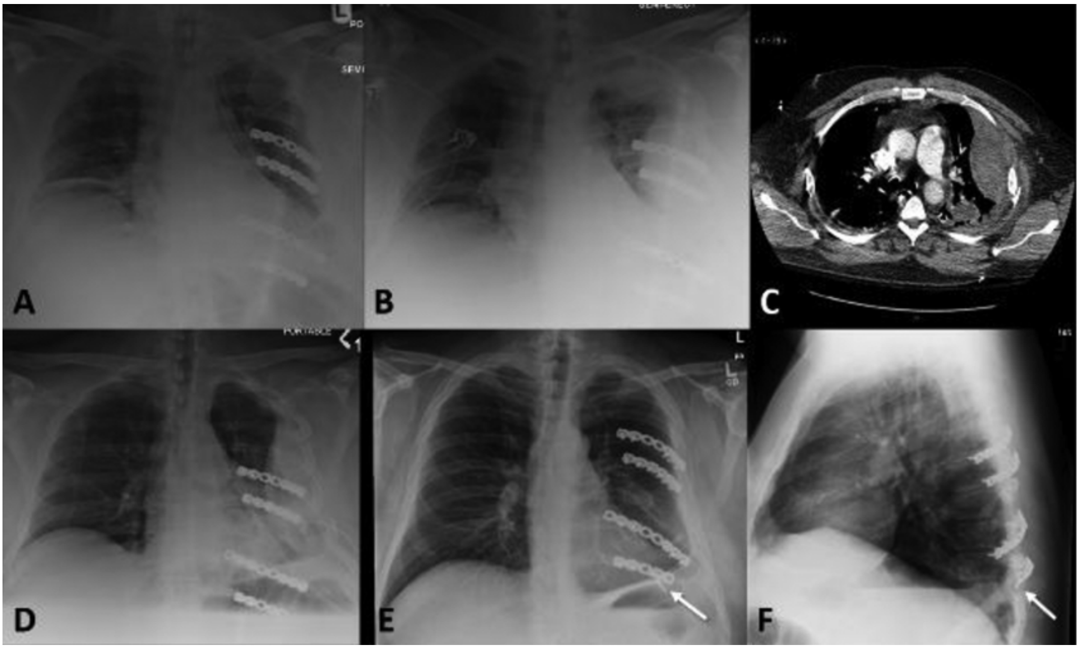

Fig. 12.4 (**a**) Initial postoperative AP chest radiograph of a 61-year-old male patient who underwent rib fracture fixation for a left-sided flail chest. (**b** and **c**) AP chest radiograph and axial CT cut on postoperative day 5 showing retained hemothorax. (**d**) AP chest radiograph 4 days after placement of pig-tail catheter and injection of intrapleural tissue plasminogen activator (tPA). (**e** and **f**) Nine-month follow-up radiographs of the chest (PA and lateral) showing resolution of hemothorax, *white arrows* indicate an asymptomatic loose screw located in the muscles outside of the thoracic cavity. No treatment was required for the screw

The diagnosis of persistent/recurrent pneumothorax is made on the basis of failure to seal an air leak and achieve full lung expansion within 72 h. Treatment consists of prolonged chest tube drainage, VATS, or thoracotomy. The favorable risk–benefit ratio and minimally invasive nature of VATS, when compared to conventional thoracotomy (the only available surgical option in the past), are the probable causes of the recent trend in the literature towards early management of this complication with VATS [12].

Nonunion

Only a single case of nonunion requiring repeat surgical intervention has been reported in the literature on rib fracture fixation. Campbell et al. described 1 case of nonunion requiring revision surgery in a series 32 patients (3 % rate) treated with a resorbable plating system [14]. Rib fracture healing is very difficult to assess on plain radiographs, particularly in the presence of metal plates, and this may be a significant factor in underreporting of this complication. Marasco et al. used 3-month follow-up CT scanning in 46 patients randomized to nonoperative treatment or rib fracture fixation using resorbable plates [5]. They reported a nonunion rate of 14 % (3/21) in the surgical group versus 6 % (1/17) in the nonoperative group. In a separate retrospective review of surgical fixation in 52 patients, again using resorbable plates in the majority of patients, Marasco et al. reported a nonunion rate of 11 % (6/52 patients) [15]. It is unclear from either publication if any of the patients with "nonunion" in the two Marasco studies required repeat intervention, or if they were symptomatic. It is likely that 3 months is too early a time point to assess for nonunion: by convention in the orthopedic research literature, a long bone fracture is defined as being non-united at a minimum of 6 months post-injury, and this designation typically implies that the fracture will not go on to union unless

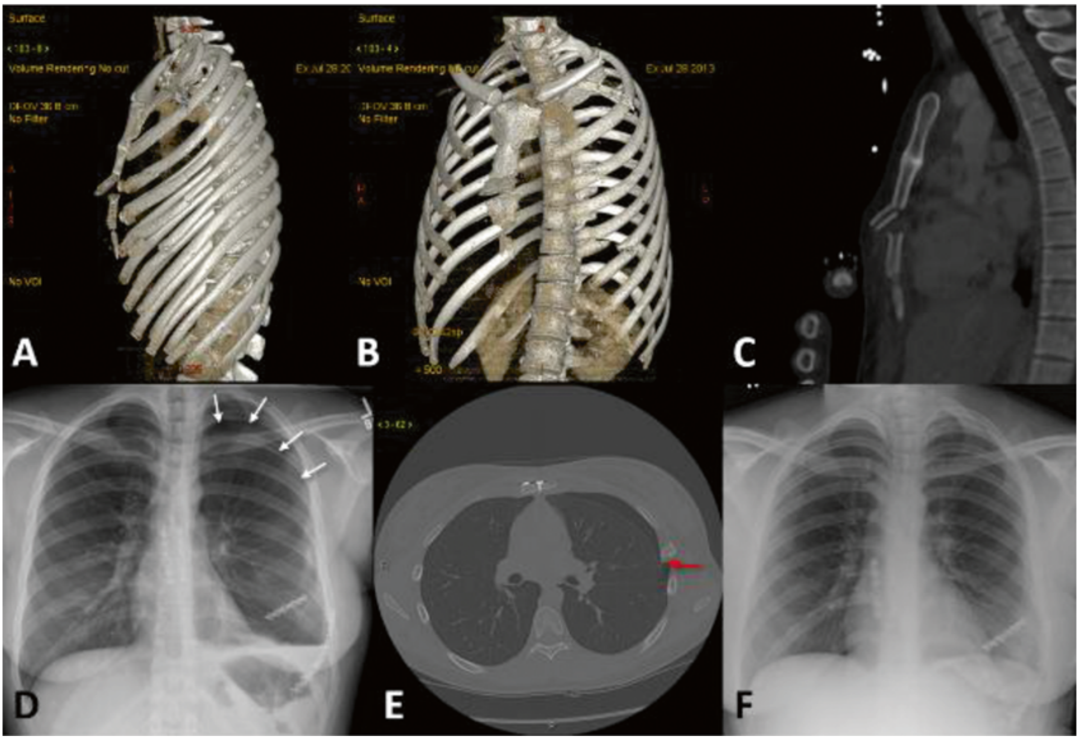

Fig. 12.5 (**a**, **b** and **c**) Initial preoperative 3D CT reconstructions and sagittal views demonstrating a displaced sternal fracture and displaced left-sided rib fractures in a 32-year-old female patient. (**d** and **e**) PA chest radiograph and axial CT views demonstrating recurrent pneumothorax at 3 weeks post-ORIF of sternal fracture and left-sided rib fractures. *White arrow* indicates the edge of the lung parenchyma. The *red arrow* illustrates a spike of bone from one of the rib fractures (that was not fixed) protruding into the pleural space. The pneumothorax recurred despite treatment with a pig-tailed catheter to suction for several days. (**f**) AP chest radiograph following VATS with resection of small apical bleb and resection of protruding spike of bone seen in (**e**) resulting in resolution of pneumothorax

some repeat intervention is performed. In addition, the use of resorbable plates may lead to a higher rate of this specific complication. In the experience of the authors of this chapter, symptomatic nonunion requiring revision surgery is exceedingly rare when metal plates and screws are used for rib fracture fixation.

Symptomatic Hardware/Loose Hardware

Rates of hardware loosening and symptomatic hardware have varied widely in the literature on rib fracture fixation, likely reflecting the diverse nature of fixation techniques that have been employed. In our systematic review, the overall rate of hardware loosening was 0.95 %, and the rate of symptomatic hardware requiring removal was 1.91 %. Migration and loosening of k-wire fixation have been reported in the literature, precluding its safe use for rib fracture fixation in the opinion of the authors of this chapter [16, 17]. In addition, resorbable plate fixation has generally been associated higher rates of failure and nonunion than metal plates [5, 14, 15]. In the opinion of the authors of this chapter, the use of metal plates and screws should be considered the gold standard for rib fracture fixation. We have used both locking plates and non-locking plates (3.5 mm and/or 2.7 mm pelvic reconstruction plates) for rib fracture fixation. We have observed screw loosening when non-locking plates and screws are used, particularly in elderly patients

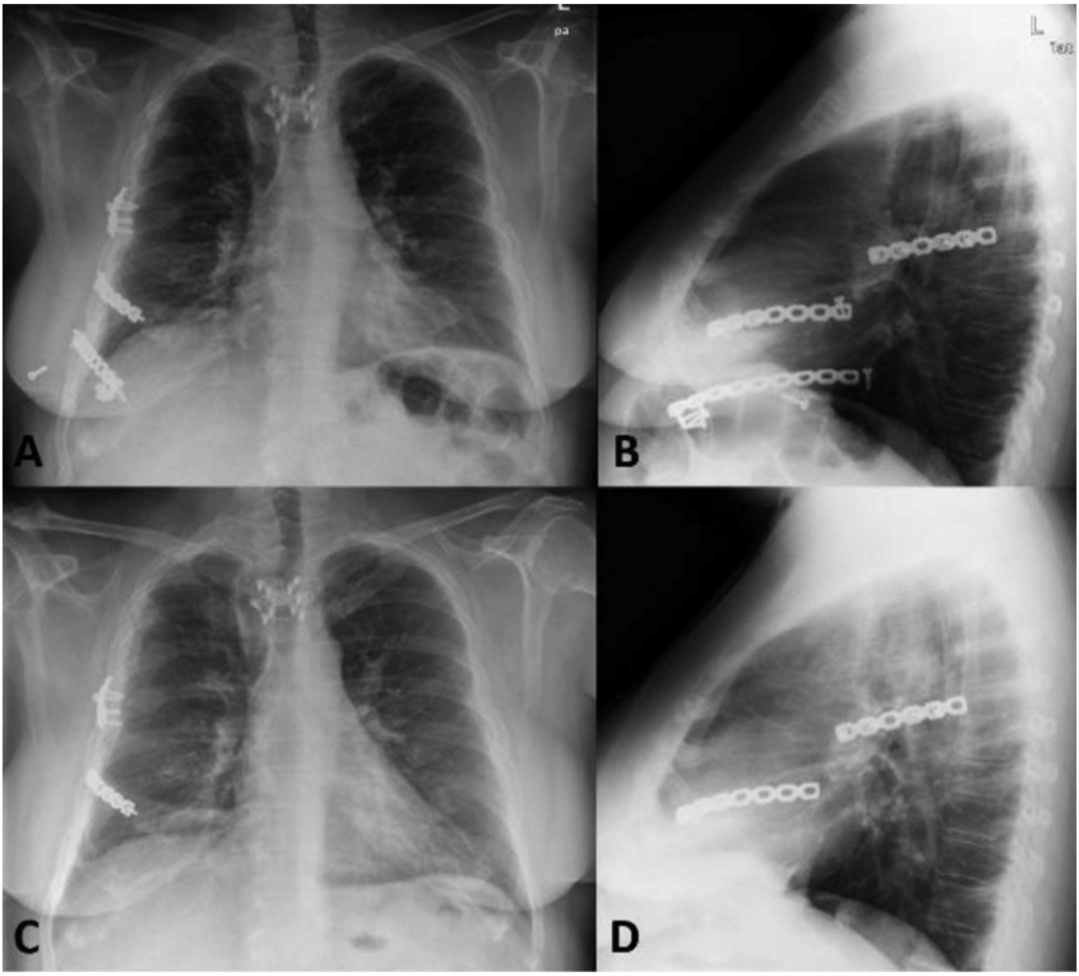

Fig. 12.6 (**a** and **b**) PA and lateral chest radiographs 6 months postoperative showing fixation of multiple right-sided rib fractures and sternal fracture in a 63-year-old female patient with osteopenic bone. There are multiple loose screws in the muscles outside of the right hemithorax. The patient was complaining of persistent chest wall irritation and was concerned about the loose hardware; therefore, she underwent removal of the loose hardware. At the time of hardware removal, her rib fractures were noted to be healed. (**c** and **d**) Postoperative PA and lateral chest radiographs following removal of the loose hardware

with osteopenic bone. This complication has been reported in the literature [18]. Two modern series using locked plating for rib fracture fixation have been published in the literature recently [19, 20]. Both series reported no hardware failures or loosening (Althausen et al. = 0/20 patients and Bottlang et al. = 0/22 patients), suggesting that the use of locked plating may avoid this particular complication. In the opinion of the authors of this chapter, the potential benefits of locked plating for rib fracture fixation must be weighed against the substantial increase in costs when these implants are used. We generally reserve the use of locked plating for elderly patients with osteopenic bone. When screw loosening does occur, it is often asymptomatic and can be managed conservatively (see Fig. 12.4), provided that the hardware does not migrate into the intrathoracic space. Occasionally, if loose hardware is symptomatic, it can be removed once rib fracture healing has occurred (see Fig. 12.6). Additionally, symptomatic hardware requiring removal has been described in the literature with rates ranging from 4.5 to 33 % [18, 21, 22]. This complication is more common in thinner patients with plates placed anterolaterally.

Chronic Pain/Chest Wall Rigidity

Chronic pain is a common complication following flail chest injury. In our systematic review, the rate of chronic chest pain was 2.98 % following surgical management and 3.80 % in nonsurgically managed patients with flail chest injury. This is consistent with previous literature which has generally shown that surgical intervention decreases rates of chronic pain following flail chest injury [3, 8, 23]. Again, it s likely these figures substantially underestimate the occurrence of this complication. The cause of chronic pain is commonly viewed as multifactorial, although damage to the intercostal nerves (usually from the violence of the injury, see Fig. 12.7) may be a substantial factor as patients often describe a radicular and dermatomal distribution to their pain. One of the criticisms of surgical stabilization of flail chest injuries has been the potential to damage these structures further. In the experience of the authors of this chapter, the damage to these structures has already been imparted at the time of injury, and surgical intervention is unlikely to cause further significant damage (see Fig. 12.7).

Chest wall rigidity has also been described following rib fracture fixation. Campbell et al. noted that 60 % of patients experienced chest wall stiffness following surgical stabilization of rib fractures using a resorbable plating system [14]. In addition, Mayberry et al. described a single case of chest wall rigidity following rib plating that improved following removal of the hardware [8]. In the absence of a large-scale, pivotal randomized trial, it is difficult to know if chest wall rigidity is a consequence of the severe injury or of surgical treatment.

Conclusions

The introduction of any new surgical procedure is inevitably accompanied by surgical complications. Rib fracture fixation for the stabilization of flail or unstable chest wall injuries is a relatively novel procedure that has seen a dramatic increase in use over the last decade. Unfortunately, the currently available literature on surgical complications following rib fracture fixation is quite limited. On the basis of this evidence, rib fracture fixation does appear to result in lower general complication rates relative to nonsurgical management (i.e., lower rates of pneumonia, tracheostomy, sepsis, and death). The surgery-specific complication rates that have been reported to date are exceedingly low and likely substantially biased due to underreporting. Underreporting of complications and adverse events has been an issue in the past with the introduction of new surgical technologies [24]. Further investigation with large-scale randomized trials and prospective

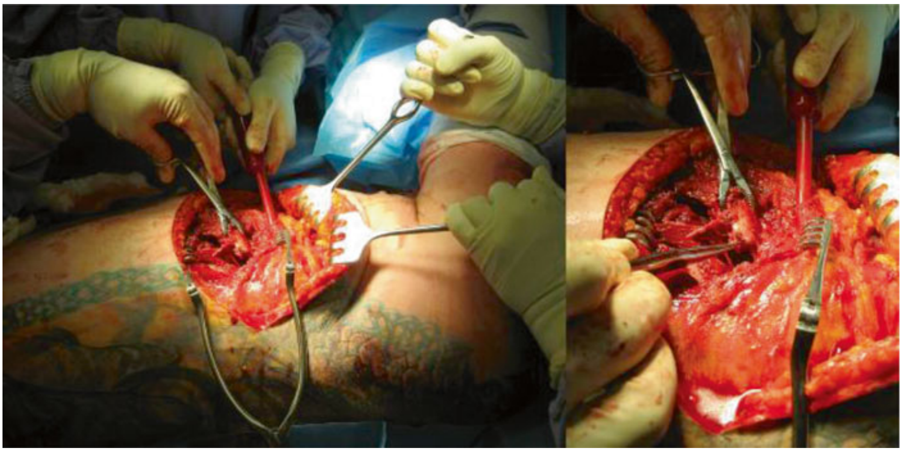

Fig. 12.7 Intraoperative photographs demonstrating gross disruption of soft tissues and intercostal nerves/blood vessels in the setting of badly displaced rib fractures

data collection on rib-specific implants with rigorous monitoring and reporting of complications and adverse events is necessary to identify the true rates of complication related to rib fracture fixation surgery.

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Postoperative Care Including Chest Tube Management

13

Barbara Haas and Avery B. Nathens

Chest Tube Management

Specific indications for operative intervention for both chest wall injuries and intrathoracic pathology do exist and are detailed in other chapters of this book. However, the majority of blunt chest wall injuries do not require operative intervention and can be managed non-operatively with a chest tube (tube thoracostomy) and careful observation. These principles hold true for the postoperative management of the patient who has undergone chest wall fixation and/or thoracotomy.

Chest Tube Mechanics

Chest tubes are placed in the pleural space of the chest, between the visceral and parietal pleura. Once in place, the chest tube is connected to a collection canister; together, the pleural space, chest tube and canister form a single closed system. Chest drainage canisters consist of three separate compartments, which reproduce the classic “three-bottle system”. The first compartment collects fluid drained from the pleural space. The second compartment contains a column of water, which acts as a one-way seal between the collection canister and the atmosphere. The column of water allows air to escape, but does not allow any air to re-enter the chest tube and therefore the pleural space. The third compartment allows negative pressure to be applied to the chest tube. The amount of negative pressure applied was traditionally controlled by the height of the water column placed in the third compartment; however, most commercially available chest evacuation systems control negative pressure by means of a mechanical valve.

Indications for Chest Tube Insertion

In the context of traumatic injury, chest tubes serve to drain either fluid (hemothorax) or air (pneumothorax) from the pleural space. When hemothorax or pneumothorax results in clinical symptoms (dyspnea, tachypnea or other signs of respiratory distress), chest tube insertion is indicated. Pleural drainage in asymptomatic patients requires consideration of a number of factors.

General consensus exists that hemothorax clearly visible on chest radiography requires drainage regardless of symptoms. Blunting of the

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costophrenic angle on an upright chest radiograph suggests that there is approximately 400–500 mL of fluid in the thoracic cavity; when left undrained, hemothorax can result in pleural space infection or other complications. In the case of hemothoraces visible only on CT scanning, optimal management remains controversial. While some retrospective data exist to suggest that hemothoraces smaller than 1.5 cm on CT can be managed expectantly, this approach is not widely accepted [1–3].

Although asymptomatic at the time of presentation, a small pneumothorax has the potential to progress or even to become a tension pneumothorax, particularly in the presence of positive pressure ventilation. Avoiding the potential complications of chest tube insertion in the context of a small pneumothorax must therefore be balanced against the risk of potential respiratory or hemodynamic deterioration. In the absence of positive pressure ventilation, an asymptomatic, small pneumothorax (<1.5 cm at the third rib) visible on chest radiograph can be managed expectantly with close clinical and radiographic monitoring [4]. A subset of asymptomatic pneumothoraces are not visible on chest radiography and are only visible on computed tomography (CT); a pneumothorax visible only on CT is termed an occult pneumothorax. The risk of occult pneumothorax varies widely based on the population studied; however, a recent review of severely injured patients demonstrated that 59 % of patients with rib fractures had an occult pneumothorax, as did three quarters of all patients with any chest injury [5]. As such, the presence of an occult pneumothorax should be suspected in any patient with severe chest wall injuries. Three randomized controlled trials have been conducted comparing chest tube insertion for occult pneumothorax with expectant management, with conflicting results [6–8]. The largest of these studies, which focused only on patients with occult pneumothoraces receiving positive pressure ventilation, demonstrated that one third of patients treated expectantly eventually required a chest tube; moreover, one patient among the 50 managed expectantly developed a tension pneumothorax [8]. Given these data, tube thoracostomy should be considered in most mechanically ventilated patients with any significant pneumothorax, particularly those who will be mechanically ventilated for several days. All patients treated expectantly must be followed with frequent chest radiography, and any respiratory or hemodynamic deterioration should prompt chest imaging.

Chest Tube Insertion Technique

The patient should be positioned in the supine position. Raising the arm on the affected side above the patient's head often increases ease of insertion. Prior to proceeding with tube thoracostomy, it is essential to confirm that the imaging reviewed was for the correct patient and that the chest tube is being inserted on the correct side. Adequate intravenous access should be ensured, and consideration should be given to using intravenous sedation if adequate monitoring and personnel are available. Tube thoracostomy should be performed under sterile conditions, with sterile gown and gloves and mask/goggles or facial shield for personal protection. The patient's chest should be prepped and draped widely. It is useful to include the axilla, ipsilateral nipple and clavicle in the sterile field to aid with landmarking during the procedure. A 28 F chest tube is adequate for a pneumothorax; a chest tube 32 F or larger should be used if there is any component of hemothorax.

The chest tube should be inserted at the fourth or fifth intercostal space, between the anterior axillary and mid-axillary line. In patients where the intercostal spaces cannot be palpated due to adipose or breast tissue, the inframammary line can be used to identify the correct intercostal space. Additionally, the skin incision should be placed after adipose tissue and breast tissue have been pushed as medially as possible, both for cosmetic reasons and to avoid excessive tissue dissection.

Achieving adequate local anaesthesia is often the most challenging aspect of the procedure. In addition to anaesthetizing the location of the skin incision, care should be taken to ensure adequate local anaesthetic is injected in the intercostal space and in the pleural space. The intercostal and pleural space should always be entered immediately above the rib to avoid injury to the neurovascular bundle located on the inferior aspect of each rib.

The skin incision should be long enough to accommodate the operator's finger and the chest tube. The incision should be deepened by means of blunt dissection with a snap or Kelly clamp. Once the dissection has reached the level of the chest wall, the dissection should proceed through the intercostal muscles immediately above the rib, perpendicularly to the chest wall. Entering the pleural space requires firm, controlled pressure. Once the pleural space has been entered, the pleural space is palpated to confirm correct location and to ensure that there are no adhesions between the visceral and parietal pleura which might interfere with safe chest tube insertion. The chest tube should then be placed along the posterior chest wall, with a Kelly clamp used to direct the chest tube. At this juncture, the chest tube can inadvertently be placed along the chest wall in an extrapleural position; to avoid this, ensure that the chest tube can be palpated entering the pleural space. Once the chest tube has been placed, it should be fixed in place with a heavy silk or nylon suture. A second interrupted suture may be required to close the skin around the chest tube site. Finally, a sterile occlusive dressing should be placed. A chest radiograph should be performed immediately after insertion to ensure proper placement of the chest tube.

Chest Tube Placement After Operative Fixation of Rib Fractures

Patients undergoing operative fixation of rib fractures will require chest tube placement for resolution of postoperative pneumothorax and for evacuation of pleural fluid. In general, preexisting (and potentially contaminated) chest tubes are replaced. One large-bore chest tube directed posteriorly towards the apex of the lung will suffice. The chest tube should be placed under direct evaluation intra-operatively and should be placed through a small incision separate from the primary incision, usually caudally (see Chap. 12). Optimally, chest tubes should be placed and kept away from implanted hardware to decrease the possibility of hardware contamination and infection.

