



Review Article

The Chinese consensus for surgical treatment of traumatic rib fractures 2021 (C-STTRF 2021)

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ABSTRACT

Rib fracture is the most common injury in chest trauma. Most of patients with rib fractures were treated conservatively, but up to 50% of patients, especially those with combined injury such as flail chest, presented chronic pain or chest wall deformities, and more than 30% had long-term disabilities, unable to retain a full-time job. In the past two decades, surgery for rib fractures has achieving good outcomes. However, in clinic, there are still some problems including inconsistency in surgical indications and quality control in medical services. Before the year of 2018, there were 3 guidelines on the management of regional traumatic rib fractures were published at home and abroad, focusing on the guidance of the overall treatment decisions and plans; another clinical guideline about the surgical treatment of rib fractures lacks recent related progress in surgical treatment of rib fractures. The Chinese Society of Traumatology, Chinese Medical Association, and the Chinese College of Trauma Surgeons, Chinese Medical Doctor Association organized experts from cardiothoracic surgery, trauma surgery, acute care surgery, orthopedics and other disciplines to participate together, following the principle of evidence-based medicine and in line with the scientific nature and practicality, formulated the Chinese consensus for surgical treatment of traumatic rib fractures (STTRF 2021). This expert consensus put forward some clear, applicable, and graded recommendations from seven aspects: preoperative imaging evaluation, surgical indications, timing of surgery, surgical methods, rib fracture sites for surgical fixation, internal fixation method and material selection, treatment of combined injuries in rib fractures, in order to provide guidance and reference for surgical treatment of traumatic rib fractures.

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Introduction

Rib fracture is the most common injury in chest trauma. In 2019, there were about 248,000 cases of rib fractures in the United States each year, of which 46,000 cases required hospitalization, indicating a trend of annual increase.¹ At present, China lacks a comprehensive trauma database, and it is difficult to obtain accurate data on trauma. It is conservatively estimated that the number

of patients with rib fractures can reach 1.5 to 2.0 million per year.² Most of patients with rib fractures were treated conservatively, but up to 50% of patients, especially those with combined injuries such as flail chest, presented chronic pain or chest wall deformities, and more than 30% had long-term disabilities, and were unable to retain a full-time job.³ The surgical treatment of rib fractures, from early chest wall traction to internal fixation with plates in the 1980s, has advanced slowly in the history of nearly 100 years.⁴ In the past two decades, thanks to the development of material technology, surgery for rib fractures has become simple and widely applied, achieving good outcomes. However, in clinic, there are still some problems including inconsistency in surgical indications and quality control in medical services.² Before year of 2018, there were 3 guidelines on the management of regional traumatic rib fractures published at home and abroad, focusing on the guidance of the overall treatment decisions and plans^{5–7}; another clinical guideline about the surgical treatment of rib fractures⁸ lacks recent related

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progress in surgical treatment of rib fractures. The Chinese Society of Traumatology, Chinese Medical Association, and the Chinese College of Trauma Surgeons, Chinese Medical Doctor Association organized experts from cardiothoracic surgery, trauma surgery, acute care surgery, orthopedics and other disciplines to participate together, following the principle of evidence-based medicine and in line with the scientific nature and practicality, formulated the Chinese consensus for surgical treatment of traumatic rib fractures (2021). This expert consensus put forward some clear, applicable, and graded recommendations from seven aspects: preoperative imaging evaluation, surgical indications, timing of surgery, Surgical methods, rib fracture sites for surgical fixation, internal fixation method and material selection, treatment of combined injuries in rib fractures, in order to provide guidance and reference for surgical treatment of traumatic rib fractures.

Methods and evidences

Expert panel

The panel includes multidisciplinary experts in thoracic surgery, trauma surgery, acute care surgery, orthopedic surgery, neurosurgery.

Source of information

The databases including PubMed, EMBASE, Clinicaltrial.org, Cochrane Library, CNKI, Wanfang Data were searched for related literature and research data published from January 2000 to March 2021. The key words “rib fractures” “flail chest” “wounds and injuries” “surgical treatment” “surgical stabilization of rib fractures” “open reduction and internal fixation” were used for search. A total of 3198 literatures were retrieved, 869 literatures were retained after preliminary screening, and 197 literatures were retained after secondary screening through reading abstracts for intensive reading and collation.