Antibiotic Prophylaxis Following Chest Tube Insertion

Antibiotic prophylaxis following tube thoracostomy aims to prevent post-procedural infection of the pleural space and lung parenchyma (empyema and pneumonia). The Eastern Association for the Surgery of Trauma (EAST) refers to antibiotics given in this context as "presumptive antibiotic therapy", in order to reflect the fact that the pleural injury occurs prior to tube thoracostomy insertion. In 1998, the EAST Practice Management Guidelines Work Group published guidelines that recommended the use of antibiotics following chest tube insertion. However, the revised version of these guidelines, published in 2012, reversed this recommendation based on new evidence [9]. According to the most recent guidelines, there is insufficient evidence to recommend for or against antibiotic prophylaxis at the time of chest tube insertion.

A meta-analysis published in 2012 reviewed 11 randomized controlled trials including a total of over 1,200 patients [10]. Although this meta-analysis demonstrated a reduced risk of infection among patients who received antibiotics at the time of chest tube insertion, this effect was limited to patients with penetrating chest wall injuries; presumptive antibiotics did not affect the rate of chest infection among patients with chest injuries due to blunt injuries.

Daily Chest Tube Management

Daily examination of the patient with a tube thoracostomy in situ includes careful examination of the chest tube and collection system. The amount of drainage, as well as the type of drainage (blood, fluid, pus), should be recorded daily.

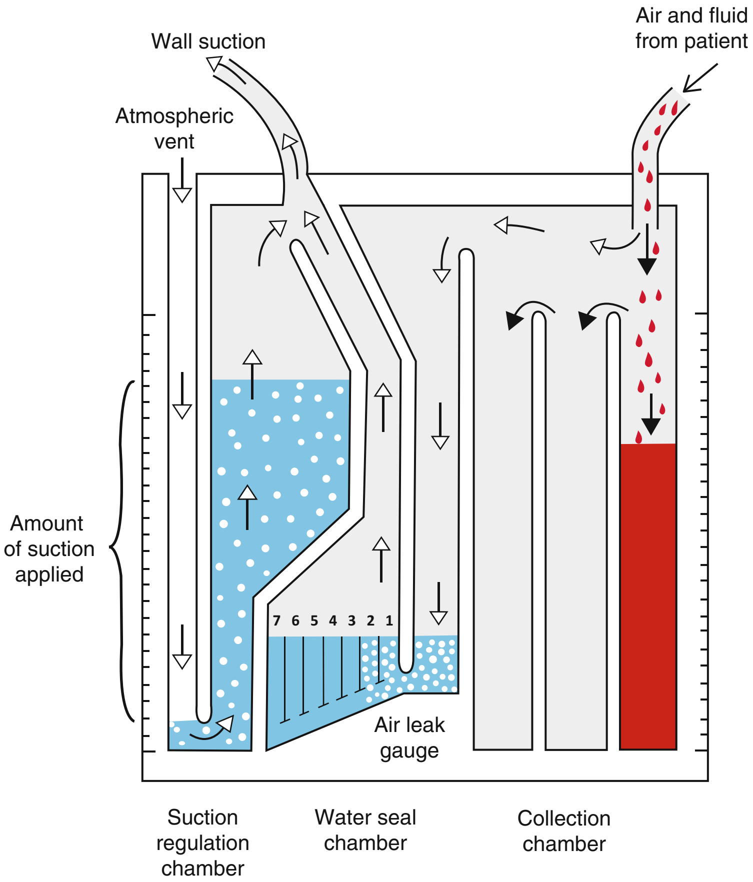


Fig. 13.1 Chest tube collecting system—contemporary chest tube collecting systems reproduce the traditional “three-bottle system”. The first compartment collects fluid drained from the pleural space. Air then passes to the second compartment, where a column of water acts as a one-way seal between the collection canister and the atmosphere. Air leaks can be visualized at the level of the second compartment. The third compartment allows negative pressure to be applied to the chest tube. *Source*: UpToDate

The skin incision should be inspected for signs of cellulitis or purulent drainage. Finally, the underwater seal should be examined for air bubbles, both when the patient is breathing normally and when they are coughing. While air bubbles in the underwater seal compartment are a normal finding early after chest tube insertion, persistent bubbling indicates either an intrathoracic air leak (e.g. from a lung laceration) or an air leak within the chest tube system itself. Whether the air leak originates from within or from outside the thoracic cavity can easily be differentiated by applying a clamp to the chest tube at the level of the patient’s skin; if there continue to be bubbles in the underwater seal compartment after the chest tube is clamped, there is an air leak in the chest tube collecting system (Fig. 13.1).

Negative pressure applied to the chest tube system increases the rate of lung re-expansion following pneumothorax. However, once the lung is completely re-expanded, the chest tube can be placed to underwater seal.

Traditionally, patients with a chest tube in situ have undergone daily chest radiography. There is no data to support this practice, and it is associated with significant cost and unnecessary discomfort to the patient [11]. Multiple studies have demonstrated that, following lung resection and with chest tube placement, daily chest radiographs in asymptomatic patients contribute minimally to patient management decisions [12]. As with any investigation, thought should be given to the indication for the test. Early after chest tube insertion, chest radiography allows visualization of lung re-expansion and drainage of hemothorax. A chest radiograph should also be ordered to investigate any respiratory symptoms which could indicate either pneumonia or a chest tube complication: shortness of breath, tachypnea, increased pain, increased oxygen requirements or hypoxia. Finally, a chest radiograph should be performed whenever any modifications are performed on the chest tube, whether this be repositioning or modification of the collection system (change in suction, tipping over of the collection canister).

In the case of persistent pleural fluid on chest radiography 48 h following chest tube insertion, CT should be performed to assess the patient for significant retained hemothorax [2]. If hemothorax persists despite previous tube thoracostomy, additional drainage is required. Persistent hemothorax after primary chest tube insertion is associated with a 33 % risk of empyema [13]. Although it might appear reasonable to attempt drainage of retained hemothorax with a second chest tube, this may not be optimal. In a small randomized controlled trial comparing surgical evacuation [video-assisted thoracoscopic surgery (VATS)] with the insertion of a second chest tube, patients undergoing VATS had shorter length of stay and shorter need for chest tube drainage [14]. Furthermore, almost half of the patients treated with a second chest tube required surgical intervention. Retained hemothorax should prompt expert consultation and should be considered for surgical evacuation within 3–7 days of admission [2].

Air leaks in the trauma population generally resolve within 48 h of injury. Patients who develop a persistent air leak following chest wall injury require further evaluation to rule out underlying injury to the lung. The EAST guidelines recommend VATS evaluation for an air leak that persists beyond 48 h after admission, though this recommendation is based only on moderate evidence [2]. Persistent air leak should prompt consultation with a thoracic surgeon.

Complications of Tube Thoracostomy

Complications associated with tube thoracostomy can occur during insertion, while the chest tube is in situ, and during chest tube removal. The most feared complication of chest tube insertion is injury to intrathoracic or intra-abdominal structures. Although injuries to the lung parenchyma and the intercostal bundle are most common, injuries to the heart, mediastinum, diaphragm, spleen, liver and even hollow viscus can occur. To avoid these (potentially fatal) injuries, landmarking for chest tube insertion must be meticulous, and care must be taken to enter the pleural cavity in a controlled fashion. Special caution should be taken in patients with previous thoracic surgery, difficult landmarking due to obesity and those at high risk of having pleural adhesions (history of tuberculosis, multiple previous lung infections).

While a chest tube is in place, the patient is at risk of complications related to the malfunction of the chest tube system, as well as infectious complications related to having a foreign body in the pleural cavity. Chest tubes can migrate, kink or become disconnected from the collecting system. Although any leak in the chest tube/collecting system can cause pneumothorax, a kink in the chest tube prevents air from escaping the thoracic cavity. Air accumulated in the thoracic cavity can cause tension pneumothorax, which can lead to severe respiratory and hemodynamic compromise. Kinking of the chest tube can occur iatrogenically if a clamp is applied to the chest tube and left in place; for this reason, chest tubes should never be left clamped, except in a highly monitored setting under very select circumstances.

Chest Tube Removal

The timing of chest tube removal depends largely on the initial indication for insertion. If the chest tube was inserted purely for pneumothorax and the lung has re-expanded completely, removing the chest tube after 24 h is reasonable. Recommendations regarding the appropriate timing of chest tube removal in the case of pleural collection vary widely; daily rates of drainage from 100 to 400 mL have been cited as an indication for chest tube removal [15]. In our practice, chest tubes are left in place until drainage is 100 mL or less per day.

If the chest tube is under negative pressure at the time when chest tube removal is considered, it should be placed to underwater seal for 6–8 h prior to removal [16]; a chest radiograph should be obtained after this time interval to ensure that the lung remains re-expanded. Chest tubes should be removed when the patient's intrathoracic pressure is positive, in order to avoid re-accumulation of a pneumothorax.

Whether a chest radiograph needs to be obtained after chest tube removal is somewhat controversial. A systematic review of studies examining routine chest radiography in the context of cardiothoracic surgery concluded that routine post-chest tube removal X-rays are not beneficial and that patients requiring re-intervention (i.e. reinsertion of chest tube) have symptoms that would prompt imaging [17]. In the elective cardiothoracic surgery patient, however, the incidence of post-chest tube removal complications may be lower than in the trauma population, both because patients following cardiac surgery have a lower a priori risk of pneumothorax and because of the conditions under which the chest tube was originally inserted (in the operating room, with minimal tissue dissection). In addition, for many patients with chest wall trauma, chest tube removal is the last event that occurs prior to discharge to home; as such, discharging patients without chest radiography could put them at risk of deteriorating outside the hospital.

Analgesia Following Chest Wall Injury/Surgery

Meticulous analgesia following operative fixation of chest wall injuries is essential to ensuring optimal patient outcomes. As with patients whose injuries are being managed non-operatively, the optimal analgesic regiment for patients who have undergone surgery must be tailored to each individual patient. Among patients who have undergone thoracotomy for the purpose of chest wall fixation, strong consideration should be given to regional anaesthesia techniques (among patients who have no contraindications to epidural or paravertebral nerve blocks). Close collaboration with the anaesthesia team, as well as a multimodal approach to pain management, should be standard in this patient population.

Direct operative exposure provides additional opportunities to improve postoperative pain control. Specifically, intercostal nerve blocks can easily be administered under direct visualization in the operative room prior to chest wall closure. In addition, where expertise exists, paravertebral nerve blocks can also be administered intra-operatively.

A comprehensive approach to pain control is essential to avoiding adverse events. Adequacy of analgesia is closely related to the patient's ability to mobilize and maintain normal respiratory function and pulmonary toilet. Pain prevents patients from coughing and taking deep breaths and leads to a drop in functional residual capacity (FRC). These changes are associated with atelectasis, inadequate clearance of pulmonary secretions and suboptimal ventilation and oxygenation. Inadequate analgesia is linked to increased incidence of pneumonia and increased mortality.

Analgesic options commonly used following chest wall trauma include systemic opioids, non-opioid analgesics and a variety of regional anaesthetic techniques. The latter category includes intercostal blocks, epidural anaesthesia (opioid, local anaesthetic or combined), paravertebral blocks and intrapleural injections. Each of these modalities is associated with advantages and disadvantages that must be tailored based on the patient's underlying injuries, mobility, frailty and preference. Close collaboration with the anaesthesia team is essential to optimize outcomes among patients with chest wall injuries [18].

Opioids can be administered orally, intravenously on an intermittent basis, as a continuous infusion, or intravenously by means of patient controlled analgesia. Opioid analgesia is often most easily ordered and administered on a standard surgical ward; this approach may be adequate for patients with minimal injuries. However, opioids suppress respiratory drive and cough and may therefore exacerbate the negative respiratory effects associated with chest wall injuries. Furthermore, opioid analgesia used alone is often inadequate to suppress pain caused by severe chest wall injuries. Opioids are therefore best used in the context of multimodal analgesia, both to ensure adequate analgesia and to minimize the total dose received by the patient. In the absence of contraindications, acetaminophen and nonsteroidal anti-inflammatory drugs should routinely be used in conjunction with opioids.

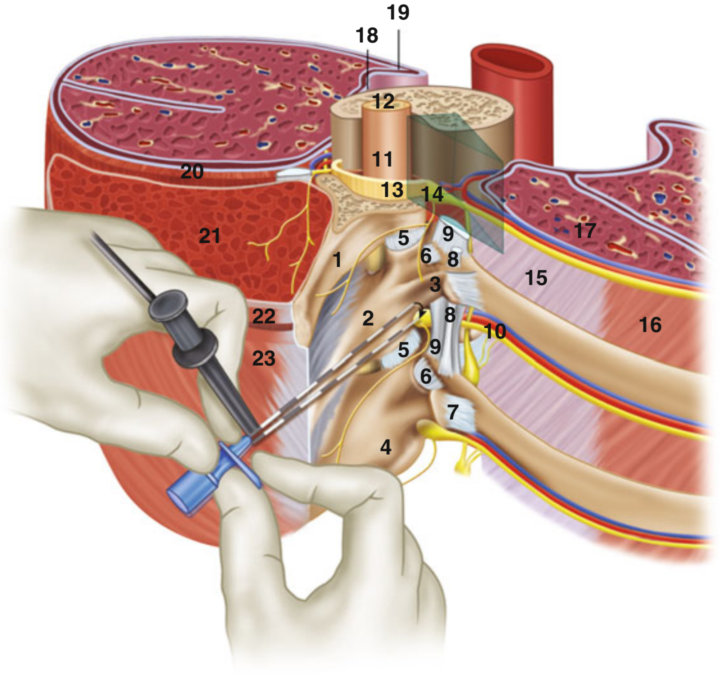
Intercostal nerve blocks with a long-acting local anaesthetic are an attractive option in patients with localized pain due to a small number of closely spaced rib fractures. The procedure involves injection of local anaesthetic posterior to the mid-axillary line at the level of the intercostal bundle (inferior to the rib), blocking the lateral cutaneous and anterior branch of the intercostal nerve. Typically, a block needs to be administered up to one rib level above and one rib level below the injury. Intercostal nerve blocks in a patient with rib fracture at multiple levels are not optimal; in these patients, intercostal nerve block is time consuming, is painful for the patient and might require excessively high doses of local anaesthetic.

Epidural analgesia involves infusion of local anaesthetic, opioids or both into the epidural space at the level of the thoracic or lumbar spine. Epidural analgesia can provide pain relief superior to that provided by opioids. The EAST Practice Management Guidelines for analgesia in blunt chest trauma recommend epidural analgesia in the setting of multiple rib fractures, particularly in elderly patients with more than four rib fractures and in patients with flail chest [19]. These guidelines included data from both randomized and non-randomized studies. A recent meta-analysis of randomized controlled trials of epidural analgesia in the context of rib injuries found no reduction in mortality or length of stay [20]. A large number of patients are not candidates for epidural analgesia; epidural analgesia is contraindicated in patients with ongoing hemodynamic instability or hypovolemia, given that epidural analgesia can lead to further hypotension. Finally, the insertion of an epidural catheter can be technically difficult in a patient with significant pain and limited mobility and is not technically feasible in patients with significant spinal injuries or coagulopathy.

Paravertebral nerve blocks are an alternative modality to epidural catheters. The paravertebral space is a wedge-shaped area on either side of the spine; the paravertebral space is continuous with the intercostal space and the epidural space. Injection of local anaesthetic into the paravertebral space leads to anaesthetic effects not only to the nerve root at the level of the injection but to nerve roots caudally and cranially as well. Paravertebral nerve blocks provide analgesia comparable to epidural analgesia [21] and are considered superior to epidural anaesthesia by some authors [22, 23]. Because paravertebral nerve blocks do not produce hemodynamic instability, they can safely be used in patients with ongoing hemodynamic compromise. Compared to epidural infusions, paravertebral nerve blocks do not produce sensory or motor blocks of the limbs, are not associated with urinary retention, produce less nausea and vomiting and are not associated with the risk of epidural abscess or hematoma [24]. Paravertebral nerve blocks are also safer than epidural catheters in patients receiving anti-platelet therapy and do not require coordination of DVT prophylaxis with epidural insertion or removal. Risks of this technique include pneumothorax and inadvertent epidural injection of analgesic. As with epidural catheters, paravertebral nerve blocks require some degree of patient cooperation. In addition, paravertebral nerve blocks produce analgesia in a smaller distribution than an epidural catheter (Fig. 13.2).

Analgesia for Elderly Patients

Coexisting comorbidities may complicate analgesia in elderly patients with chest wall injuries. First, cognitive impairment may prevent elderly



1. Spinous process of T3
2. Spinous process of T4
3. Transverse process of T4
4. Spinous process of T5
5. Zygapophyseal joint capsule
6. Costotransverse ligament
7. Lateral costotransverse ligament
8. Intertransverse ligament
9. Superior costotransverse ligament
10. Intercostal vein, artery and nerve
11. Dura mater
12. Spinal cord
13. Ligamentum flavum
14. Nerve root
15. Internal intercostal membrane
16. Internal intercostal muscle
17. Left lung
18. Parietal pleura
19. Visceral pleura
20. Internal intercostal muscle
21. Erector spinae muscle
22. Rhomboid major muscle
23. Trapezius muscle

Fig. 13.2 Paravertebral nerve block—after making contact with the transverse process, the paravertebral space is entered by traversing the costotransverse ligament or intertransverse ligament. Ultrasound is often used in contemporary practice to facilitate landmarking. *Source*: Boezaart AP. Atlas of peripheral nerve blocks and anatomy for orthopaedic anaesthesia. Philadelphia: Elsevier; 2008 patients from reporting pain or from calling for analgesia when they have pain. Elderly patients are more sensitive to the effects of analgesic medications, as well as at higher risk of side effects. Some authors recommend non-pharmacological adjuncts in elderly patients with more than a single rib fracture, patients with underlying lung disease and those with respiratory distress [22].

Incentive Spirometry

Incentive spirometers are mechanical devices designed to encourage deep breathing by the patient. Incentive spirometry aims to reverse the decrease in FRC that occurs with shallow breathing, chest wall splinting and atelectasis. Incentive spirometers have an indicator which visually confirms to the patient that they have taken a large enough breath, as “prescribed” by the physician or physiotherapist. Although widely promulgated as a means of decreasing respiratory complications, there is little data to support the use of incentive spirometry among patients with chest wall injuries. Extrapolating from studies of incentive spirometry in the setting of abdominal surgery and thoracotomy, incentive spirometry does not appear to prevent postoperative pulmonary complications. A meta-analysis of randomized controlled trials examining incentive spirometry following upper abdominal surgery found no difference in the rate of complications (pneumonia, respiratory failure, atelectasis) when comparing patients who received incentive spirometry and those who received no respiratory treatment [25]. Equivalent outcomes were also noted when comparing patients who received incentive spirometry and those who were taught deep breathing exercises [25]. Similarly, a systematic review and meta-analysis of incentive spirometry following coronary artery bypass graft surgery failed to demonstrate any reduction in atelectasis or pneumonia among patients receiving incentive spirometry [26]. Finally, incentive spirometry following thoracic surgery does not appear to improve patient outcomes [27].

Management of Pneumonia Following Chest Wall Injury

Pneumonia is a frequent complication among patients with chest wall injuries. Among patients with flail chest, approximately one fifth develop pneumonia [28]. Among patients who require mechanical ventilation during their hospital stay, the incidence of pneumonia has been reported to be as high as 25 % [29].

Diagnosis of Pneumonia

Given the high incidence of pneumonia among patients with chest wall injuries, clinical evidence of infection or respiratory compromise should be considered suspicious. Early recognition and appropriate management are key to preventing further complications. Hospital-acquired pneumonia (HAP) is associated with a 7-day increase in length of stay and has an attributable cost of $40,000 [29]. Delay in appropriate therapy is associated with significant increase in mortality.

Pneumonia recognized within 48 h of admission should be considered community acquired. Early pneumonia in the trauma population is likely related to an aspiration event at the time of injury or in the early resuscitative period. After 48 h, pneumonia is considered to be HAP; pneumonia acquired after 48–72 h of mechanical ventilation is classified as ventilator-acquired pneumonia (VAP). Unlike pneumonia acquired in the community, HAP and VAP are associated with hospital-acquired pathogens and multidrug-resistant (MDR) organisms. Common causative organisms include aerobic gram-negative bacilli (*P. aeruginosa*, *E. coli*, *K. pneumonia*, *Acinetobacter* species) and gram-positive cocci (*S. aureus*, including methicillin-resistant *S. aureus*) [29]. Anaerobic organisms are associated with HAP among non-intubated patients at risk for aspiration. Although the reported incidence of MDR organism is increasing overall, rates vary across institutions and patient care units. MDR pathogens should particularly be considered among patients with prolonged hospitalization and prior exposure to antibiotics.

Diagnostic criteria for pneumonia include leucocytosis, fever, purulent sputum and impaired oxygenation. The presence of two of these four criteria, in conjunction with a new lung infiltrate, is adequate to make a clinical diagnosis, and empiric antimicrobial therapy should be initiated [29]. Although a lower respiratory tract sample can aid in the diagnosis and antibiotic selection among patients with VAP, sputum samples in non-intubated patients are rarely helpful.

Mechanical Ventilation Following Chest Wall Injury

Indications for mechanical ventilation in patients with severe chest trauma, including flail chest and pulmonary contusion, are the same as for any other multiply injured patient. Mechanical ventilation is not indicated in patients with adequate respiratory function, regardless of the radiographic appearance of their injuries. According to the 2012 EAST Practice Management Guidelines, patients with flail chest and pulmonary contusions should be ventilated according to institutional and provider preference. Although not specifically studied, patients with severe thoracic injury are likely to benefit from a lung protective approach to mechanical ventilation, similar to that utilized in ARDS patients.

Non-invasive continuous positive airway pressure (CPAP) in patients with chest wall injury is a modality that could potentially avoid the need for intubation and invasive mechanical ventilation in select patients. There is, however, insufficient evidence to make recommendations regarding the use of non-invasive CPAP in this patient population [30]. In addition, given the natural history of pulmonary contusions, an attempt at non-invasive ventilation may merely delay intubation, placing the patient at unnecessary risk.

Conclusions

The care of patients with severe chest wall injuries should focus on appropriate chest tube management, meticulous optimization of analgesia and maintenance of adequate pulmonary toilet. Early identification of postoperative complications such as pneumonia is essential. Finally, the care of these complex patients requires close cooperation with a multidisciplinary team, including anaesthetists, intensivists, physiotherapists and respiratory therapists. Careful patient management can minimize respiratory and infectious complications and ensure excellent patient outcomes.

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Long-Term Outcome Following Flail Chest Injuries

14

Niloofar Dehghan

Abbreviations

AIS	Abbreviated Injury Severity Score
ARDS	Acute respiratory distress syndrome
CT	Computerized tomography
GCS	Glasgow Coma Scale
ICU	Intensive care unit
OR	Odds ratio
VAP	Ventilator-associated pneumonia

Introduction

Flail chest injuries are common in patients with blunt chest trauma. These injuries are associated with high rates of short-term and long-term morbidity, with mortality rates of 10–36 % [1]. Complications associated with flail chest injuries are due to chest wall instability, as well as injury to the lung parenchyma, such as pulmonary contusions and hemorrhage. Chest wall instability may lead to paradoxical chest wall motion, as well as decreased lung volume and pulmonary function, causing respiratory distress. Pain from trauma to the chest wall also has negative consequences—decreased lung volume, inability to clear secretion, atelectasis, and pneumonia—all of which have a negative effect on pulmonary function and may cause respiratory distress [1–4].

In patients with respiratory distress, mechanical ventilation may be required to maintain oxygenation and ventilation. However, long-term mechanical ventilation has been shown to have detrimental consequences, such as ventilator-associated pneumonia (VAP), sepsis, barotrauma, prolonged intensive care unit (ICU) stay, and need for tracheostomy. The risk of VAP is increased after 4–5 days of mechanical ventilation, and despite the presence of extrathoracic injuries present in these patients, sepsis and pneumonia remain two of the most common causes of death [3]. Tracheostomy is generally recommended in patients who require mechanical ventilation beyond 14 days and has harmful physical and psychological consequences for patients.

It has been reported that patients with concurrent severe head injury or pulmonary contusions may require lengthier time on mechanical ventilation and have inferior outcomes [7]. These patients may require prolonged mechanical ventilation due to concomitant intracranial or lung parenchymal injury and are more likely to suffer from ventilator-associated complications [8].

With regard to long-term complications, patients with flail chest injuries have been reported to have chronic pain, dyspnea, abnormal

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pulmonary function, chest tightness, chest wall deformity, and low health outcomes scores on the SF-36 scale [5, 6]. Only 43 % of patients with flail chest injuries have been reported to return to full-time employment [6].

There are reports that surgical fixation of flail chest injures may lead to improved outcomes in patients with blunt chest trauma. There have been multiple retrospective and limited randomized controlled trials published on this topic, comparing surgical fixation to nonoperative management [2, 4, 7, 9–13]. These studies report that compared to nonoperative treatment, surgical fixation may decrease time on mechanical ventilation [7, 9, 11] and time in the ICU [2, 4, 9, 11], improve rate of return to work [11], and decrease risk of pneumonia [4, 9, 11], chronic pain [2], and long-term respiratory dysfunction [14, 15]. A recent meta-analysis on this topic revealed that patients treated with surgical fixation had decreased time on mechanical ventilation by 8 days, as well as decreased time in the ICU by 5 days. They also reported decreased rate of pneumonia [odds ratio (OR) 0.2], sepsis (OR 0.36), tracheostomy (OR 0.06), and mortality (OR 0.31) [16]. However, surgical fixation is associated with inherent postoperative complications, such as wound complications, infection, and hardware loosening. High-quality data on long-term complications and outcomes of patients treated with surgical fixation are lacking in the literature.

Current Outcomes

A recent study of the National Trauma Data Bank identified 3,465 patients with flail chest injuries from 2007 to 2009 [8]. This study revealed high rates of overall morbidity and mortality in patients with flail chest injuries.

A significant proportion of patients with flail chest injuries identified in this study required mechanical ventilation and ICU admission (Fig. 14.1). Mechanical ventilation was required in 59 % of patients with flail chest injury. The mean duration of mechanical ventilation was

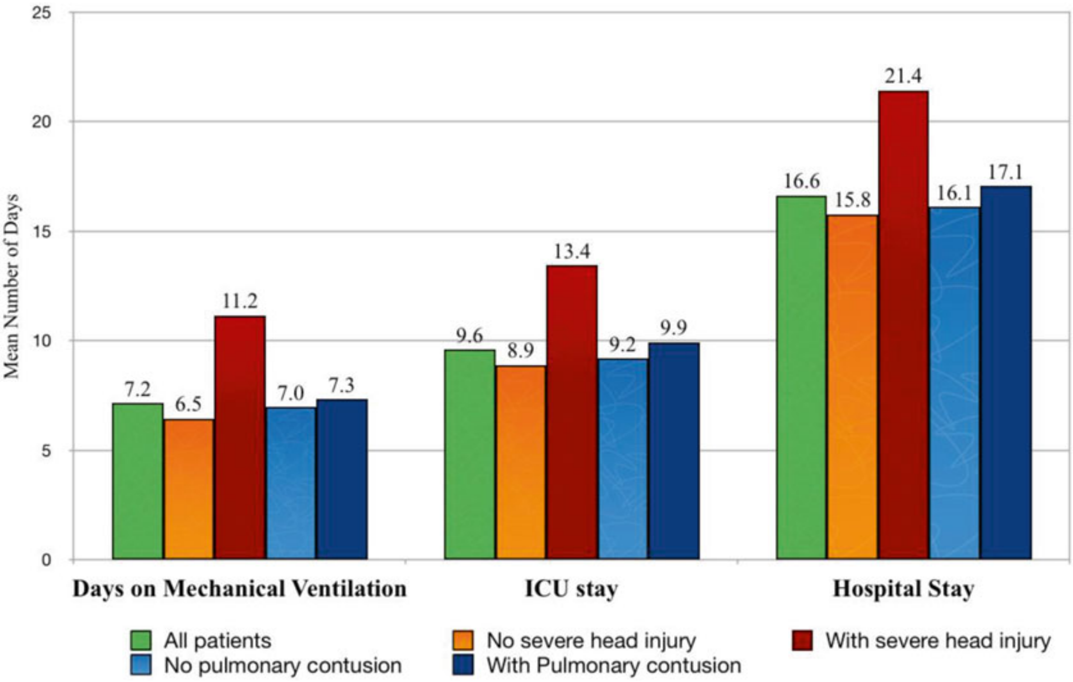

Fig. 14.1 Days on mechanical ventilation, ICU stay, and hospital stay for patients with flail chest injuries [8]

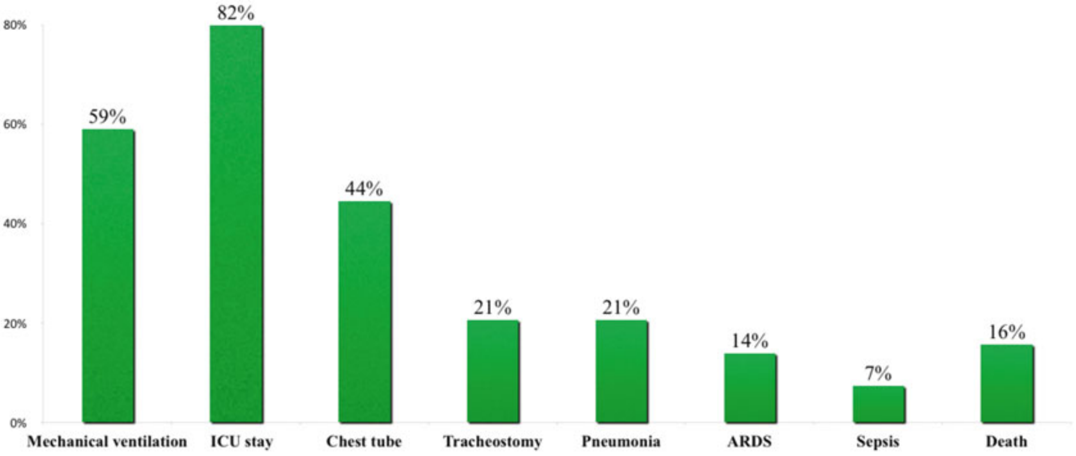

Fig. 14.2 Overall outcomes for patients with flail chest injuries [8]

7.2 days overall. However, when excluding patients who did not require mechanical ventilation (i.e., only focusing on the 59 % who required mechanical ventilation), the mean duration was 12.1 days. The majority of patients (82 %) required admission to the ICU, for a mean duration of 11.7 days. The mean total length of hospital stay was 16.6 days. Chest tubes were required in 44 %, and 21 % of patients underwent tracheostomy placement. In-hospital complications included acute respiratory distress syndrome (ARDS) in 14 %, pneumonia in 21 %, and sepsis in 7 %. The rate of mortality was 16 % in these patients with flail chest injury (Fig. 14.2 and Table 14.1).

Patients with Concurrent Head Injury

This study also investigated outcome differences in patients with concurrent severe head injury, compared to those without severe head injury. Severe head injury was identified by assessment of the Abbreviated Injury Severity Score (AIS) and Glasgow Coma Scale (GCS) and was defined as AIS head ≥3 and a motor GCS ≤4.

The results demonstrate that patients with flail chest injury and concurrent severe head injury have significantly higher rates of morbidity and mortality. Compared to patients without a severe head injury, patients with a severe head injury have a higher rate of mechanical ventilation requirement (88 vs. 54 %, $p<0.00001$) and ICU admission (89 vs. 81 %, $p<0.00001$). They also require more time on a mechanical ventilator (11.2 vs. 6.5, $p<0.001$), more days in the ICU (13.4 vs. 8.9, $p<0.001$), and more days in the hospital (21.4 vs. 15.8, $p<0.0005$). This group of patients also has higher rates of chest tube utilization (51 vs. 43 %, $p<0.001$) and tracheostomy (34 vs. 18 %, $p<0.0001$), ARDS (17 vs. 13 %, $p<0.016$), pneumonia (31 vs. 19 %, $p<0.0001$), and sepsis (11 vs. 7 %, $p<0.001$). Mortality is much higher in patients with concurrent severe head injury, 40 % compared to 11 % in patients without concurrent severe head injury ($p<0.0001$) (Fig. 14.3).

Patients with Concurrent Pulmonary Contusion

Fifty-four percent of patients with flail chest injury had concurrent pulmonary contusion, and these patients had worse outcomes compared to those without pulmonary contusion.

When comparing outcomes of patients with concurrent pulmonary contusion to those without contusion, there was a statistically significant increase in the rate of mechanical ventilation

Table 14.1 Overall outcomes and complications associated with patients suffering from flail chest injuries

Outcomes	All patients		No severe head injury		With severe head injury		*P* value	No pulmonary contusion		With pulmonary contusion		*P* value
	%	#	%	#	%	#	–	%	#	%	#	–
Number of patients	100 %	3,467	85 %	2,944	15 %	523		46 %	1,587	54 %	1,880	
Resource utilization												
Mechanical ventilation	59 %	1,762	54 %	1,369	88 %	393	0.00001	56 %	778	61 %	984	0.005
Mean day on mechanical ventilation												
Ventilated patients only	12.1	±11.0	12.0	±11.9	12.7	±12.1	0.60	12.4	±12.1	11.9	±11.9	0.91
All patients	7.2	±12.0	6.5	±10.6	11.2	±12.1	0.001	7.0	±11.0	7.3	±11.0	0.016
ICU admission	82 %	2,767	81 %	2,306	89 %	461	0.00001	80 %	1,229	84 %	±1,538	0.003
Mean days in ICU												
Patients admitted to ICU only	11.7	±11.8	11.0	±11.6	15.0	±13.4	0.0001	11.5	±11.9	11.8	±12.1	0.242
All patients	9.6	±12.0	8.9	±11.3	13.4	±13.5	0.001	9.2	±11.6	9.9	±11.9	0.0032
Days in hospital	16.6	±16.0	15.8	±14.6	21.4	±21.7	0.0005	16.1	±15.6	17.1	±16.3	0.018
Complications												
Chest tube	44.5 %	1,542	43.3 %	1,276	50.9 %	266	0.0014	41.8 %	663	46.8 %	879	0.003
Tracheostomy	20.6 %	714	18.2 %	535	34.2 %	179	0.0001	20.9 %	332	20.3 %	382	0.66
Pneumonia	20.6 %	713	18.8 %	553	30.6 %	160	0.0001	18.7 %	297	22.1 %	416	0.013
ARDS	13.8 %	480	13.2 %	390	17.2 %	90	0.0156	13.1 %	208	14.5 %	272	0.25
Sepsis	7.4 %	255	6.7 %	198	10.9 %	57	0.0008	6.8 %	108	7.8 %	147	0.25
Death	15.7 %	544	11.4 %	337	39.6 %	207	0.0001	16.1 %	255	15.4 %	289	0.57

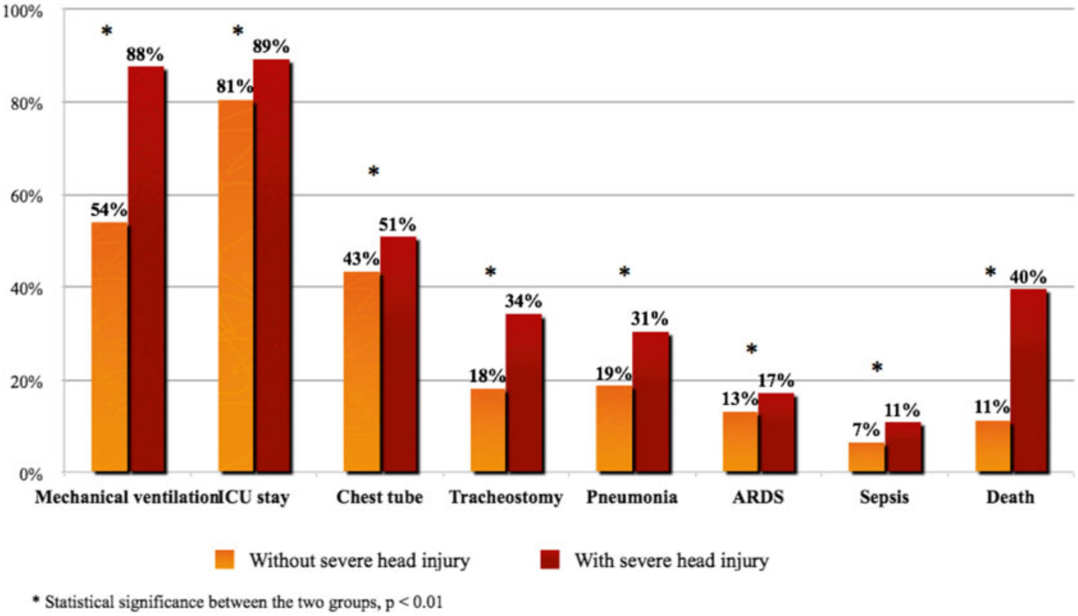

Fig. 14.3 Comparing outcomes for patients with flail chest injury with and without concurrent severe head injury [8]

(61 vs. 56 %, $p<0.005$), length of time on the ventilator (7.3 vs. 7.0 days, $p<0.016$), need for ICU admission (84 vs. 80 %, $p<0.003$), days spent in the ICU (9.9 vs. 9.2 days, $p<0.0032$), and total days in the hospital (17.1 vs. 16.1 days, $p<0.018$). Patients with pulmonary contusions also had higher rates of chest tube requirement (47 vs. 42 %, $p<0.003$) and pneumonia (22 vs. 19 %, $p<0.013$). There were no differences with regard to rate of ARDS, tracheostomy, sepsis, or death (Fig. 14.4).

While differences between these two patient groups were statistically significant for several outcomes, the magnitude of the difference was not as great as when comparing patients with the presence or absence of severe head injury. This may be due to utilizing diagnostic codes for identification of pulmonary contusion and a lack of clear definition or objective standard for the extent of contusion present. Pulmonary contusions are present in many patients with flail chest injuries and are commonly visible on computerized tomography (CT) of the thorax. However, the extent and severity of this entity are likely related to poor outcomes. There is currently no widely used grading system to classify the extent of pulmonary contusions, and there is a need for a more consistent method of diagnosis and classification of these injuries.

Summary

Patients sustaining a flail chest injury have significant morbidity, including ICU admission in 82 %, mechanical ventilation in 59 %, need for chest tube placement in 44 %, tracheostomy in 21 %, ARDS in 14 %, and sepsis in 7 %. There is also a high mortality rate of 16 %. Patients with concurrent severe head injury have significantly worse outcomes compared to those without a severe head injury. Patients with concurrent severe head injury or pulmonary contusions also have poor outcomes. Prior studies have suggested improvements with surgical fixation of these injuries; however, large-scale randomized trial in this area is lacking. More research in this area is warranted to help improve patient outcomes.

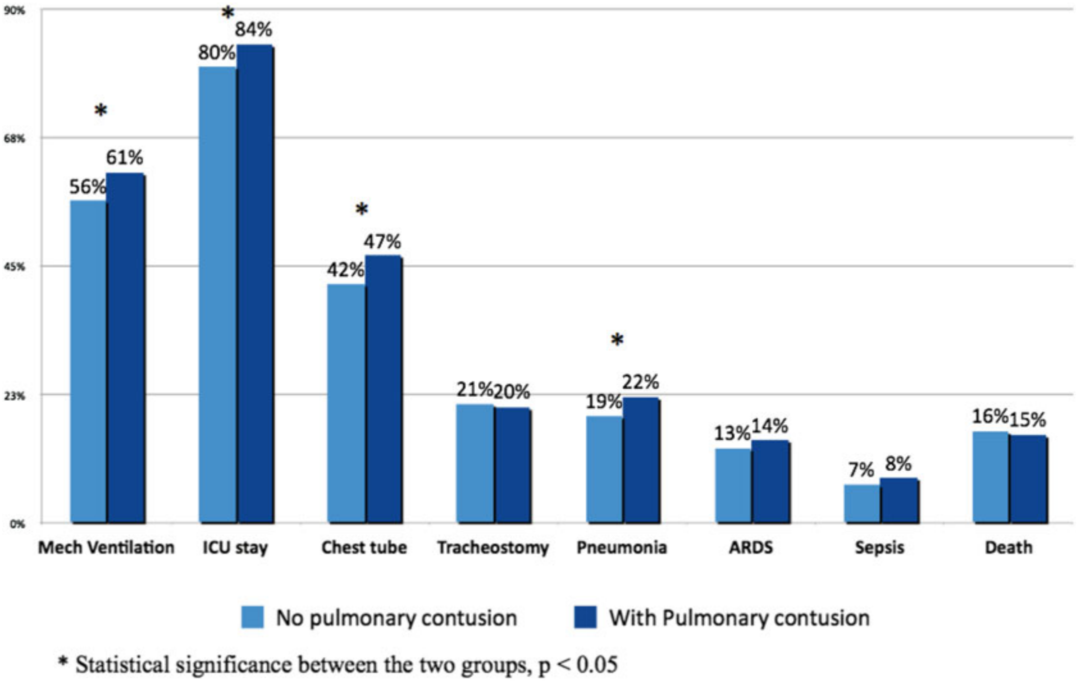

Fig. 14.4 Comparing outcomes for patients with flail chest injury with and without concurrent pulmonary contusion [8]

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15 Management of Associated Injuries (Clavicle and Scapula)

Peter A. Cole, Sara C. Graves, and Lisa K. Schroder

It is important to understand the suspensory complex which helps to link the axial and appendicular skeleton, defined by Goss as the *superior shoulder suspensory complex* (*SSSC*) [1]. This anatomical relationship consists of a bone and soft tissue "ring" at the end of a superior and inferior bony strut. The ring consists of the distal clavicle, acromioclavicular ligaments, acromial process, glenoid process, coracoid process, and coracoclavicular ligaments. The superior strut is the clavicle proximal to the coracoclavicular ligaments, while the inferior strut is the scapula. Combined, the scapula and the clavicle, their associated ligaments, together with the 18 muscles which act on or across the glenohumeral joint, provide a biomechanical platform for the function of the shoulder and upper extremity (Fig. 15.1).

Scapular and clavicle fractures are often associated with other injuries [2–5]. Commonly, they occur in conjunction with injuries to the chest wall, other portions of the SSSC, and ipsilateral fractures and dislocations. The increasing use of multidirectional CT in trauma patients has increased the detection and understanding of injuries to the shoulder girdle as well as other associated injuries. A recent review of the National Trauma Databank [6] compared patients with scapula fractures to a control group and found that the Injury Severity Score was nearly double in patients with scapula fractures (19.2 vs. 9.9). Interestingly, they found that the rate of associated rib fractures was 52.9 %, a similar rate to that found in a 1985 study [2] in which the proportion was 53.6 %.

Clavicle Fractures

Background

History

Clavicle fractures have been diagnosed and treated since antiquity. In 400 BC Hippocrates recommended a period of recumbence for those who had sustained a fracture of the clavicle: "It is of great importance, however, that the patient should lie in a recumbent posture. Fourteen days will be sufficient if he keep quiet, and twenty at most." [7] However, modern treatment has advanced considerably since this recommendation.

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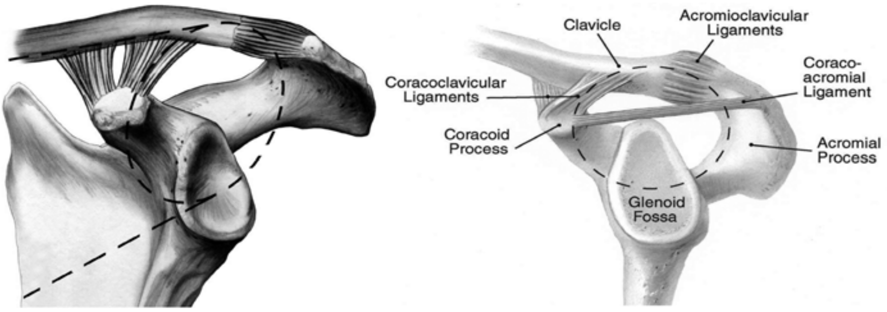

Fig. 15.1 The anatomical relationship defined by Goss [1] consisting of a bone and soft tissue "ring" at the end of a superior and inferior bony strut. The ring contains the distal clavicle, acromioclavicular ligaments, acromial process, glenoid process, coracoid process, and coracoclavicular ligaments. The superior strut is the clavicle proximal to the coracoclavicular ligaments, while the inferior strut is the scapula (Reproduced with permission. *Source*: Goss TP: Double disruptions of the superior shoulder suspensory complex. J Orthop Trauma. 1993;7(2):99–106)

Epidemiology

Clavicle fractures are the most common fracture in adults at 2–10 % [8–10]. In men, the incidence of clavicle fractures begins to decline after the age of 20; however, for women, the incidence is more constant with a tendency toward a bimodal distribution in adolescence and elderly age groups [8]. Mid-shaft fractures, representing over 75 % of the total, are most common and have a declining incidence with age [9].

Development

After birth, the clavicle continues to grow in length until the ossification centers fuse. The clavicle grows most rapidly in length prior to age 9 in girls and age 12 in boys [11, 12]. In the modern era, clavicles have been found to fuse at the age of 15 years on the average in women and 16 years of age in men.

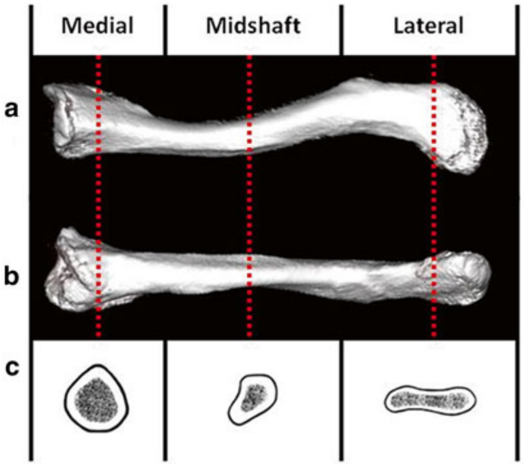

Fig. 15.2 Clavicle morphology viewed from superior to inferior (**a**) and anterior to posterior (**b**) with cross-sectional slices through medial, middle, and lateral segments (**c**). This morphology must be taken into account during implant placement and instrumentation

Anatomy

Osteology

The clavicle is an S-shaped bone with unique anatomical features. The name is derived from the Latin name for a similarly shaped musical instrument. The apices of the bone are anteromedial and posterolateral with a transition occurring approximately two thirds of the way from the sternal attachment. There is not a discrete medullary cavity associated with the bone as there is a capacious medial shape, tubular mid-portion, and flatter lateral portion (Fig. 15.2a–c). The two joints at either end are both diarthrodial joints, which have little inherent bony stability. They derive most of their stability from strong ligamentous and capsular attachments. The sternoclavicular joint is responsible for the majority of motion associated with the clavicle, with at least 35° of elevation-depression, 35° of protraction-retraction, and 50° of rotation. This contrasts with the acromioclavicular joint, which is responsible for much less motion [13, 14].

Attaching Muscle Groups/Deforming Forces

The carotid artery, vagus nerve, and jugular vein pass deep to the medial clavicle en route to the head and neck. The brachial plexus travels inferoposterior to the clavicle en route to the upper extremity. Deforming forces to the clavicle after injury include the sternocleidomastoid muscle which attaches to the superior border of the medial clavicle and the pectoralis major which attaches to the inferior border. The trapezius attaches to the superior border of the distal clavicle, while the deltoid originates from the distal/inferior clavicle. The conoid and trapezoid ligaments attach to the distal third of the clavicle and anchor it to the coracoid [15, 16]. The mid-portion is free of these muscular attachments and represents a weaker area of the bone. The different deforming forces lead to characteristic displacement patterns after fracture [17, 18].

Operative Dangers

With the anterior approach to the clavicle, the first structures encountered that should be identified are branches of the supraclavicular nerves (Fig. 15.3). These course from superior to inferior over the platysma musculature. The brachial plexus and subclavian artery and vein run inferior to the clavicle and are very closely approximated in the middle third of the bone (Fig. 15.4a, b). Inferior to the distal clavicle, the subacromial artery is encountered as well. This is relevant in the cases of inferior exposure of the bone in

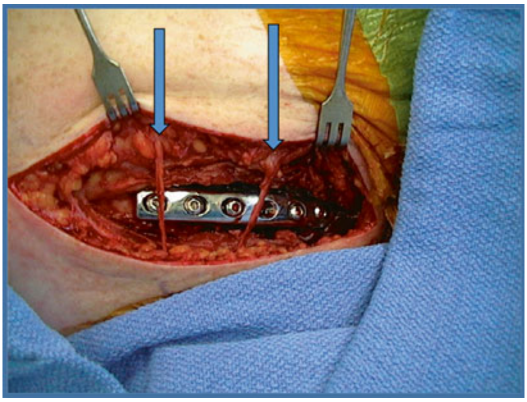

Fig. 15.3 An incision made for an open reduction and internal fixation of a clavicle fracture. The clavicle is post fixation, and crossing the wound, overlying the plate, are the two supraclavicular nerves (*arrows*), which have been protected. Sacrificing these nerves causes a patch of numbness inferior to the incision and is of little other consequence

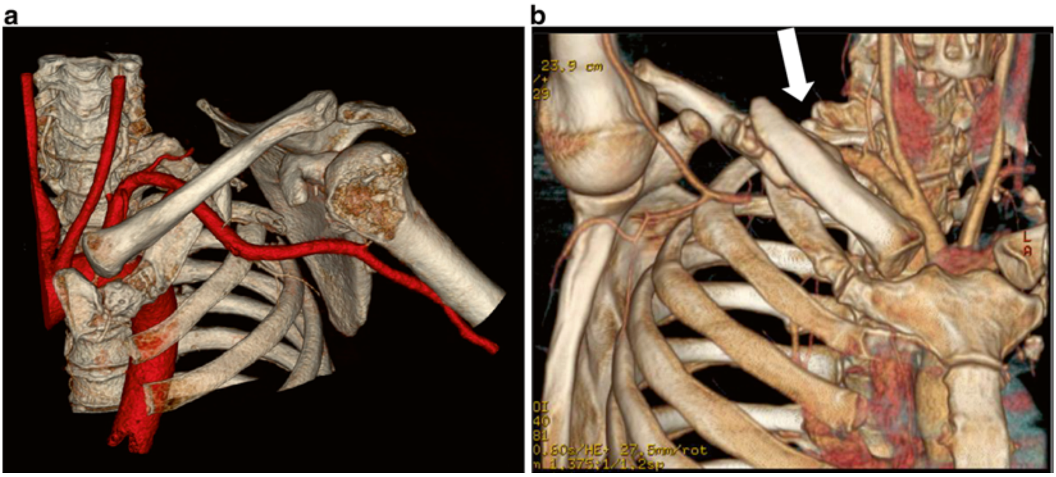

Fig. 15.4 Appreciate the intimate relationship of the subclavian artery in these arteriographic studies. (**a**) The artery is in *red* and the subclavian artery takeoff from the brachiocephalic trunk is easy to appreciate. (**b**) There is a middle one-third clavicle fracture, and the vulnerability during surgery to the subclavian vessels is easy to appreciate. The *white arrow* points to the crossover of the fractured clavicle and the subclavian artery

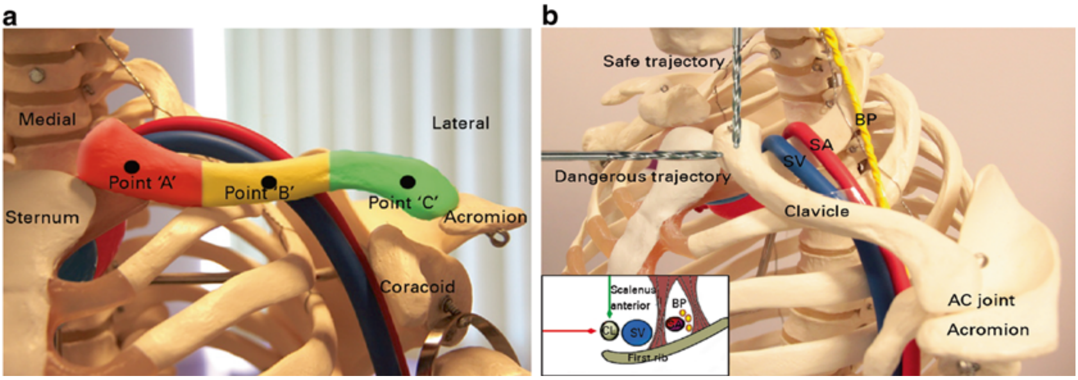

Fig. 15.5 This anatomical illustration details the relationship of the subclavian vessels to the clavicle. (**a**) An anterior to posterior orientation is shown in which a posteriorly directed drill puts the vessels at risk at the junction middle-distal 1/3rd and most medial 1/3rd of the clavicle. (**b**) A lateral to medial view illustrates both a safe and dangerous drill trajectory. Also shown with a *green arrow* (safe) and a *red arrow* (dangerous) in the inset illustration (Reproduced with permissions. *Source*: Sinha A, Edwin J, Sreeharsha B, Bhalaik V, Brownson P. A radiological study to define safe zones for drilling during plating of clavicle fractures. *J Bone Joint Surg Br*. 2011;93(9): 1247–1252. doi:10.1302/0301-620X.93B9.25739)

ensuring that inferiorly directed drills and screws are safely applied [19]. Knowledge of these anatomical relationships is critical during drill trajectory and orientation of instrumentation and implants (Fig. 15.5a, b) [20].

Classification

The Allman classification is most frequently used for clavicle shaft fractures. It divides the clavicle into anatomical thirds with the middle third being group I, the distal third group II, and the proximal third group III. These are in order of the frequency of appearance, with group I fractures representing 81 % of injuries, group II representing 17 % of injuries, and group III representing 2 % of clavicle fractures [9]. The Neer classification for distal third (Allman group II) fractures is based on whether or not the coracoclavicular ligaments are intact (Fig. 15.6) [21]. If they are intact, the fracture is at less risk for nonunion, but if torn, wider displacement is allowed and hence a higher risk of nonunion results.

Acromioclavicular Joint Dislocations

The acromioclavicular (AC) joint subluxates or dislocates when there is injury to one or more of the three important ligamentous structures which attach the lateral clavicle to the upper extremity. The coracoclavicular (CC) and coracoacromial ligaments as well as the AC joint capsule are responsible for the stability of the joint and when ruptured lead to characteristic injury patterns. Tossy and Allman developed classification schemes that describe the ligamentous injury and degree of displacement. Type I injuries represent partial tearing of the ligaments and are characterized by local AC joint tenderness: radiographs are normal. Type II injuries represent rupture of the capsule and AC ligament, but intact CC ligaments. There may be deformity and elevation of the clavicle, but this is limited to less than 1 cm. Type III injuries represent rupture of the AC capsule, and CC ligaments with pain, point tenderness, and plain films reveal complete dislocation. Rockwood later described three more severe injury patterns which are described according to the direction of displacement of the distal clavicle [22]. A type IV is complete disruption with the clavicle displaced posteriorly penetrating the trapezius. A type V is a more displaced version of a type III, where a type VI is when the clavicle is displaced and trapped caudal to the coracoid (Fig. 15.7) [22].

Clinical Evaluation

Clavicle fractures can occur with low- or high-energy trauma. Associated injuries (such as to the chest wall or scapula) should be ruled out.

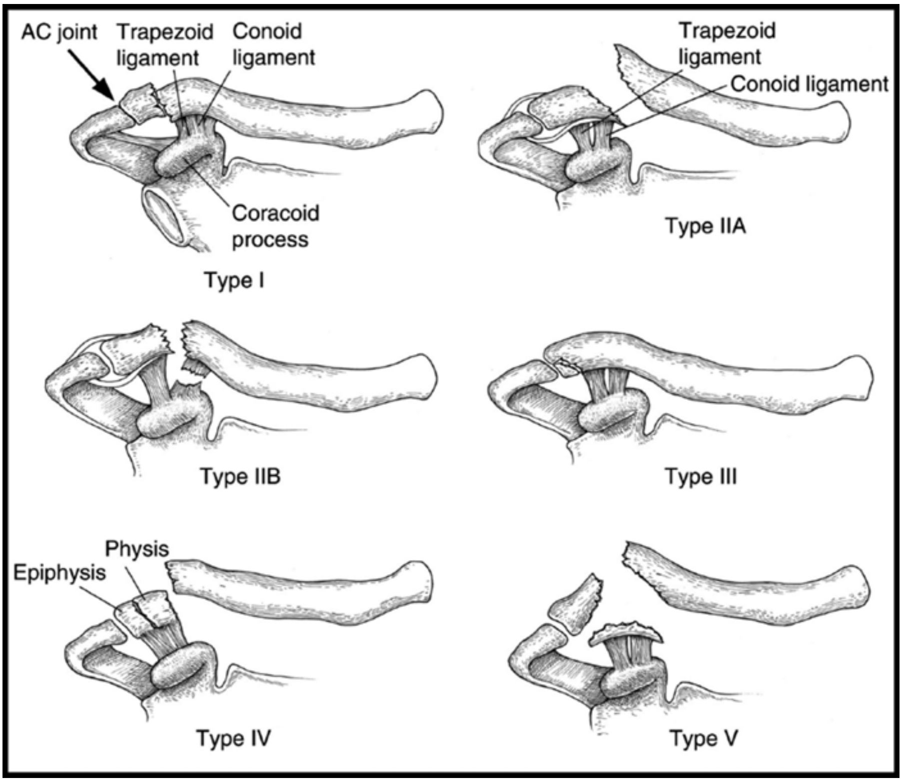

Fig. 15.6 Illustrated is Neer's lateral third clavicle fracture classification. Note the importance of the relationship to the coracoclavicular ligaments that distinguishes different patterns (Reproduced with permissions. *Source*: Banerjee R, Waterman B, Padalecki J, Robertson W. Management of distal clavicle fractures. *J Am Acad Orthop Surg*. 2011;19(7):392–401)

Given the relationship between the clavicle and the subclavian vessels and brachial plexus, close attention should be paid to a detailed distal neurovascular examination. The skin should be examined for the presence of an open fracture, severe tenting, or abrasions.

Initial radiographic imaging should consist of plain films, including a chest radiograph, which should be examined for associated thoracic injuries, including hemo- or pneumothorax and rib fractures. Clavicular films should be obtained. If patient comfort and absence of other injuries necessitating supine positioning allows, dedicated upright clavicle films should be obtained. Usually, advanced imaging modalities to assess the clavicle itself are not necessary. A CT scan can be useful to assess for other injuries in patients with a high-energy mechanism or in cases where a pathologic fracture is suspected. The protocol we use at our institution includes a supine and upright 15° caudal tilt view and a bilateral clavicle view to include both AC joints (Fig. 15.8a–c). Radiographic protocols for clavicle fractures continue to evolve.

Nonoperative Treatment

Nonoperative treatment has been the mainstay of treatment for the majority of clavicle fractures until recently. Improved clinical outcomes have not been demonstrated for any strategy over simple sling immobilization with early shoulder and elbow range of motion. Specifically, sling versus figure of eight brace immobilization have been proven to result in no difference in outcome [23].

There have been several recent randomized studies demonstrating lower symptomatic nonunion

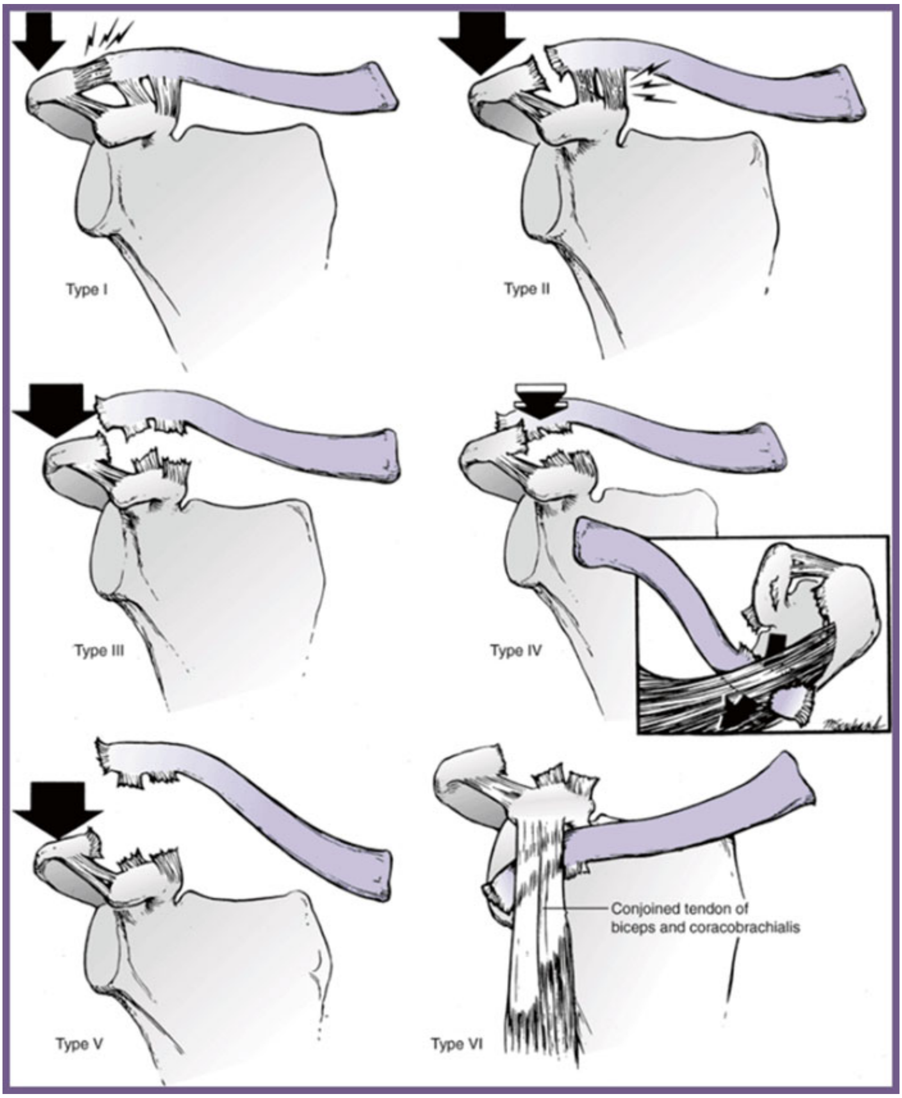

Fig. 15.7 Illustrated is the Allman acromioclavicular (AC Separation) classification which was expanded by Rockwood. Type IV and V separations are absolute indications for surgery, whereas type III surgery is controversial and probably suited only for young and active patients or to accomplish cosmetic goals (Reproduced with permissions. *Source*: Galatz LM, Williams Jr GR. Acromioclavicular Joint Injuries. In: Bucholz RW, Heckman JD, Court-Brown CM, eds. *Rockwood & Green's Fractures in Adults*. 6th ed. Lippincott Williams & Wilkins; 2006:1331–1364)

rates and better functional outcomes with reduction and operative fixation of displaced mid-shaft clavicle fractures in young (16–60 years of age), active patients, though this carries the risk of hardware irritation and the possibility of wound complications. Another relative indication for surgery is the displaced "floating shoulder" with dual injuries to the SSSC. It is important to be aware of the risk/benefit ratio for both operative and nonoperative treatment and discuss these issues with patients in a combined decision-making process.

Patients should be followed closely until the fracture consolidates with repeat upright clavicle films at weekly intervals for 3 weeks to ensure displacement remains within acceptable parameters because progressive displacement has been shown (Fig. 15.9a–c) [24]. During this period, elbow and shoulder range of motion should be encouraged.

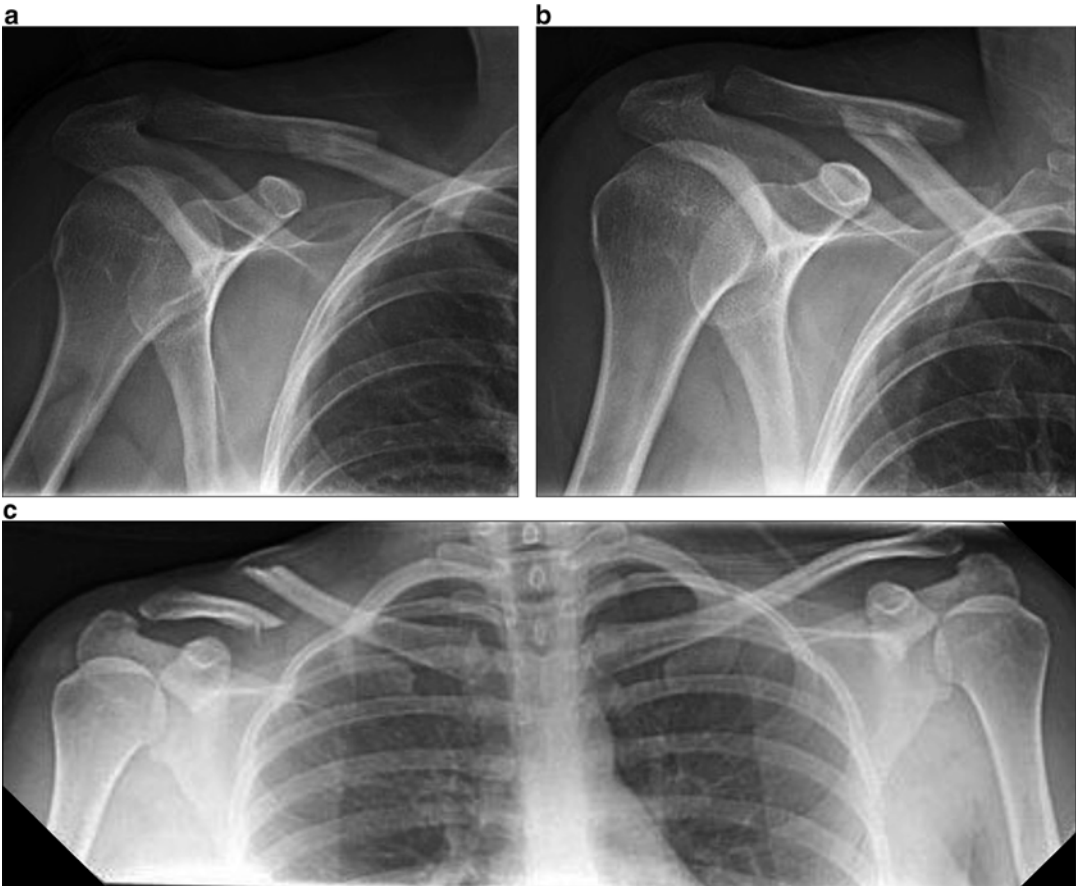

Fig. 15.8 Examples of plain radiographic imaging techniques with the patient in the supine position (**a**) and upright (**b**). (**b**) Shows increased displacement on upright films performed just after supine imaging (**a**). (**c**) Demonstrates medialization that is comparable and measurable on a bilateral upright clavicle film

Operative Treatment

Indications

For completely displaced mid-shaft clavicle fractures, several recent randomized studies have shown lower rates of nonunion, symptomatic nonunion, and higher functional outcome scores with open reduction and internal fixation [25, 26]. The rate of nonunion after the nonoperative treatment of mid-shaft clavicle fractures has been reported to range from 5 to 25 %. A 2013 retrospective review of 941 patients with nonoperatively treated displaced mid-shaft clavicle fractures by Murray and Robinson found a nonunion rate of 13.3 %. In multivariate analysis, smoking, comminution, and fracture displacement were most predictive of nonunion [27].

Functional outcomes have been shown to be better at most time points overall for patients treated with primary operative fixation [25]; however, these differences diminish when symptomatic nonunions are excluded [26]. Symptomatic malunion rates are also higher in nonoperatively treated patients [28]. An example of clavicular malunion with clinical deformity following nonoperative treatment is shown in Fig. 15.10. However, some have argued that good outcomes can be achieved in this setting by late reconstructive surgery and that the higher attendant costs and risks of primary operative fixation are not justified [29]. An understanding of the indications for operative treatment will continue to improve as further randomized studies delineate prognostic factors for poor outcome following closed treatment [30].

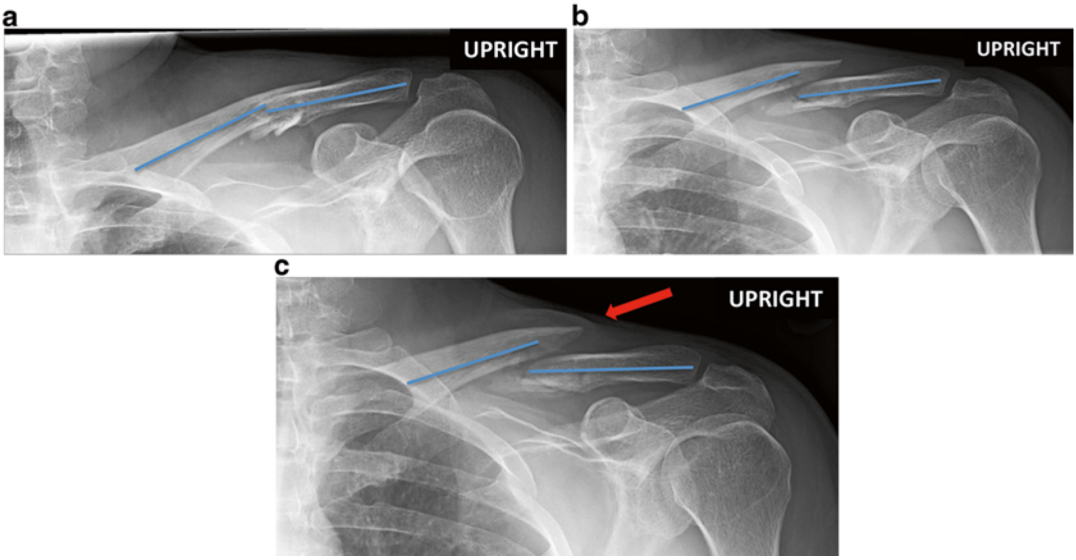

Fig. 15.9 (**a**) is an X-ray of an injury showing a middle 1/3rd clavicle fracture with minimal angular deformity or medialization. (**b**) and (**c**) demonstrate incremental displacement at 7 and 14 days after injury, respectively. This sequence shows the importance of serial radiographs at weekly intervals to assess displacement and determine surgical indications

Fig. 15.10 Cosmetic deformity associated with clavicle malunion. One can appreciate a common complaint, in which straps slip down the shoulder

Medial third clavicle fractures are relatively rare accounting for <5 % of injuries to the clavicle; however, the degree of displacement is also linked to the risk for nonunion. Lateral third clavicle fractures with ruptured coracoclavicular ligaments are also associated with higher nonunion rates [28]. The precise degree of displacement associated with an unacceptably high risk of symptomatic nonunion and diminished function remains to be determined: patient selection is highly relevant in the proper decision for surgery.

Surgical Technique

The surgeon should preoperatively analyze the fracture pattern and displacement with the plan to restore length, alignment, and rotation. The patient is positioned in the beach chair position with all bony prominences well padded. The ipsilateral limb should be prepped to aid in fracture reduction and allow for easier restoration of length, alignment, and rotation. The patient's anatomy is marked for a proper incision which should be just caudal to the bony prominence so hardware is not directly beneath the incision.

Plate Fixation

The length of plate fixation depends on the quality of the bone, the degree of comminution, the type of plate, the age of the patient, and their anticipated compliance. Plate placement can be in the superior or anterior position. Anterior plate

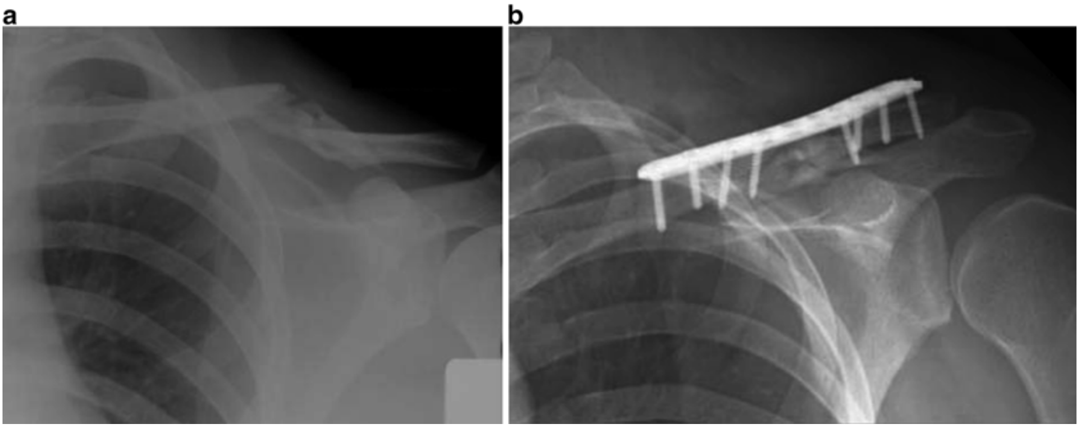

Fig. 15.11 (**a**–**b**) Bridge plating technique for a shortened comminuted clavicle fracture. Using this technique, the surgeon must preserve blood supply and employ a low strain zone over a longer working length of the plate; otherwise, the plates will be too stiff for the anatomy prescribed for this technique

placement was shown in one biomechanical cadaveric study to provide greater stiffness [31], and it has been associated with less prominence of the plate and diminished risk of injury to nerve or vessels and failure of fixation [32, 33]. However, superior plating remains more common in clinical practice [33], is familiar for most surgeons, and may yield a biomechanical advantage in middle third clavicle fractures over anterior plating.

The incision is taken down through subcutaneous tissue to expose the fascia surrounding the platysma musculature. The platysma is then cut directly to the periosteum, and cautery is useful for this vascular plane. A thick cuff is preserved to facilitate later repair. Any identified cutaneous branches of the supraclavicular nerve, usually present more medially within the platysma muscle, are preserved to prevent peri-incisional numbness. The patient should be warned of this potential for numbness preoperatively so expectations are managed. Minimal, but sufficient, periosteal dissection to allow for fracture exposure, reduction, and plate placement is performed. Careful retraction should respect posterior and inferior vital structures. Bone reduction forceps can be placed on either end of the fracture and used to manipulate the bone fragments back into position. Free draping of the arm allows elevation and rotation to achieve the appropriate alignment is useful and minimizes soft tissue trauma in obtaining reduction. Once aligned, bone reduction forceps placed in pilot holes on each side of the fracture can be used when stable bone ends allow for compression. K-wires can be used to provisionally hold large butterfly fragments. Greater comminution should be bridged, and devascularization and exposure of the comminution zone should be avoided. In such cases, the fracture is fixed distally first, and the plate used as a reduction aid to restore length and rotation. With the fracture reduced, lag screw fixation is employed when possible. Small, comminuted fragments that cannot be captured with lag screw fixation can be fixed in location with suture, and such fractures should be spanned with a plate in the bridging mode (Fig. 15.11a, b). A plate of the appropriate size is selected and contoured to the patient's anatomy. The goal should be a minimum of three bicortical screws on each side of the fracture. Straight dynamic compression plates are often prominent, while pelvic recon plates may not be strong enough for the forces acting on the fracture: for these reasons, the implant of choice is a pre-contoured compression plate designed specifically for clavicular fixation.

A single flat-plate radiograph or C-arm image should be obtained prior to closure to ensure that no screw tips are prominent as brachial plexus irritation or trauma to the subclavian artery or vein has been reported. It can be helpful to place a flat plate behind the patient's shoulder prior to prepping and draping, so that the cassette is in position for good imaging without disruption of the sterile field after fixation. Closure of the platysma and fascia as one layer is performed using 2-0 braided sutures. The subcutaneous tissues are re-approximated with inverted sutures, and the skin is best approximated with subcuticular absorbable monofilament suture that provides a cosmetic closure.

Intramedullary Nail Fixation

For simple, non-comminuted fracture patterns, intramedullary fixation is an attractive option as it requires less operative dissection [34]. Historically, Rockwood [35, 36], Hagie [37–40], and Knowles [41] pins were used for intramedullary fixation of clavicle fractures, but particularly in comminuted or rotationally unstable fracture patterns, they have been associated with high rates of implant failure and infection due to hardware prominence at the insertion site [36, 37]. Intramedullary nailing is demonstrated in Fig. 15.12a, b. Another technique is the use of titanium elastic nails [41]. The technique described for this includes the use of a medial opening point on the clavicle using an awl or a drill, followed by closed or mini-open reduction of the fracture and advancement of the nail past the fracture site. Nails are removed after fracture union. These have good results in several small case series and retrospective studies [41–43]. Other nailing systems have recently been developed and allow for locking and length-stable fixation which is an attractive option: it remains to be seen what their exact role will be in this area.

Distal Third Clavicle Fractures

Distal clavicle fractures and acromioclavicular separations represent a surgical challenge to treat due to the frequent lack of bone to support fixation at the end of the clavicle. Furthermore, the deforming forces are strong and differ depending on whether the injury is a pure dislocation of the AC joint or a distal clavicle fracture with disrupted CC ligaments. The deforming forces cause superior migration of the proximal segment, while the distal segment often caudally displaces because of the force of gravity and muscular contractions across the shoulder. Pre-contoured locking plates which allow for fixation in osteoporotic bone can be useful as well [41]. These implants take advantage of multiple distal clavicular screws at different vectors to maximize purchase in the short distal segment. These plates can also be augmented with a repair of the coracoclavicular ligaments, a treatment combination which may enhance stability [44]. Alternatively, simple reconstruction of the coracoclavicular ligaments in isolation with tape or an endobutton technique has also been used successfully in isolation [45, 46] but may be more vulnerable to failure (Fig. 15.13a, b).

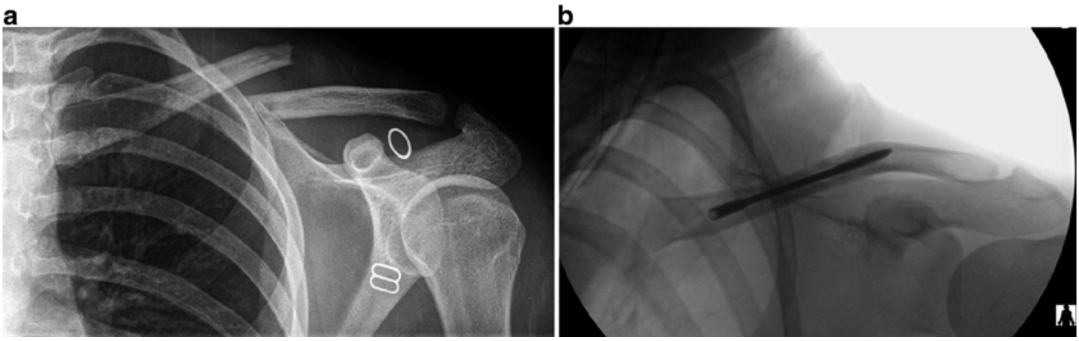

Fig. 15.12 Pre- (**a**) and postoperative (**b**) images of a clavicle fracture fixed with a nail. This transverse midshaft clavicle fracture is perfectly suited, because it can be reduced closed or with a mini-open technique minimizing the scar. Comminuted clavicle fractures may be rotationally and axially unstable after nailing and lead to malunion

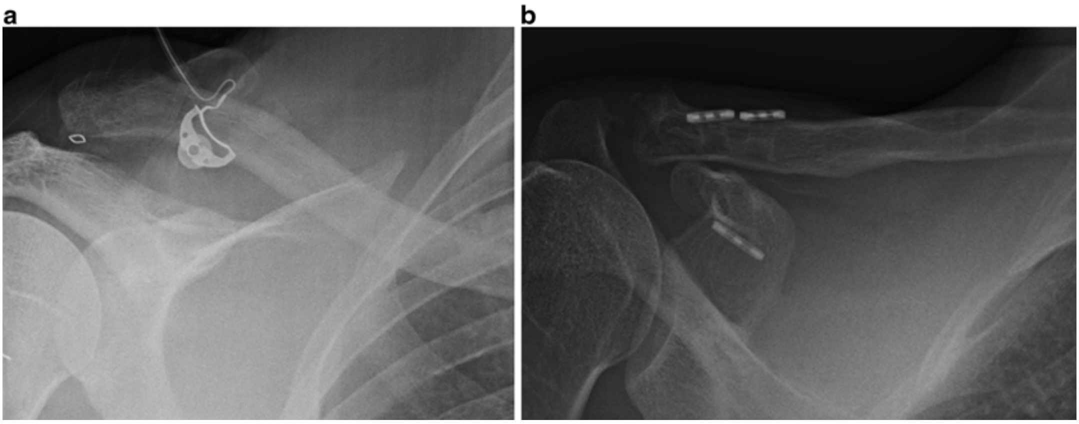

Fig. 15.13 A pre- (**a**) and postoperative (**b**) image of an acromioclavicular dislocation which was fixed with a tightrope technique in which two heavy fiber wire suture are passed through the clavicle and coracoid, both tethered to their respective bones and tied over small metal stays to help prevent cutout

For far lateral clavicle fractures, it is often difficult to obtain sufficient purchase in the distal fragment with plate fixation: in such cases, a specially contoured hook plate (Synthes Depuy, USA, Paoli, PA) has been used [47] which is slid beneath the acromion posterior to the AC joint. This implant allows for screw fixation into the clavicle, while the distal hook levers under the neck of the acromion (Fig. 15.14a–c). These typically need to be removed after fracture union because the implant does cross a mobile joint, and osteolysis and fracture of the acromion has been reported [48]. The hook plate is also a viable treatment option for isolated AC joint dislocations.

Sternoclavicular Dislocations [49–53]

Sternoclavicular dislocations occur as a result of direct trauma or indirect forces through the shoulder. In skeletally immature patients up to approximately 20 years, medial physeal fractures can be mistaken for dislocations. Dislocations are either anterior or posterior. Concomitant injury to mediastinal structures in posterior dislocations must be ruled out. These may include injuries to the trachea or larynx, and esophagus. The brachiocephalic trunk and neurologic injury to the phrenic nerve should be ruled out with a thorough history and physical examination. A CT angiogram or arteriography is indicated in posterior dislocations to assess the great vessels for injury that may include intimal damage, pseudo-aneurysm, or simple compression. These findings will help guide treatment.

When attempting manipulation of the posterior dislocation, it is important to have communicated directly with a cardiac surgeon so that they can be on standby in the event of a major arterial hemorrhage. This is imperative if a preoperative arteriographic radiography has not been done or has shown any abnormality. Postreduction clinical examination and observation are mandatory. In the acute setting, closed reduction and stabilization is recommended for both anterior and posterior dislocations to restore anatomy, reduce deformity, and improve long-term function. The decision to proceed with open reduction if closed reduction is unsuccessful depends on the health and activity level of the patient. Physeal disruptions are also amenable to operative fixation. In such cases, a plate is used to capture the medial fragment, ideally with locked fixation to avoid loosening and pullout (Fig. 15.15a–e). Suture fixation alone with heavy-braided suture is possible. These patients must be immobilized for approximately 2 weeks because they can experience cutout due to deforming forces.

For closed reduction of anterior dislocations, the patient is placed supine with a pad between the shoulders, and direct pressure is applied on the

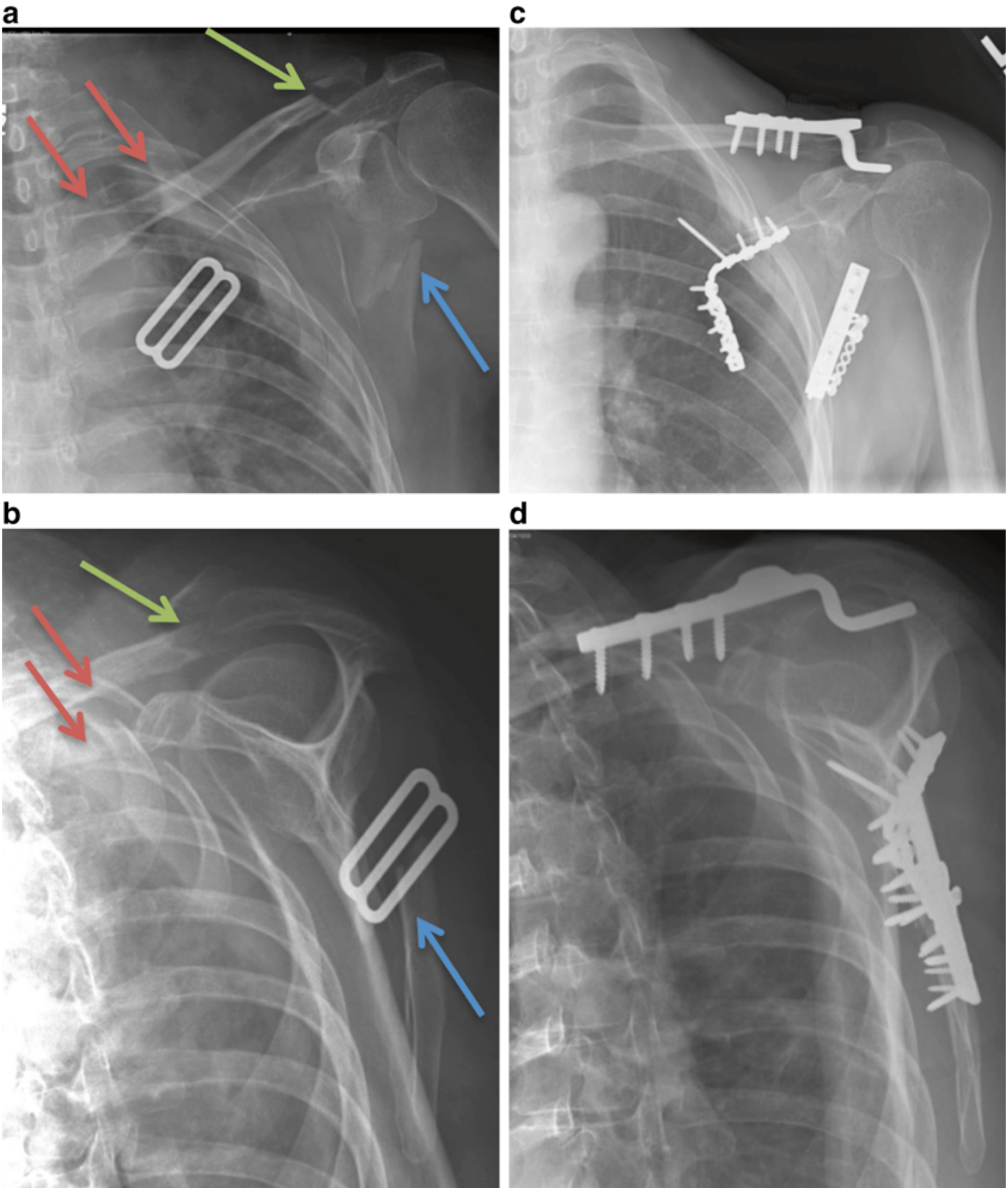

Fig. 15.14 Illustrative example of a hook plate (Synthes USA, Paoli, PA) fixation of a lateral third clavicle fracture (*green arrow*) with ipsilateral scapula (*blue arrow*) and no. 2 and no. 3 rib fractures (*red arrows*) as seen preoperative anterioposterior (**a**) and scapula Y (**b**) radiographs. Following consolidation of all fractures as seen on the anterioposterior (**c**) and scapula Y (**d**) follow-up radiographs, the patient underwent hook plate removal

medial clavicle in a posterior direction. These can be quite stable after reduction: if not, an open reduction may be indicated in a high-demand patient. The technique for posterior dislocation involves the placement of a pad between the scapulae; traction is applied to an extended/abducted arm with counter traction or posterior pressure applied to the shoulder. A sterile towel clip can also be used percutaneously to grasp the medial clavicle and reduce it (Fig. 15.16a).

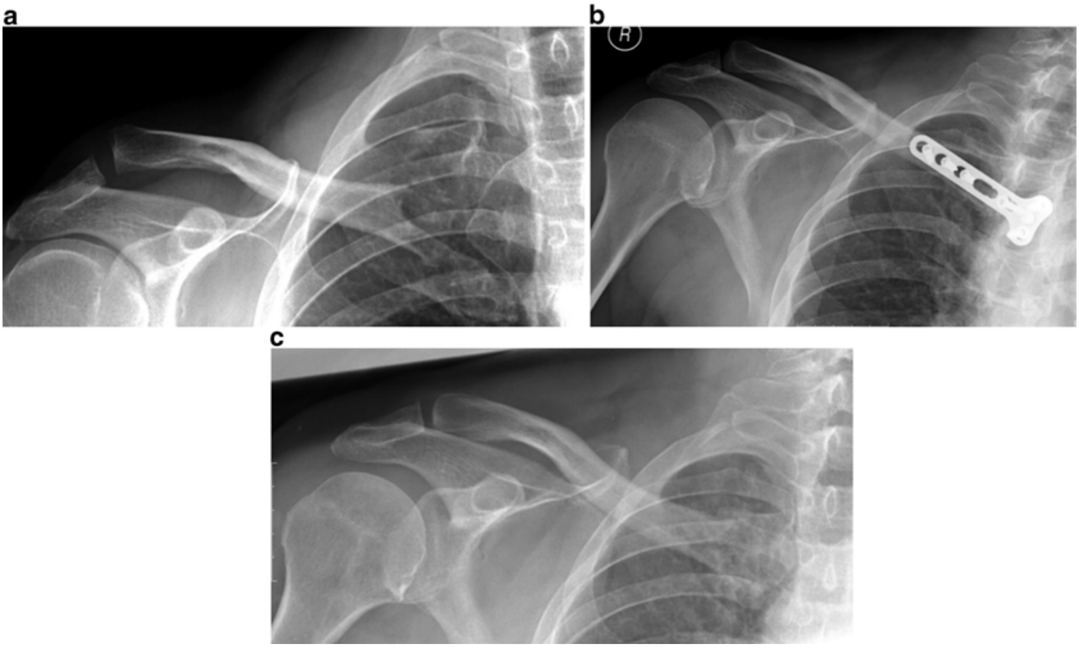

Fig. 15.15 Example of locking plate fixation of a medial third clavicle fracture dislocation injury (**a**), postfixation (**b**), and healed following hardware removal (**c**) anterioposterior X-rays

Posterior dislocations are frequently stable once reduced, but if closed reduction fails, open reduction and stabilization is performed with heavy-braided suture repair of the capsule and periosteum (Fig. 15.16b, c). Ligamentous reconstruction has been described, but typically for chronic dislocation variants and they are fraught with high failure rates. The authors' preferred management strategy for painful chronic dislocations is medial clavicle resection with imbrication of the scar tissue and capsule. Generally patients are very satisfied with resolution of both deformity and pain. The use of smooth pins for stabilization of dislocations is to be avoided due to the potentially catastrophic complication of pin loosening and migration.

Scapula Fractures

Background

History

In the first description of a scapula fracture in 1579, Dr. Ambroise Pare wrote, "When the fracture involves the neck of the scapula the prognosis is almost always fatal, as was also the case of some famous people, for instance the King of Navarre." It is unclear whether it was the fracture itself that he thought the mortality was attributable to or to the likely associated injuries. Other French surgeons such as Jean-Louis Petit, Joseph Guichard Duverney, and Pierre-Joseph Desault furthered the classification and treatment considerations of scapula fractures. Albin Lambotte is credited with the first internal fixation of a scapula fracture in 1911 [54].

Epidemiology

In a Massachusetts General Hospital study from 1938, the incidence of scapula fractures was found to be 1 % of all fractures. A study in the Swedish population from 1995 found an incidence in the population of 0.01 % [55]. Scapular fractures are associated with large amounts of force imparted: concurrent injuries are present in up to 85–95 % of cases [2, 3, 6, 56]. The most frequently associated injuries were rib fractures (52.9 %), lung injury (47.1 %), and head injury (39.1 %) in a 2008 National Trauma Data Bank retrospective review by Baldwin et al. [6].

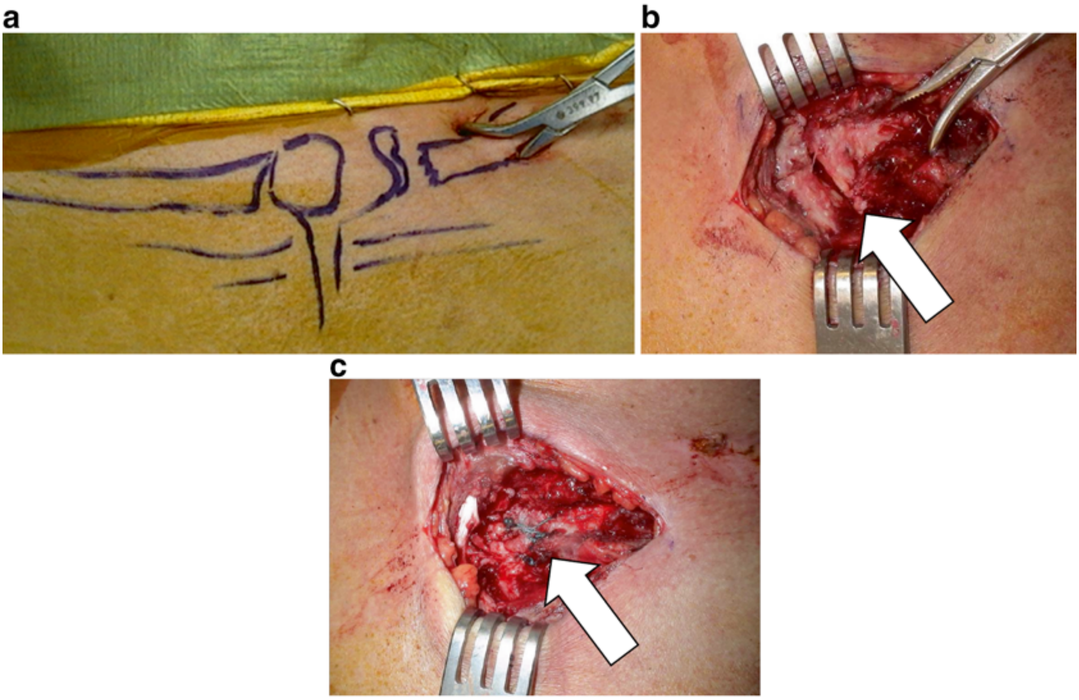

Fig. 15.16 An 18-year-old patient with proximal clavicle physeal dislocation. Closed reduction was possible with percutaneous application of a towel clip, as shown (**a**). Due to instability, the dislocation was exposed (**b**) and heavy-braided suture used in repair (**c**). The dislocation (**b**) and suture repair (**c**) are indicated by the *white arrows*

The results reported in their paper are shown in Table 15.1. Approximately 13 % of scapula fractures have associated neurovascular injuries that are important to identify prior to the initiation of treatment. The axillary and suprascapular nerves are most commonly injured, although other brachial plexus injuries can occur. The brachial, subclavian, or axillary arteries are injured in just over 10 % of fractures [2].

Development

Embryology

The scapula begins to form during 6–8 weeks of gestation at the level of the 4th–5th ribs. During further development, it descends under the direction of the apical ectodermal ridge. It undergoes intramembranous ossification. There are several well-described conditions associated with the normal development of the scapula. For example, in os acromiale, an (occasionally symptomatic)

Table 15.1 Frequency of associated injuries with scapula fractures in Baldwin's review of the National Trauma Database from 1994 to 2002 with 9,453 scapula fractures included in the study [6]

	Percentage sustaining (Baldwin National Trauma Database Study) (%)	Historical reports (%)
Rib fracture	53	44–53
Any lung injury	47	20–66
Head injury	39	20–45
Spinal fracture	29	10
Clavicle fracture	25	16–39
Upper extremity fracture	23	44–50
Lower extremity fracture	22	
Abdominal injury	17	3
Pelvic fracture	15	5–18
Facial fracture	12	9–20
Death before hospital discharge	6	0–14

segment of the acromion process is present in ~8 % of the population. This is a bilateral condition in 33.3 % of those who have it [57].

Anatomy

Osteology

The scapula is broad and curves with the posterior aspect of the thorax between the second to seventh ribs, and it serves as the insertion or origin for 18 muscles. Triangular in shape, it tapers from greater width along the lateral border, is thin in the middle, and medially there is a slightly developed vertebral border. It has three distinct processes and two articular surfaces as well as the scapulothoracic joint all with important roles. The scapular spine in the middle separates the infra- and supraspinatus muscle groups and is an attachment for the posterior deltoid and trapezius muscles. The scapular notch is near the base just medial to the coracoid, and in this notch, the overlying suprascapular artery is separated from the underlying nerve by the transverse scapular ligament. Compression of the nerve here at the notch leads to weakness of both the infra- and supraspinatus.

The coracoid process originates from the upper portion of the scapula and is oriented anterolaterally at 120–160°. It forms the attachment site for the coracoclavicular ligaments at its base, as well as the coracohumeral and coracoacromial ligaments. It is the origination site of the coracobrachialis, short head of the biceps, and pectoralis minor. The acromial process articulates with the clavicle at the acromioclavicular (AC) joint and is the insertion site for the deltoid laterally. The rotator cuff tendons pass below it. The geometry of the acromion varies among individuals from a flat surface, to a gentle curve, to a hooked shape.

The glenoid is retroverted approximately 5°, with 10–15° of upward inclination, although the degrees of inclination vary between individuals. The glenohumeral joint has the least bony constraint of any joint in the body. The glenohumeral ligaments attach here and increase the stability of the shoulder joint. The broad, flat portion of the scapula on its anterior surface serves as the origin of the subscapularis. The scapula is balanced and moves through concerted motion of the muscles that attach on its surface. Injury to the long thoracic nerve or serratus anterior dysfunction causes medial winging of the scapula (Fig. 15.17). Injury to the spinal accessory nerve or trapezius causes lateral winging with shoulder depression and inferior angle lateral rotation.

Fig. 15.17 A clinical photograph of an 18 year-old male with an injury to the long thoracic nerve or serratus anterior dysfunction causing medial winging of the right scapula

Classification

There are a number of different classification schemes depending on which part of the scapula is injured. Fractures of the coracoid can be classified by the Ogawa classification, in which a type I fracture is posterior to the coracoclavicular ligament and is associated with other shoulder injuries. A type II fracture is anterior to the coracoclavicular ligament and can usually be treated nonoperatively [58]. The Eyres classification [59] divides coracoid fractures into the tip (I), midbody (II), base (III), with scapular body involvement (IV), and with glenoid involvement (V) with A and B suffixes denoting additional injury to the SSSC.

The Ogawa classification for acromion fractures divides them into lateral and medial, based on their extension to the spinoglenoid notch [60].

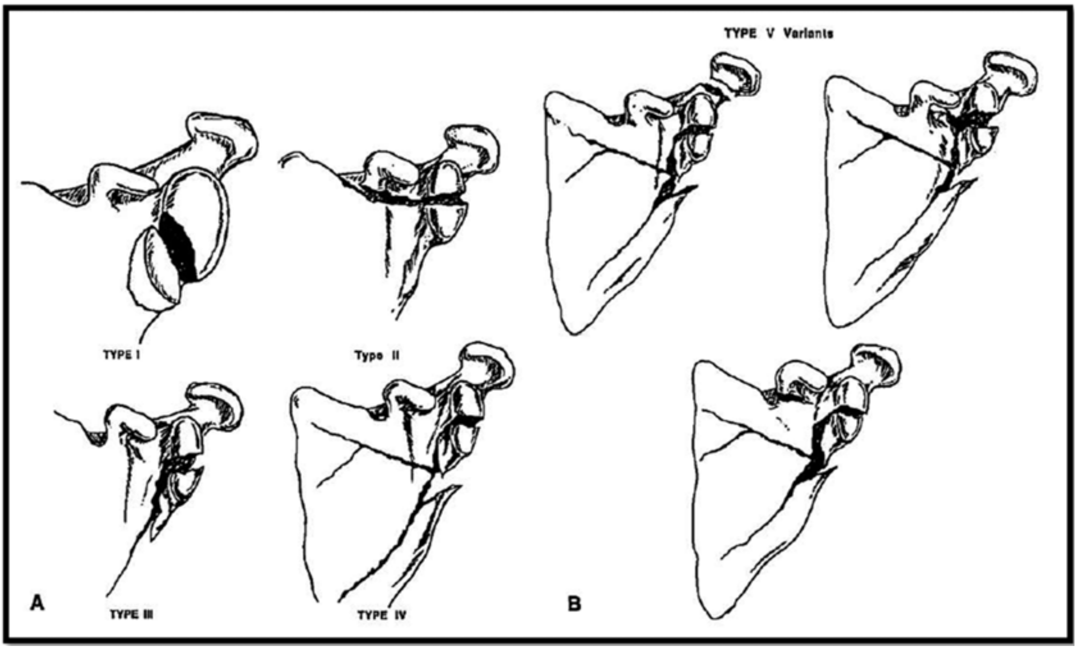

Fig. 15.18 Modified Ideberg classification of scapular glenoid fractures (Reproduced with permissions. *Source*: Mayo KA, Benirschke SK, Mast JW: Displaced fractures of the glenoid fossa. Results of open reduction and internal fixation, Clin Orthop Relat Res 347:122–130, Febr 1998)

Kuhn also proposed a classification system that classifies acromial fractures by the location, direction, and degree of displacement. A type III reduces the subacromial space and therefore requires treatment [61].

Glenoid fractures and scapular body fractures can be classified by the modified Ideberg classification (Fig. 15.18) [62]. The AO foundation also proposed a classification system, based on fracture pattern and location [63].

Clinical Evaluation

History and Physical Examination

Given the extremely high rate of associated injuries with scapula fractures, it is critical to perform a thorough evaluation for other areas of pain or discomfort. Any other potential area of injury should be appropriately followed up with imaging and necessary surveillance. A thorough history and complete physical examination should be performed. Pre-injury activity level, functional status, and surgical risk factors should be obtained. A detailed physical examination to rule out other injuries and assess neurovascular status including the suprascapular and axillary nerves should be performed. Abrasions or degloving injuries over the scapula should be accounted for in planning treatment and potential incisions (Fig. 15.19).

Radiographic Evaluation

The initial radiographic imaging for scapula fractures should include a chest radiograph, AP (Grashey), scapula Y, and axillary views of the shoulder joint. The clavicle should also be assessed as a part of the initial work-up.

Intra-articular involvement and degree of displacement should be determined. Intra-articular involvement should be assessed by CT scan. Criteria assessed on the initial radiographs include the glenopolar angle, angular deformity, and medialization or lateral border offset [64]. Definitions for these are as follows:

Glenopolar angle—On the AP view of the scapula, the glenopolar angle is the angle between a line drawn from the inferior glenoid to superior glenoid and a line from the superior glenoid to the inferior angle of the scapula (Fig. 15.20a).

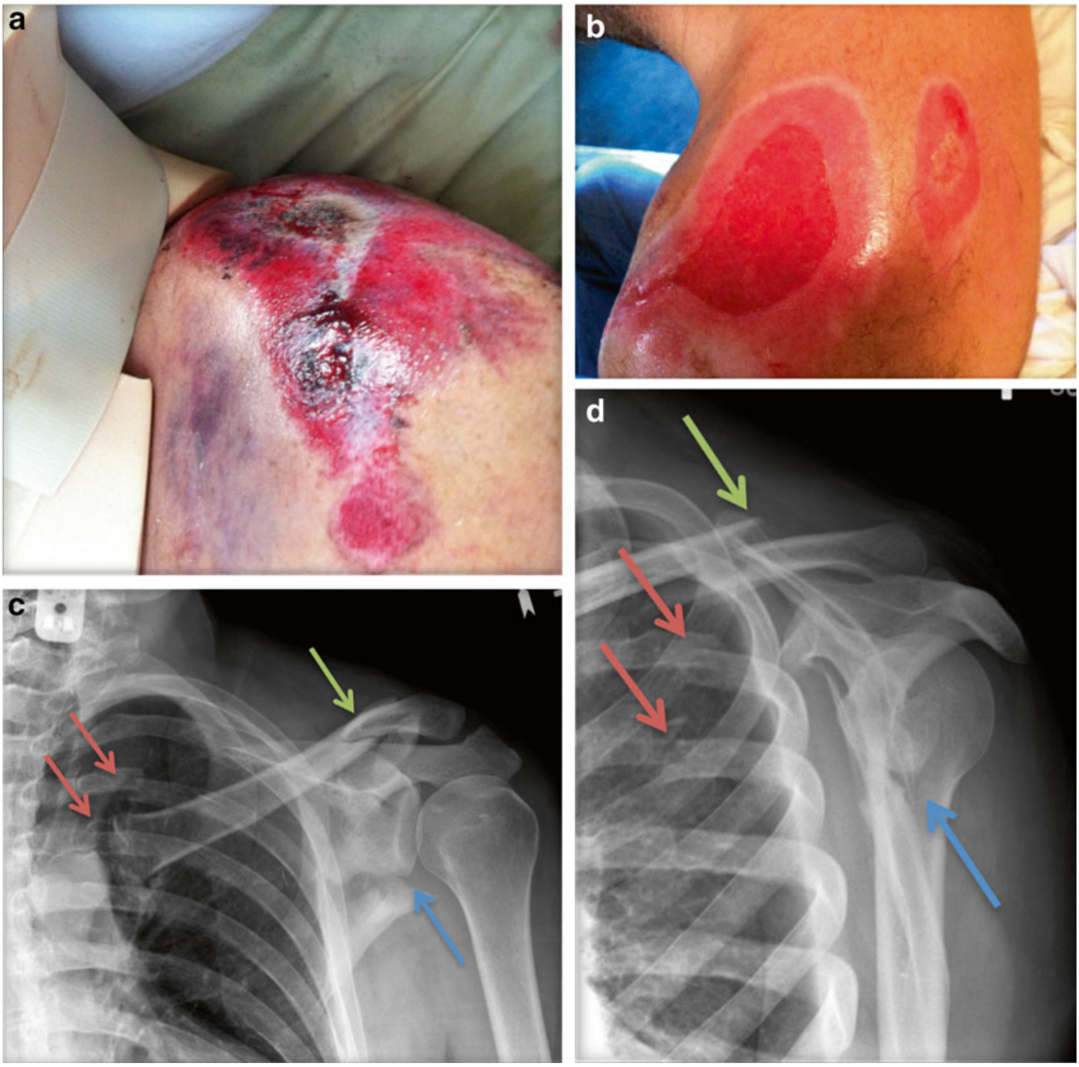

Fig. 15.19 (**a**) A clinical image of the skin abrasion in a patient having a severe high-energy shoulder girdle injury involving the clavicle (*green arrows*), scapula (*blue arrows*), and ribs no. 3 and no. 4 (*red arrows*) as seen in the anterioposterior (**b**) and scapula Y (**c**) injury radiographs. Operative repair is delayed until skin re-epithelialization occurs to reduce the risk of postoperative complication (**d**)

Angular deformity—is measured on the scapular Y view and is measured from lines parallel to the proximal fragment and distal fragments (Fig. 15.20b).

Lateral border offset—represents the width of displacement of the lateral border proximal fracture apex to its originating location inferior to the glenoid. This is also referred to as "medialization of the glenoid," but as there are degrees of glenoid medialization and scapula body lateralization, lateral border offset is a more accurate term (Fig. 15.20c) [64].

Advanced Imaging Indications

If the initial imaging reveals significant displacement, then a CT scan is the advanced imaging of choice for precise determination of preoperative displacement and for operative planning purposes [65]. If the patient has already received a CT scan as a part of their initial trauma evaluation, 3D

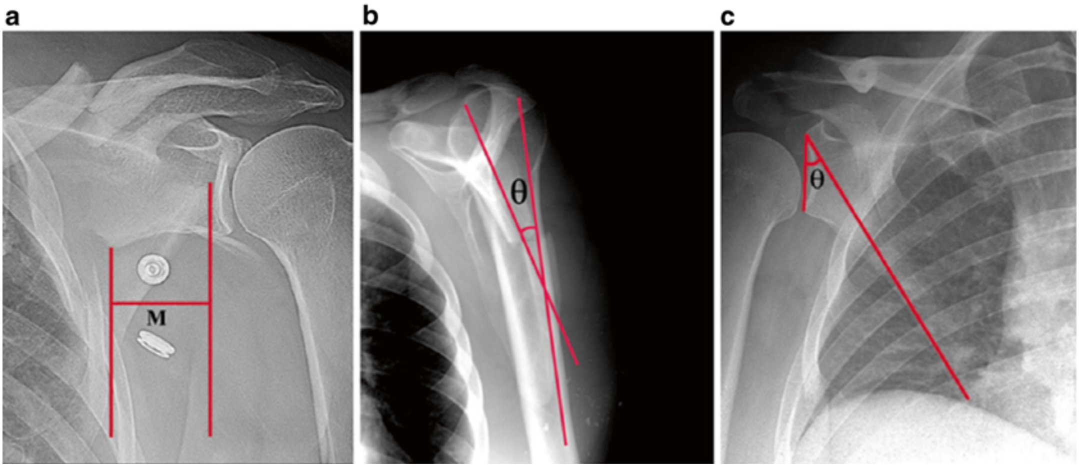

Fig. 15.20 (**a**–**c**) Initial measurement of displacement for scapular body fractures occurs, utilizing 2D radiographs. Medialization or lateral offset (**a**), angulation (**b**), and glenopolar angle (**c**) measurements are shown here

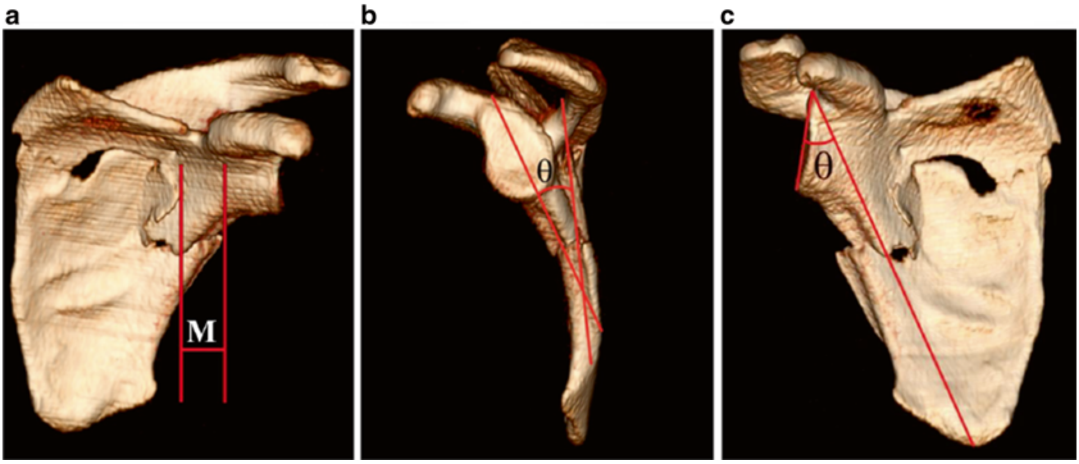

Fig. 15.21 (**a**–**c**) 3D reconstructions of the scapula are utilized to measure with a greater accuracy. Medialization or lateral offset (**a**), angulation (**b**), and glenopolar angle (**c**) measurements

reconstructions can be obtained and utilized to repeat radiographic measures of the scapula fracture with a greater accuracy (Fig. 15.21a–c).

Nonoperative Treatment

Nonoperative treatment has historically been the mainstay for most fractures of the scapula with the exception of displaced intra-articular fractures involving the glenoid and highly displaced body and neck fractures. Emerging evidence suggests that other fracture patterns which traditionally had been treated nonoperatively may have superior functional outcomes following operative fixation [66–71].

Indications for nonoperative treatment include non-displaced or minimally displaced fractures throughout the scapula. Nonoperative treatment for most scapula fractures entails sling immobilization with elbow and pendulum range of motion for 2–3 weeks with progressive gentle range of motion as tolerated. It is important to see the patient and obtain repeat radiographs at 1 week intervals after the injury to ensure further displacement has not occurred, until there is fracture

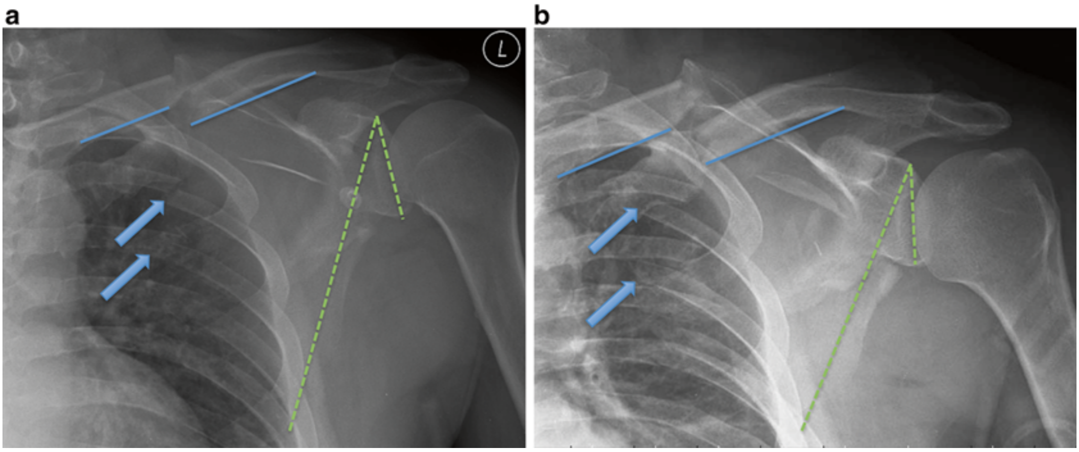

Fig. 15.22 This patient presented with a double disruption of the SSSC having both clavicle and ipsilateral scapula neck fractures with concomitant rib fractures. Though initially treated nonoperatively, this case illustrates a substantially unstable injury pattern which was initially a non-displaced fracture pattern (**a**). Serial radiographs taken at day 7 post-injury reveal a significant worsening of alignment despite immobilization (**b**)

consolidation [72]. This careful follow-up becomes particularly critical in the presence of associated rib fracture as the underlying support structure of the thoracic cavity is also compromised (Fig. 15.22a, b). Given the rich muscular and vascular envelope of the scapula, scapular fractures heal very quickly in most individuals. By 3 months, most patients can return to full activity.

Operative Treatment

Acromion

Fractures of the acromion can be managed nonoperatively if they are minimally displaced. The author's criteria for fixation include: (1) symptomatic nonunion (these are defined by an obvious fracture line on radiographs 6 months after injury with CT documentation or no progressive healing for 3 months with localized pain), (2) subacromial impingement (if the acromion tips into a caudad position due to the deforming forces of extremity weight and gravity, impingement can result), (3) displacement greater than or equal to 5 mm on radiographic examination, (4) open fractures, and (5) multiple disruptions of the SSSC [73, 74]. The surgical approach is dependent on the location of the fracture. Transverse fractures across the base or neck can be addressed with the patient in a lateral position and approached along the posterior border of the acromion just off the prominence. The deltoid is elevated from the posterior aspect of the spine and reflected with the infraspinatus to expose the fracture. Small fragment lag screws and 2.7 mm reconstruction plates can be applied to fix the fracture after it has been reduced. A thin superior plate can be used to augment fixation in comminuted variants and provides a tension band effect. More distal fracture patterns can be managed with tension band fixation along the posterior surface with mini-fragment plates or even a tension band figure of eight wire. In these specific fracture patterns, good or excellent results can be obtained in with regard to clinical outcomes [73].

Coracoid

Unstable, displaced fractures or fractures with other SSSC injuries can lead to discomfort and altered function due to the number of structures inserting or attaching to the coracoid process. The authors' indications for surgical intervention include (1) symptomatic nonunion with focal pain, (2) greater than 1 cm of displacement on radiographs, and (3) multiple disruptions of the SSSC [74, 75]. Most coracoid fractures involving the tip, midbody, and base can be addressed through an anterior deltopectoral approach using beach chair positioning. The clavipectoral fascia over the coracoid is incised. The superior slope of the coracoid is dissected until the fracture can be identified, freed of intervening soft tissues, and reduced. In coracoid fractures through the base, the coracoclavicular ligaments must be dissected off the posterior surface of the coracoid to appreciate the fracture. A 4 mm Shantz pin in the coracoid can be used to manipulate it and compress it for reduction. Small fragment lag screws or 1/3 tubular plates can be used to secure the fixation. For fractures involving the glenoid, in which the superior glenoid fracture exits below and involves the coracoid, an anterior approach can be extended to a formal deltopectoral approach to the shoulder in order to evaluate the articular reduction and obtain fixation at the level of the glenoid first. If fractures are associated with the scapular body, the coracoid can be indirectly reduced by an anatomic scapular body reconstruction if it is attached to the cephalad neck segment [75].

Glenoid

Displaced fractures of the glenoid articular surface should be operatively addressed to maintain the stability of the glenohumeral joint and prevent joint incongruity, which can lead to arthrosis. The precise level of displacement or fracture size that corresponds to fragments requiring fixation remains controversial: generally accepted indications for operative fixation include 2–4 mm of articular step-off, fragments >25 % of the articular surface, or displacement associated with joint subluxation. A deltopectoral approach to the shoulder and restoration of the articular surface with lag screws and plate fixation is utilized for the most common anterior fracture patterns. Mini fragment fixation is useful in such cases, applying a buttress plate to the anterior glenoid (Fig. 15.23) [76]. Arthroscopic visualization of the joint surface can be used to assess the reduction in the case of percutaneous fixation of small glenoid fragments. Glenoid rim fractures are frequently associated with shoulder dislocations (bony Bankart lesions) and are less commonly associated with chest wall injuries, but rather the result of sporting and lower energy activities.

Fractures involving the posterior glenoid can be isolated or combined with scapula neck fractures. In such cases, a posterior approach, while the patient is in the lateral decubitus position leaning slightly forward, is most useful (Fig. 15.24). A straight incision is used over the glenohumeral joint, elevating the deltoid and working anterior to it between the infraspinatus and teres minor along the posterior glenoid rim. Alternatively, a Judet incision is more useful for glenoid fractures associated with scapula body fractures.

Extra-articular Fracture Patterns

The indications for surgical intervention remain somewhat controversial and lacking in high level evidence to support operative versus nonoperative treatment for scapular neck and body fractures. One should pursue the basic principles of operative decision making for fractures in general, seeking to restore stability, length, alignment, and rotation of displaced patterns. Using this principle, indications for operative fixation include (1) angular deformity greater than or equal to 45° on a scapular Y radiograph or 3D CT scan, (2) lateral border offset (formerly viewed as medialization of the glenoid) greater than 2 cm, (3) glenopolar angle less than 22° on a Grashey AP view, or (4) displaced double disruptions of the SSSC greater than or equal to 1 cm [77]. With these operative criteria, the senior author has been able to demonstrate low complication rates and good functional outcome scores [71]. These criteria should be used in concert with assessment of the fracture characteristics, risk factors and functional expectations of the individual patient, as well as the skill and experience of the surgeon.

The preferred technique for the operative treatment of most scapular body fractures is a Judet incision with either an extensile approach or intermuscular windows between teres minor and infraspinatus. This decision depends on characteristics and age of the fracture as well as the experience of the surgeon. These patients often present late to the operating surgeon because of management of more critical injuries. In this delayed context, abundant callus is often present

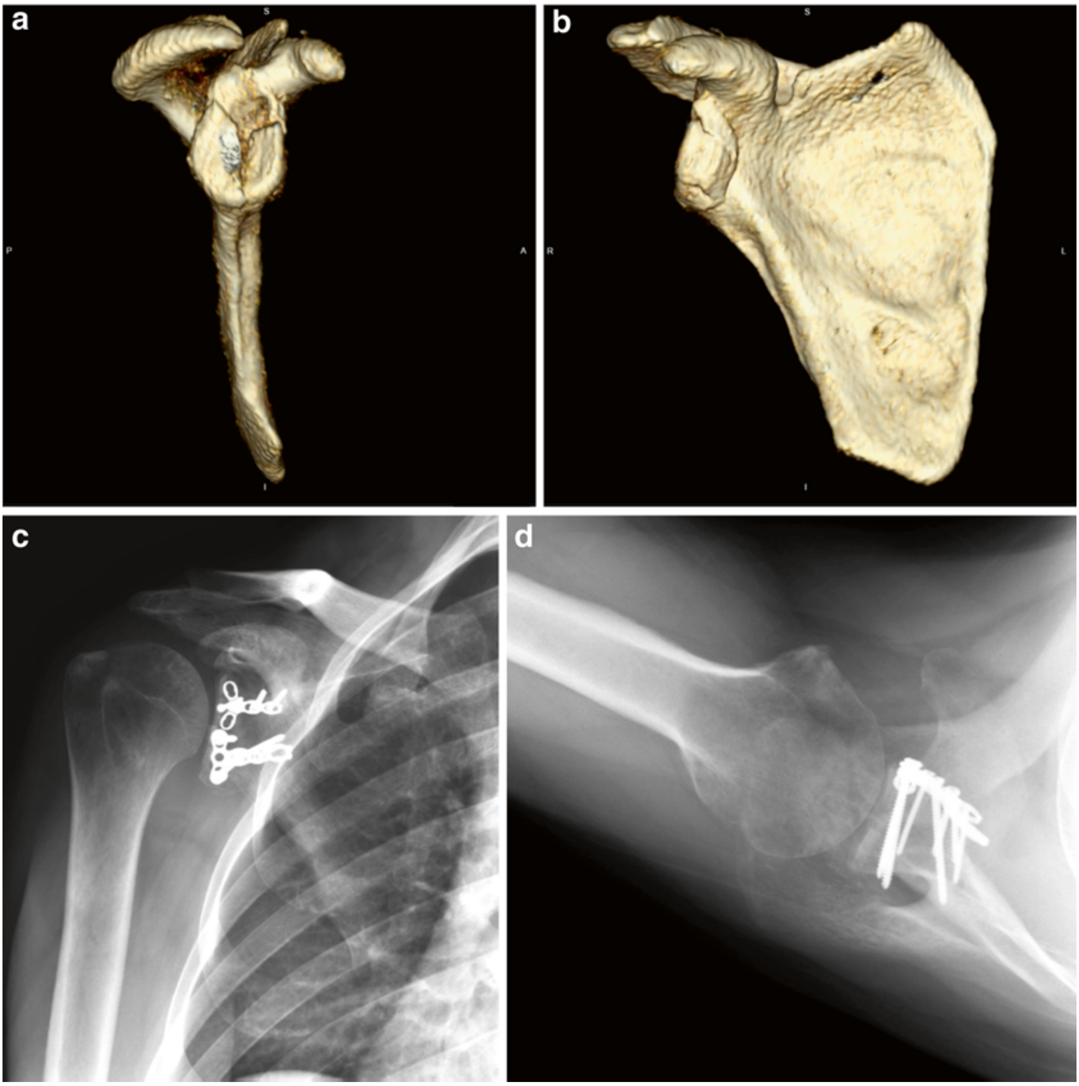

Fig. 15.23 The 3D reconstructed CT image oriented in the anterioposterior (**a**) and the scapula Y (**b**) views for a patient presenting with a displaced anterior scapular glenoid fracture requiring operative fixation. Mini fragment fixation was placed anteriorly, and postoperative anterioposterior (**c**) and axillary (**d**) radiographs show fracture consolidation and healing at final follow-up

and makes the reduction more challenging even as early as 2 weeks. If this is the case, the full extensile Judet approach is utilized, in which the entire muscular envelope of the rotator cuff and deltoid is elevated on its pedicle. The setup for the approach to the scapula includes the lateral position, allowing the patient to fall forward slightly. This involves the use of an arm-board attachment for the standard operating room table. The nonoperative arm is well-padded and in a relaxed, non-tensioned position on the arm-board. Specialized Bone Foam (Bone Foam Inc., USA, Plymouth, MN) positioners with room for the well-arm are optimal. With the patient forward approximately 30° in a “floppy lateral” position, full access to the hemithorax to the vertebral line is obtained. The involved arm, back, and neck are sterilely prepped and draped.

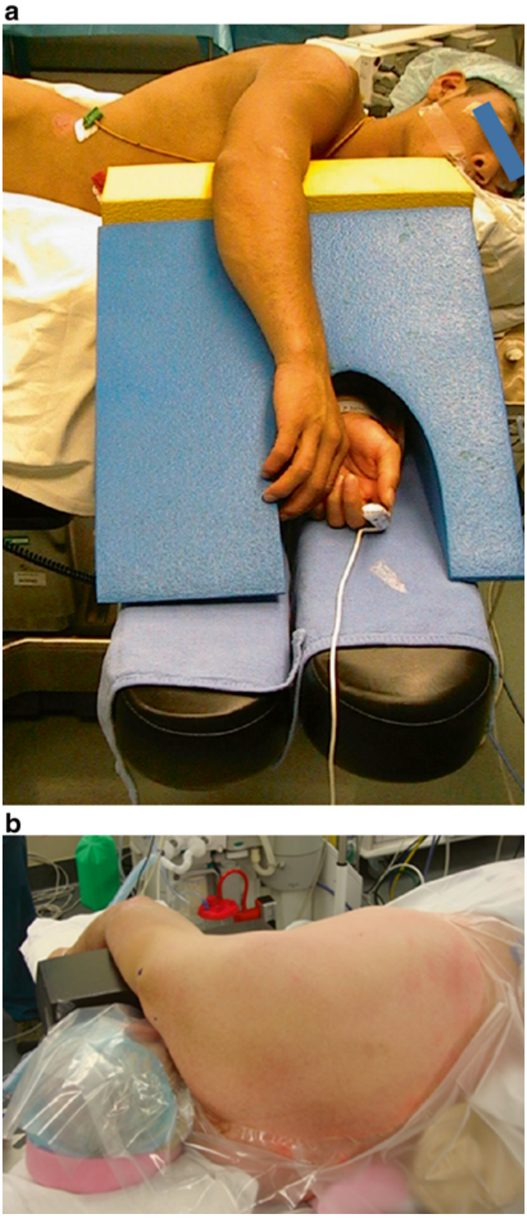

Fig. 15.24 (**a**–**b**) These patients are positioned for a posterior surgical approach to the scapula. In the lateral decubitus (floppy forward) position, the entire injured arm is sterilely prepped and remains free for manipulation to assist in reduction maneuvers during the procedure

The axilla is sequestered with a strip of adherent plastic sheeting.

The bony anatomy of the shoulder and scapula is marked on the skin. Even in larger patients, a sulcus which marks the scapular spine and interval between supra- and infraspinatus is often palpable. The skin incision should be a centimeter caudal and 1 cm medial to the vertebral border of the scapula and slopes from the spine around the superior angle roughly in the shape of a boomerang. Sharp dissection is carried down through the skin and subcutaneous tissues to the fascia overlying the muscle. Depending on whether the full Judet extensile dissection is desired (as is the case for more complex patterns or delay in presentation) or whether an intermuscular approach is desired (for simple fracture patterns), the surgeon should be prepared to elevate the muscles off the glenoid fossa or elevate the subcutaneous tissue off the posterior muscular fascia.

For the Judet approach, the infraspinatus, teres minor, and deltoid are elevated off their origins as one musculocutaneous flap. These muscles are elevated en bloc off the scapular spine and the infraspinatus fossa subperiosteally and then rotated on the lateral suprascapular neurovascular pedicle to reveal the body and neck of the scapula. The subscapularis muscle anterior to the scapula is undisturbed and provides great vascularity for high healing potential (Fig. 15.25a–c). Alternatively, as stated above, intermuscular windows can be used to access different portions of the scapula when less complete visualization or mobilization is necessary. Windows can be created along the spine of the scapula (between deltoid and trapezius), the vertebral border (between rhomboids and infraspinatus), or more laterally between infraspinatus and teres minor to access the lateral border and posterior glenoid.

Callus and interposed tissue are removed to expose fracture fragments both along the medial and lateral border, and the fracture fragments mobilized. A lamina spreader inside of fracture lines around the periphery, or Schanz pins in either the glenoid neck or lateral border can be utilized to mobilize fracture fragments. Provisional reduction is then effected using small pointed reduction clamps. It is most often useful to obtain the reduction of the lateral border first. Once the adequate medial and lateral border reductions have been affected, fixation of these may commence: a 2.7 mm reconstruction plate which lies along the inferior border of the

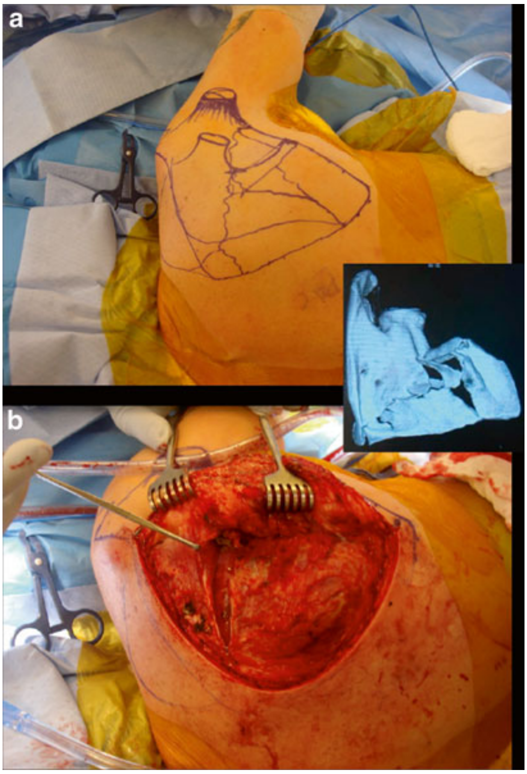

Fig. 15.25 (**a**) A modified posterior Judet approach is carefully planned, utilizing strategically placed intermuscular windows to address the patients common fracture pattern (*blue lines*). (**b**) Intraoperative photographs of the superficial anatomy illustrate a full-thickness fasciocutaneous flap, which is developed utilizing these landmarks: 1 cm caudal to the acromion spine and 1 cm lateral to the vertebral border and retracted laterally (*top* of image). Also shown is an intermuscular window between the trapezius and the deltoid (*arrow*) to access the inferior and medial margins of the scapular spine for plate fixation (**b**)

scapular spine, curving along the vertebral border is contoured around the angle for the most common fracture pattern (Figs. 15.26, 15.27, and 15.28). The surgeon may want to reinforce this fixation with a second adjacent 2.7 mm reconstruction plate for strength. The thickest bone and best fixation is found laterally. In the case of large comminuted midbody fracture fragments, spring plates with very short screw fixation can be utilized if the displacement is severe, but displacement can be tolerated in general in this very thin bone segment.

Once fixation has been performed, any devitalized muscle is debrided, the wound is irrigated, and closure commences. Drains are typically employed both deep below the fascia as well as under the subcutaneous flap when appropriate. The author's preferred technique for repair of the flap to the scapular spine is to use heavy-braided no. 2 sutures through drill holes along the scapular spine, supplemented with strong no. 1 vicryl closure for the rest of the fascial closure. The fascia is also re-approximated using these sutures. The subcutaneous layers and skin are closed with any preferred technique.

Rehabilitation begins with full shoulder passive and active range of motion for the first month and a light 3–5 pound weight restriction in the second month. Strength is then advanced according to symptoms until all restrictions are removed at 3 months post-op. Hand and wrist and elbow range of motion are encouraged from day one. Drains are discontinued when drainage is less than 15 mL per 8-h shift [78]. Generally good to excellent outcomes are to be anticipated with operative treatment of scapular body fractures that meet certain criteria. Patients usually return to close to their preoperative level of function with scapular body fractures with prudent and judicious application of operative fixation.

Summary

Scapula and clavicle fractures occur commonly in association with chest wall injuries. Typically, these injury associations occur after high-energy traumatic mechanisms, and all four combinations are common, namely, scapula-clavicle, ribs-clavicle, scapula-ribs, and ribs-scapula-clavicle combination. Most commonly in this scenario, the rib fractures are multiple and frequently constitute a typical "flail chest" in which there are more than four consecutive ribs fractured in two locations. Therefore, it is very important in patients who have multiple rib fractures, with or without pneumothorax or hemothorax, to carefully inspect the periphery of the chest radiograph for scapula or clavicle fractures.

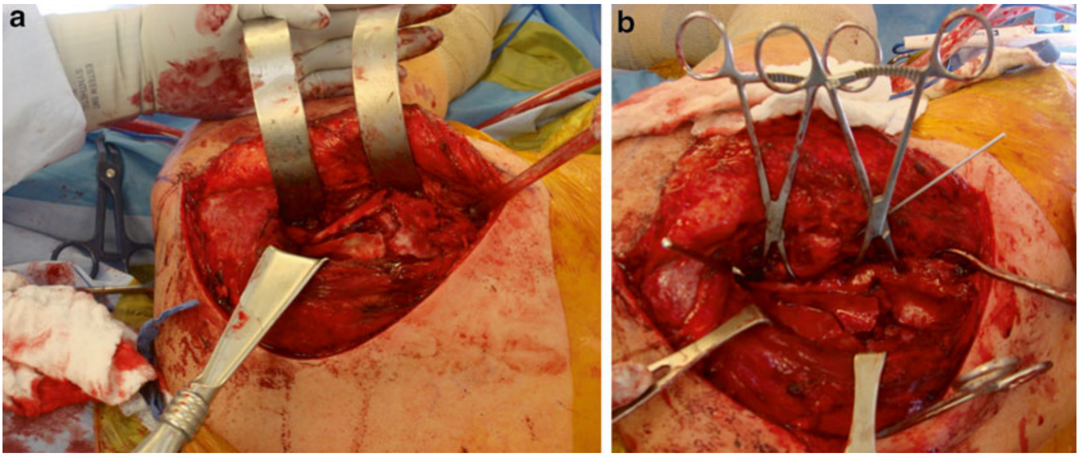

Fig. 15.26 (**a**) Intraoperative photographs indicating the intermuscular interval between teres minor and infraspinatus to access the bony anatomy of the displaced lateral border (**a**). Temporary reduction techniques utilizing small drill holes with towel clamps or k-wires are utilized prior to internal fixation with plates and screws (**b**)

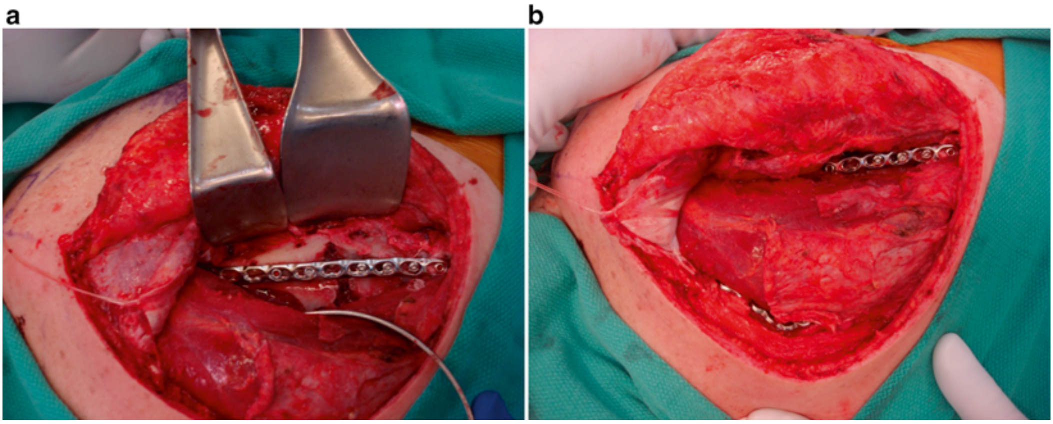

Fig. 15.27 Plate placement occurs in the internervous plane between the infraspinatus and teres minor, allowing good visualization of the lateral border and glenoid neck (**a**). Open reduction and internal fixation of the displaced scapula fracture completed both medially and laterally via superomedial and lateral intermuscular windows (**b**)

If there is any suspicion, formal shoulder films should be obtained. Similarly, in a patient with a high-energy scapula and/or clavicle fracture detected on shoulder films, formal inspection of the ribs on radiographs and physical exam of the chest should follow. Lastly, a full-body secondary survey must be done, and repeated, because the associated injury rate to other bodily areas and systems is very high.

From a treatment standpoint, it is useful to understand that multiple fractures occurring in the ipsilateral forequarter respond best to stabilization throughout the peri-injury period and rehabilitation phase of recovery. Lack of osseous stability promotes shoulder stiffness, and ultimately deformity is associated with dysfunction. Restoring stability to the displaced scapula and clavicle in this setting is beneficial, and it is often synergistic with operative fixation of multiple rib fractures.

Acknowledgment The authors acknowledge Amir Rizkala, M.D., for the assistance in selecting and preparing the images for this chapter.

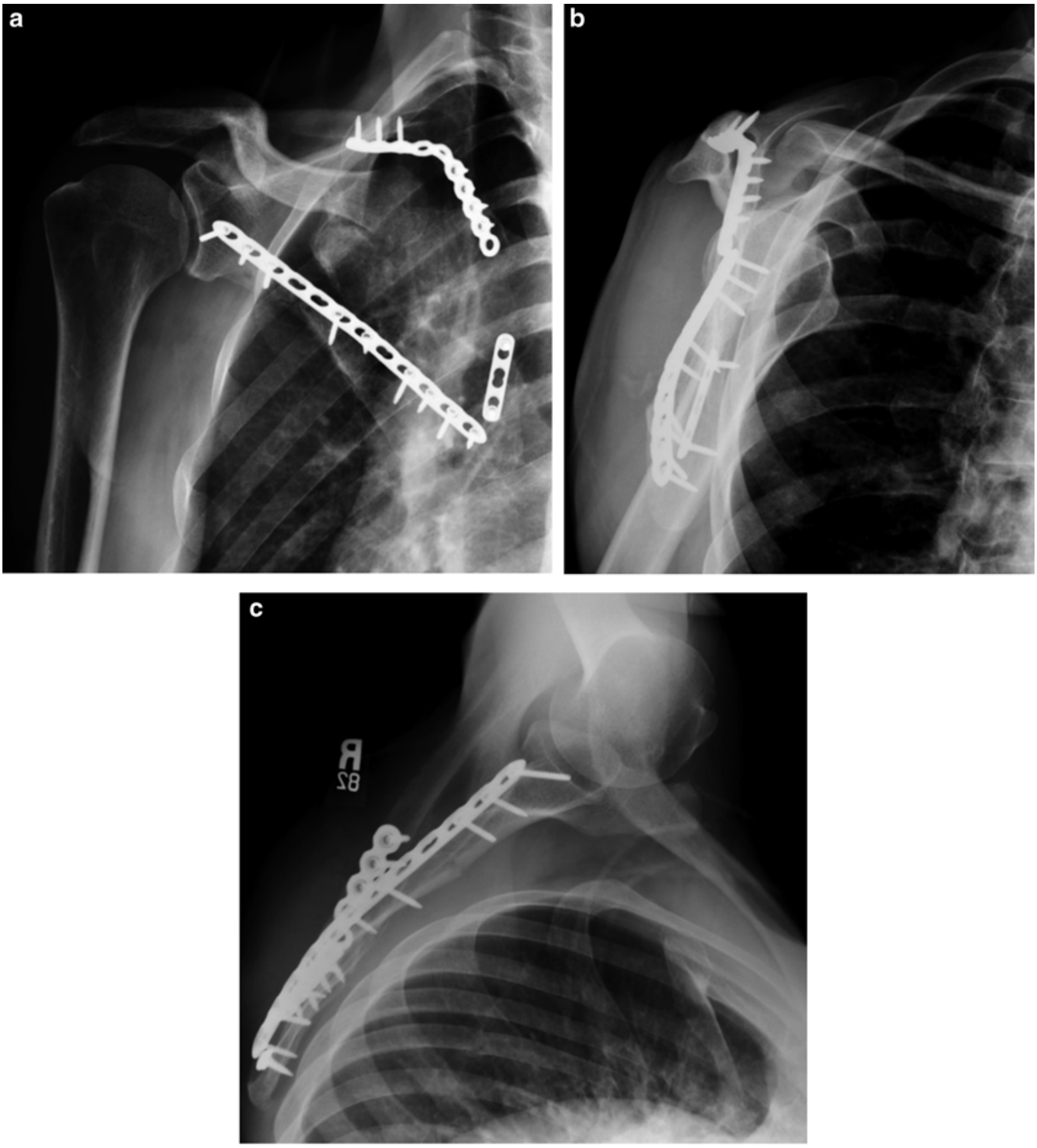

Fig. 15.28 Postoperative anterioposterior (**a**), scapula Y (**b**), and axillary (**c**) radiographs of the patient from the operative case illustrated in Figs. 15.25, 15.26, and 15.27

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Unstable Chest Wall Injuries: Future Directions

16

Emil H. Schemitsch and Zachary Morison

Adoption of New Technologies in Orthopedic Surgery

There is a current move to increased surgical management of unstable chest wall injuries. Patients with unstable chest wall injuries continue to present with significant morbidity and mortality despite modern ICU management [1]. Patients presenting with these injuries have high rates of prolonged ventilation/ICU stay, pneumonia, sepsis, tracheostomy, and high healthcare costs [2–4]. As a result, there has been a recent trend toward operative management of these injuries in an effort to reduce time spent on mechanical ventilation, as well as the associated morbidity, complications, and attendant healthcare costs [5]. Unfortunately, the surgical management of these injuries is not well supported in the literature and the indications for surgical treatment remain uncertain. This chapter strives to shed light on the state of the current evidence and provide guidance for the future direction of the management of these injuries, so changes in clinical practice do not occur in advance of the evidence.

In order to allow for innovation and advancement of knowledge in orthopedics, while minimizing the potential harm to patients, it is imperative that the clinical decision-making process incorporates the best and most current available evidence into clinical practice. One solution to the issue of incorporating evidence into clinical practice is "Evidence-Based Medicine" (EBM). EBM has been a widely accepted approach to the practice of medicine since the term was coined by Gordan Guyatt in 1991 and later described by the EBM Working Group at McMaster University in 1992 [6, 7]. Evidence-Based Orthopedics (the application of EBM to the field of Orthopedics) involves clearly defining the relevant clinical questions through a literature search, critically appraising the available evidence and its applicability to the clinical situation, and performing a balanced application of the evidence to the clinical problem [8].

Applying EBM to the treatment of unstable chest wall injuries begins with the definition of a research question. The research question should allow direct comparison of surgical fixation versus the standardized conventional, nonsurgical treatment of unstable chest wall injuries and should allow evaluation of the level of evidence for this primary research question. The primary outcome should be an important, clinically relevant,

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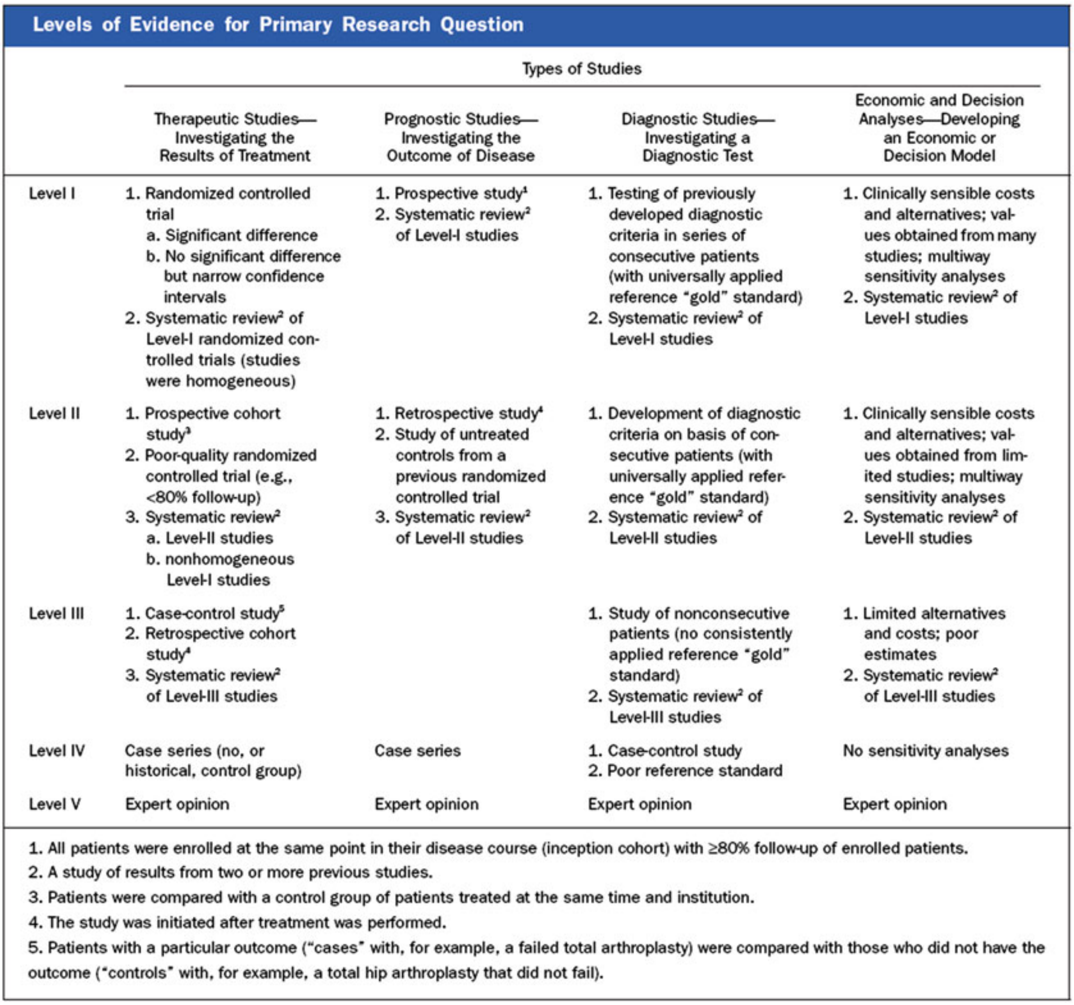
objective measure such as the assessment of days spent free from a mechanical ventilator in the first 28 days following injury. The critical appraisal of the literature is the major focus of this chapter and will be assessed in further detail. The literature to date on surgical intervention for these injuries has consisted primarily of retrospective studies and three small randomized trials conducted outside of North America [3, 9–12]. All three RCTs had small sample sizes, lacked standardized and modern conservative management of these injuries, and used variable methods of surgical fixation. A recent meta-analysis of the literature on operative versus nonoperative management of flail chest injuries found a significant benefit to operative management in regard to ventilation days, ICU stay, complications, and mortality [5]. However, the literature available for the analysis consisted of mainly retrospective studies and had substantial limitations. At the present time, it appears that there is insufficient evidence concerning the operative management of chest wall injuries to determine that it is a more appropriate treatment than nonoperative management. A large-scale, randomized controlled trial comparing surgical treatment to modern conservative management, with standardized treatment groups, is needed to address this problem.

Bhandari et al. have outlined the four most important principles in EBM as the following: the patient's values; the need for evidence; that not all evidence is equal; and integrating evidence and clinical expertise [8]. The incorporation of patient values and the need for evidence are self-evident principles. However, the relative importance of evidence and integration of evidence and clinical expertise are two topics that can lead to misconceptions regarding EBM. One such misconception is that evidence-based orthopedics replaces the judgment of the clinician in clinical decision making. The judgment of the clinician derived from professional training and experience is highly valuable in clinical practice and is irreplaceable. Evidence-based orthopedics seeks to supplement rather than replace the authority of the clinician by expanding the tools he or she uses. A second misconception of EBM is that randomized controlled trials (RCTs) are the only acceptable form of evidence. RCTs are considered to be the highest level of evidence, as randomization is the optimal method to balance known and unknown prognostic factors in treatment and control groups in therapeutic studies.

However, even RCTs should be evaluated carefully to ensure the reliability of the findings and should not be used as the exclusive source of information. In order to address the variability between randomized control trials, an international group of clinical trialists, statisticians, epidemiologists, and biomedical journal editors developed the CONsolidated Standards Of Reporting Trials (CONSORT) Statement. The CONSORT Statement is an evidence-based minimum set of recommendations including a checklist and flow diagram for reporting RCTs and is intended to facilitate the complete and transparent reporting of trials and aid their critical appraisal and interpretation.

While some surgeons understand the importance of incorporating evidence in their clinical decision making and are able to critically evaluate the literature and integrate the evidence with their clinical expertise to make decisions with their patients, other surgeons struggle with determining what constitutes the best evidence. Hierarchies or levels of evidence are used to assist clinicians in appraising the medical literature by providing a measure of quality (Fig. 16.1). In general, such hierarchies' rank-order research studies from the most methodologically sound (well-designed RCTs), to those with less methodological rigor and a higher propensity for biased results (Case series and expert opinion) (Fig. 16.1). It is these hierarchies, along with the benefits vs. harms, practical issues for the clinical setting, and baseline population risk, that determine how strongly an intervention can be recommended [8]. The hierarchies of evidence function as a tool for clinicians to determine the "best available" evidence and, in turn, facilitate evidence-based decision making. Historically, there have been few examples where case series have provided major advances in orthopedics. For example, Sir John Charnley's original publication on cemented total hip arthroplasty



Levels of Evidence for Primary Research Question

	Types of Studies			
	Therapeutic Studies—Investigating the Results of Treatment	Prognostic Studies—Investigating the Outcome of Disease	Diagnostic Studies—Investigating a Diagnostic Test	Economic and Decision Analyses—Developing an Economic or Decision Model
Level I	1. Randomized controlled trial a. Significant difference b. No significant difference but narrow confidence intervals 2. Systematic review[2] of Level-I randomized controlled trials (studies were homogeneous)	1. Prospective study[1] 2. Systematic review[2] of Level-I studies	1. Testing of previously developed diagnostic criteria in series of consecutive patients (with universally applied reference "gold" standard) 2. Systematic review[2] of Level-I studies	1. Clinically sensible costs and alternatives; values obtained from many studies; multiway sensitivity analyses 2. Systematic review[2] of Level-I studies
Level II	1. Prospective cohort study[3] 2. Poor-quality randomized controlled trial (e.g., <80% follow-up) 3. Systematic review[2] a. Level-II studies b. nonhomogeneous Level-I studies	1. Retrospective study[4] 2. Study of untreated controls from a previous randomized controlled trial 3. Systematic review[2] of Level-II studies	1. Development of diagnostic criteria on basis of consecutive patients (with universally applied reference "gold" standard) 2. Systematic review[2] of Level-II studies	1. Clinically sensible costs and alternatives; values obtained from limited studies; multiway sensitivity analyses 2. Systematic review[2] of Level-II studies
Level III	1. Case-control study[5] 2. Retrospective cohort study[4] 3. Systematic review[2] of Level-III studies		1. Study of nonconsecutive patients (no consistently applied reference "gold" standard) 2. Systematic review[2] of Level-III studies	1. Limited alternatives and costs; poor estimates 2. Systematic review[2] of Level-III studies
Level IV	Case series (no, or historical, control group)	Case series	1. Case-control study 2. Poor reference standard	No sensitivity analyses
Level V	Expert opinion	Expert opinion	Expert opinion	Expert opinion

1. All patients were enrolled at the same point in their disease course (inception cohort) with ≥80% follow-up of enrolled patients.
2. A study of results from two or more previous studies.
3. Patients were compared with a control group of patients treated at the same time and institution.
4. The study was initiated after treatment was performed.
5. Patients with a particular outcome ("cases" with, for example, a failed total arthroplasty) were compared with those who did not have the outcome ("controls" with, for example, a total hip arthroplasty that did not fail).

Fig. 16.1 Table showing levels of evidence (I–V) for a primary research question

(THA) showed the technique was quite substantially superior to prior methods, such that a randomized trial was not needed [13]. However, in most clinical conditions, case series do not provide definitive answers and may be misleading. Moreover, observational studies are particularly valuable if the goal of the research is not to determine treatment efficacy but rather to evaluate the prognosis of patients who take a particular therapy. Unlike the randomized controlled trial, however, the observational design creates the risk of confounding variables.

The failure to incorporate evidence, via EBM or otherwise, has led to the adoption of new technologies into clinical practice which later proved problematic. A recent example of new technology being widely accepted without extensive critical appraisal of evidence is the use of modular neck systems in THA. It has been reported that more than 30,000 THAs with modular neck systems have been implanted worldwide [14], and in the United Kingdom more than 6,000 various modular neck stems have been registered with the National Joint Registry [15]. The change from monoblock to modular stem–neck junctions was driven by the ability to make independent adjustments to the vertical and horizontal offsets, the leg length, and the version of the neck, which is especially advantageous in patients with complex anatomy. Evidence had shown that restoration of femoral offset and soft-tissue balancing can reduce abductor muscle imbalance, pain, and rates of wear [16]. Furthermore, the ability to adjust version and offset is useful in the prevention of impingement between the socket and neck, and bony and muscular impingement [17]. In a previous study of monoblock stems, femoral offset and limb length were not restored in 36 % of patients (28 of 79) [18]. At the time this technology was brought to market, in vitro studies suggested that an insignificant amount of corrosion and fretting occurred at the modular neck–stem junction [18, 19] and a similar study of the effect of machine surface finish on fretting and corrosion concluded that the degree of degradation was "within a clinically noncritical range" [20]. With this limited evidence, it appeared as though the benefits of modularity outweighed the potential risks. However, many studies have since reported that stems with increased modularity present an additional site for failure by introducing a second taper junction. These studies report failure mechanisms and increased failure rates of modular hip designs, the most common failure mechanisms being crevice corrosion and fretting corrosion.

Another example of the questionable introduction of new technology includes the use of intramedullary (IM) nailing for humeral shaft fractures. IM nails proved to be an effective method of treating femoral and tibial shaft fractures and became one of the preferred procedures in orthopedics. In general, IM nailing in the lower extremity is associated with high union rates and low complication rates. IM nails present a greater biomechanical advantage for construct stability over a plate and screws as a result of their location at the center of the bone. Compared to plate and screw fixation constructs placed on the cortical surface, biomechanical evidence continues to demonstrate that IM nails provide superior support for axial, bending, and torsional loads while stabilizing the fracture to promote healing. With sound evidence supporting the use of IM nails in lower extremity long bones, it was a logical transition to apply the same technology to the operative treatment of humeral shaft fractures. The use of IM nail fixation in fractures of the femur and tibia has been highly successful and has minimized many of the problems associated with plate fixation. Larger diameter, "locking" humeral nails were introduced in the hopes that they would overcome some of the shortcomings associated with early IM fixation devices or plates. The initial use of humeral nails appeared promising; however, conclusions were largely based on favorable retrospective reviews of the experience of experts with the implant, and these new devices were vigorously marketed for a wide range of indications [21–27]. Unfortunately, reports on the efficacy and success rates associated with the use of locking humeral nails have been inconsistent at best [28–31]. A wide range of complications have been reported, leading some authorities to question the role of these devices in the treatment of humeral shaft fractures. Data from randomized clinical trials directly comparing these implants to standard plate fixation have now emerged and the usage of humeral nails has significantly declined (Fig. 16.2) [32–34].

An example of clinical decision making being transformed by the practice of EBM has been seen in the management of clavicle fractures. Clavicle fractures are common injuries accounting for between 2 and 10 % of all adult fractures [35, 36]. Mid-shaft clavicle fractures account for approximately 80 % of all clavicle fractures, and similarly to rib fractures, they have traditionally been treated non-operatively [37]. The nonoperative treatment strategy was based on early observational studies that suggested that clavicular non-union was rare. A study by Rowe reported the prevalence of four non-unions in 566 patients; a separate study by Neer reported only three non-unions in 2,235 patients [37, 38]. Furthermore, clavicular malunion was described as being of radiographic interest only, with no clinical importance [37–39]. However, more recent studies of displaced mid-shaft clavicular fractures have shown a non-union rate of 15 % (8 of 52 patients) in one series as well as unsatisfactory patient-oriented outcomes in 31 % of patients. Additionally, using an objective strength testing protocol

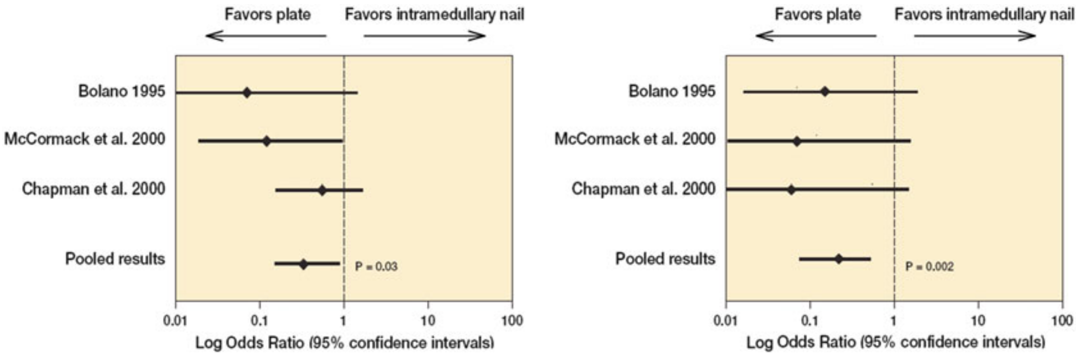


Fig. 16.2 (**a**) Statistical pooling of three studies (155 patients) revealed that plate fixation results in a significant reduction in reoperation rates ($p=0.03$) as compared to intramedulary nail fixation. (**b**) Statistical pooling of 3 studies (155 patients) revealed that plate fixation results in a significant reduction in reoperation rates ($p=0.002$) as compared to intramedulary nail fixation

for both maximal effort and endurance strength, deficits ranging from 10 to 35 % were found in patients a mean of 54 months after nonoperative care of a displaced fracture of the clavicular shaft [40].

This led to a number of randomized clinical trials that compared operative to nonoperative treatment of displaced fractures of the clavicle. In particular, a large multicenter RCT was conducted by the Canadian Orthopaedic Trauma Society (COTS) which included 132 patients with a displaced mid-shaft fracture of the clavicle. This study found that the Constant Score and DASH scores were significantly better at all-time points for the operative group of this study ($p<0.01$) [41]. The COTS study also found that there were two non-unions in the operative group (3 %), significantly fewer than the seven non-unions in the nonoperative group (14 %) ($p=0.042$) [41].

The choice to proceed with operative intervention for a displaced mid-shaft fracture of the clavicle remains a decision to be made between surgeon and patient. However, there is increasing evidence from well-designed level 1 prospective randomized trials that provide clear facts about the outcomes of treating clavicle fractures that can be used when counseling patients regarding treatment options.

The previous examples of modular necks in THA and the use of IM nails for humeral shaft fractures reinforce the principles of EBM that were characterized by Bhandari. The advancement of an existing procedure and the development of new technology were adopted into orthopedic practice prior to adequately and systematically applying EBM. These two examples show that integrating questionable evidence into a clinical approach, or going forward with an innovative technique prior to studying all of the relevant evidence, may cause more harm than benefit to the patient. It is important that orthopedic surgeons as a group do not rush into the treatment of unstable chest wall injuries and avoid following a similar path seen with previously unsuccessful innovation. Therefore, a careful evidence-based approach must be employed regarding the treatment of these injuries. The evidence currently available on management of these injuries is insufficient to determine whether fixation is an appropriate treatment, or whether it is more favorable than nonoperative treatment. The principles of EBM would dictate that such relevant information be attained and evaluated prior to adopting this new technique into clinical practice.

Unstable Chest Wall Injuries

Chest wall trauma is a significant cause of morbidity and mortality for trauma patients. An estimated 25 % of annual trauma deaths occur as a result of chest trauma [42]. Rib fractures are common injuries and occur in up to 39 % of patients with blunt chest trauma [2]. As many as one-third of patients with rib fractures require admission to hospital [42]. These fractures are routinely treated non-operatively, and many heal without major complications. However, a significant fraction (10–15 %) [3] of these injuries can cause chest wall instability, which has high rates of short-term mortality (up to 33 %) [2] and long-term morbidity. Unstable chest wall injuries can occur in cases with flail chest, and rib fractures with severe displacement or chest wall deformity. While surgical treatment of these injuries is technically possible, indications remain controversial and definitive studies have not been performed.

Unstable chest wall injuries can be caused by a flail chest, which is defined as fracture of three or more consecutive ribs in two or more places, creating a flail segment [42]. This definition also applies to (≥3) bilateral consecutive rib fractures, and (≥3) rib fractures associated with a sternal fracture, as both of these also lead to the creation of a flail segment [4]. These injuries severely injure the thorax and can lead to profound sequelae. A study by Velmahos et al. has shown that 73 % of patients with a flail chest who were not initially intubated developed respiratory failure and required intubation with mechanical ventilation [43]. Other causes of an unstable chest wall can be a crush injury that causes a “caved-in chest,” or severe displacement/overriding of the ribs. These can lead to chest wall deformity, loss of thoracic volume, and impaling of lung or intrathoracic structures by the fractured rib fragments [4].

Unstable chest wall injuries have been shown to have a high incidence of complications, including severe pulmonary restriction due to paradoxical movement of the flail segment, loss of lung volume, and inability to control pain despite maximal nonoperative measures (e.g., epidural catheter) [2–4, 9]. The resulting instability, decreased lung volumes, and pain lead to decreased pulmonary function and can leave patients dependent on long-term mechanical ventilation. Such long-term ventilation can lead to high rates of pneumonia, sepsis, tracheostomy, barotrauma, prolonged intensive care unit (ICU) stay, and high healthcare costs [2–4, 9–11]. Following discharge from hospital, patients often report long-term dyspnea and chest pain and have abnormal pulmonary function when assessed with spirometry [42].

The current and almost universal treatment of severe chest wall injuries consists of nonsurgical management via intubation and intermittent positive pressure ventilation (internal pneumatic splint), analgesia, pulmonary toilet, and chest physiotherapy [2, 4, 44]. However, such an approach may not produce optimal results. In addition to the complications listed above, studies have shown that only 43 % of patients return to their previous full-time employment [45], and many complain of chronic pain, subjective dyspnea, chest tightness, and chest wall deformity [45, 46] and have low scores on the SF36, indicating poor functional outcomes [47]. The current suboptimal outcomes following nonsurgical management of these injuries suggest that other approaches may be beneficial and that a large prospective clinical trial would be advantageous.

Unstable chest wall injuries are associated with compromised pulmonary function, substantial morbidity related to prolonged mechanical ventilation, and lengthy stays in the ICU and hospital [2]. At long-term follow-up, flail chest injuries are associated with dyspnea in up to 63 % of patients, chest pain in up to 49 %, and long-term disability in up to 64 %, with abnormal spirometry results in up to 57 % [45, 46]. These injuries are associated with the consumption of a significant amount of healthcare resources when treated non-operatively. Yet, nonoperative care has been the gold standard, in part, because rib fractures do heal without surgery, and in part, related to concerns around surgical fixation including potential complications such as infection, injury to neurovascular structures, lung injury, and the need for subsequent surgery to remove implants [2]. Perhaps one of the largest barriers to surgical treatment is the fact that most surgeons are unfamiliar with the procedure. While nonoperative care of these injuries is almost universal, there have been a limited number of retrospective and long-term studies in the thoracic surgery and trauma literature that have demonstrated the benefit of surgical fixation of severe chest wall injuries when compared to conservative treatment and suggest that this treatment may be cost-effective. This benefit includes decreased days on mechanical ventilation (3.7–10.8 vs. 15–30.7) [10, 11, 48], decreased days spent in ICU (6.8–16.5 vs. 21–28.3) [3, 9–11], decreased chest infections (7.6–24 vs. 50–77 %) [9–11], earlier return to work (95–100 vs. 43 %) [11], decreased chronic pain (5.5–11 vs. 49 %) [3], and decreased long-term respiratory dysfunction [49, 50].

A randomized controlled trial by Tanaka et al. showed that on average, patients with surgical fixation were extubated 2.5 days postoperatively, compared to 18.3 days of intubation in the nonoperative group [11]. In a similar study, Granetzny et al. demonstrated the total days of mechanical ventilation to be 2 days in the surgical group and 12 days in the nonsurgical group [9]. While generating considerable interest in internal fixation, these trials have significant methodological limitations including small sample sizes, lack of modern and standardized nonoperative treatments, as well as the use of variable and outdated methods of rib fracture fixation. Very recently, a randomized controlled trial by Marasco et al. [12] used modern and standardized nonsurgical treatment of these injuries compared to surgical treatment. This study demonstrated reduced ICU stay and use of tracheostomy in the operative group but no differences in duration of mechanical ventilation, spirometry at 3 months, or quality of life at 6 months. This trial also had significant methodological limitations including small sample size, significant delays to randomization and operative treatment, and the use of unconventional implants for rib fixation.

There continues to be marked uncertainty around the management of acute unstable chest wall injuries. We recently completed a retrospective analysis of the injury patterns, management, and clinical outcomes associated with flail chest injuries at 199 North American trauma centers over a 3-year period and found that only 1 % of these injuries received surgical fixation. Yet, a recent survey of 405 general, orthopedic, and thoracic surgeons revealed that 82 % of the general surgeons, 66 % of the orthopedic surgeons, and 71 % of the thoracic surgeons felt that operative repair of rib fractures was indicated in selected patients. Only 22 % of respondents were familiar with a randomized trial in this area [2, 51]. Of those who felt that operative treatment was not indicated, 82–95 % felt that a definitive randomized trial was necessary to change their opinion [51].

We have used the National Trauma Databank (the largest aggregation of US/Canadian trauma registries) to perform a retrospective analysis of the injury patterns, management, and clinical outcomes associated with flail chest injuries. Patients with a flail chest injury admitted from 2007 to 2009 were included for analysis. Outcomes included treatment with surgical fixation or epidural catheter use, number of days on mechanical ventilator, days in ICU, days spent in hospital, rates of pneumonia, tracheostomy, chest tube placement, and death. In total, 354,945 adults with an Injury Severity Score (ISS) greater than nine were admitted to 199 trauma centers from 2007 to 2009. Flail chest was identified in 3,467 patients. Surgical fixation of the chest wall was performed in only 1 % of patients. Mechanical ventilation was required in 59 %, for an average of 12.1 days. ICU admission was required in 82 % of patients, for an average of 12 days. Mean length of hospital stay was 16.6 days. Chest tubes were utilized in 44 %, and 21 % required a tracheostomy. Complications included pneumonia in 21 %, acute respiratory distress syndrome (ARDS) in 14 %, sepsis in 7 %, and death in 16 %. This analysis confirms the significant morbidity and mortality associated with these injuries.

A group from Vancouver has recently conducted and published a meta-analysis of the literature on surgical fixation versus nonoperative management for flail chest injuries [5]. Their analysis included 753 patients from 11 studies conducted between 1972 and 2009. Pooled analysis of the results demonstrated that operative treatment resulted in a mean decrease in ventilator days of 7.5 (95 % CI = 5.0–9.9), ICU days of 4.8 (95 % CI = 1.6–7.9), and hospital days of 4.0 (95 % CI = 0.7–7.4). The odds ratios for mortality (0.31), pneumonia (0.18), septicemia (0.36), tracheostomy (0.12), and dyspnea (0.40) were all statistically significant in favor of operative treatment. The number of patients who needed to be treated operatively to prevent a single case of pneumonia or tracheostomy was three. However, despite the substantial benefits to operative treatment identified in this analysis, the authors noted several weaknesses in the available literature. Only 2 of the 11 studies analyzed were prospective randomized trials, with the remainder of the studies being retrospective and subject to selection bias. Only one of the studies was conducted in North America. None of the studies used modern rib fixation techniques exclusively, and most had a mix of different implants. They concluded that the results of this meta-analysis suggest that surgical fixation of flail chest injuries may have substantial critical care benefits; however, the analyses are based on the pooling of primarily small retrospective studies and must be interpreted with care. They further concluded that additional prospective randomized trials are still necessary. These findings and conclusions were further supported by a second systematic review and meta-analysis that was recently published [52]. The authors included nine studies with 538 patients published before February 2012 and found that the operative management of flail chest injuries was associated with a shorter duration of mechanical ventilation, reduced ICU and hospital length of stay, and decreased mortality, pneumonia, and tracheostomy.

The divergence of opinion and chosen treatments, the limited evidence, and the profound impact of the problem have generated significant enthusiasm within the surgical and critical care communities for a definitive trial to resolve the merits of these two different treatment approaches. Decreasing the number of days on mechanical ventilation decreases the rates of pneumonia, sepsis, barotrauma, and number of days spent in the ICU [3, 9–11]. This can result in decreased morbidity and mortality and also dramatically decrease medical costs. Patients on mechanical ventilation require ICU admission, and the average cost of ICU care in Ontario is about $3,745 per day [53]. Decreasing the length of ICU stay, by even a few days, could produce dramatic savings in healthcare expenses. Those who have surgery for rib fixation do have a small chance of complications associated with surgery, such as wound infection (1.2 %), failure of the plates and screws (1.2 %), pain from plates and screws that may require further surgery for removal (1.4 %), and anesthetic risk (less than 1 %) [4], but these risks pale in comparison to the potential advantages of operative intervention. The hypothesis for a proposed trial would be that the early surgical fixation of unstable chest wall injuries will significantly improve patient outcomes over conventional, nonsurgical treatment. The findings of such a proposed study would have major resource implications for healthcare systems and the economy in general, both presently and in the future.

In summary, the rationale for a proposed trial is as follows:

1. Although nonoperative treatment of chest wall injuries is almost universal, there is mounting evidence that operative treatment can result in substantial benefits and the available evidence is at odds with current practice.
2. There remains significant controversy and divergence of opinion with regard to the best treatment for patients with unstable chest wall injuries.
3. The available evidence at the present time suffers from several limitations and there is a need for a definitive and large-scale randomized trial.
4. The impact of unstable chest wall injuries on the Canadian Healthcare System is profound and high-level evidence is required to optimize the use of scarce resources.

A pivotal trial in this area will have a profound impact. The current treatment of severe chest wall injuries consists of nonsurgical management via intubation and intermittent positive pressure ventilation (internal pneumatic splint), analgesia, pulmonary toilet, and chest physiotherapy [2, 4, 44]. However, such an approach may not produce optimal results as the evidence suggests the potential for substantial improvement in outcomes with surgical treatment [5]. A clinical trial has the potential for global impact across the multiple health disciplines that treat patients with unstable chest wall injuries. A positive result from a large-scale, well-conducted, randomized trial would significantly impact the care and outcomes of these severely injured trauma patients. In addition, this trial is well-positioned to provide evidence for substantial healthcare savings with surgical intervention, as the focus of investigation would be a relatively low-cost, one-time intervention (surgery) that has the potential to significantly decrease the need for high-cost medical interventions (days in ICU and on a mechanical ventilator). If this trial showed that internal fixation of these injuries is optimal in selected cases, the potential for a paradigm shift in management exists. Currently 1 % of these injuries are treated surgically, whereas a recent survey suggests that 66–82 % of surgeons would consider use of internal fixation in selected cases [17].

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