Level of evidence

The evidence classification method of Oxford Centre for Evidence-based Medicine and GRADE were referred.

Level IA: Based on high-level well-designed systematic reviews/meta-analysis and large-scale randomized controlled clinical trials, with sufficient evidence, the expert panel unanimously agreed.

Level IB: Based on rigorous systematic reviews/meta-analysis, large-scale randomized controlled clinical trials, with sufficient evidence, there is little controversy in the expert group.

Level IIA: Based on medium-level systematic reviews/meta-analysis, small-scale randomized controlled studies, large-scale retrospective studies and case-control studies, with good evidence, the expert panel reached a consensus.

Level IIB: Based on medium-level systematic reviews/meta-analysis, small-scale randomized controlled studies, large-scale retrospective studies and case-control studies, the expert group basically reached a consensus, with little controversy.

Level III: Based on uncontrolled clinical studies, case reports and expert opinions, the expert group made relevant recommendations, but there were some differences on the opinion.

Consensus formation

The working group wrote the first manuscript based on relevant domestic and foreign literature, made recommendations, invited relevant experts to have face-to-face discussion twice, and then sent the draft to experts by email for suggestions using the Delphi

method and the suggestions will be sorted out and fed back. The consensus has been completed and submitted in June 2021.

Definitions of related terms

Traumatic rib fracture (TRF): direct or indirect violence acts on the ribs, causing the ribs to bend and break inward at the force-bearing site or making the fractured ends outside the point of action broken outwards.

Multiple rib fracture (MRF): fractures of 2 or more ribs.

Flail chest (FC): double or more fractures of ≥ 3 adjacent ribs and/or costal cartilage. The local chest wall is softened due to the loss of rib support, causing abnormal breathing movement, i.e., the softened chest wall sinks inward during inhalation and protrudes outward during exhalation, while the rest of the thorax performs the opposite.⁹

Preoperative imaging evaluation

The imaging examination currently used for preoperative evaluation of TRFs includes chest X-ray, ultrasound and chest CT. Chest X-ray is the basic method for diagnosing rib fractures. Although it shows low sensitivity, it can detect serious injuries besides rib fractures, such as pneumothorax, hemothorax, FC, or lung contusion, as early as possible and as quick as possible. Standard chest X-ray is usually sufficient for the evaluation of rib fractures, because no evidences indicate that undiagnosed simple rib fractures will affect the treatment or prognosis of blunt chest injuries.¹⁰ In the diagnosis of rib fractures, some studies demonstrate that ultrasound may be superior to chest X-ray, but it still needs to be confirmed by clinical randomized controlled studies.¹¹ The high sensitivity of CT in diagnosing rib fractures may not be necessary to change the outcome of treatment or rescue for patients without organ injuries. However, the patients with rib fractures caused by high-energy injuries show high risk of thoracic and abdominal organ damage, so CT of the chest and abdomen is required, even enhanced CT should be given if necessary.¹⁰ Chest CT also provides valuable information on the number, location and displacement of rib fractures for surgical planning. Compared with 2D images, 3D CT can provide more information before operation. New technologies, including 3D printing, percutaneous navigation and electromagnetic navigation, are useful in the surgical treatment of rib fractures, worthy of further study.^{12–15}

Recommendation 1: Chest CT examination of rib fracture should be performed before surgery, even 3D-CT if necessary (level IIA)

Surgical indications

FC

The conservative treatment methods for floating chest caused by FC include wide tape fixation, cotton pad compression dressing, elastic chest strap, etc. Although the above-mentioned methods can relieve pain and assist coughing, they reduce the ventilation function of the chest on the injured side, which may lead to atelectasis and respiratory insufficiency, significantly increasing the incidence of complications. Moreover, the fractured ends are not anatomically fixed. Therefore, conservative methods are basically abandoned now. The curative effects of chest wall traction fixation and internal fixation of ventilator are not reliable.^{16,17} In recent years, progress has been made in surgical treatment of FC. Five prospective randomized controlled trials and one prospective case-control study showed that compared with non-surgical treatment, FC patients who received surgical stabilization of rib fractures (SSRF) had significantly shorter mechanical ventilation time and

intensive care unit (ICU) stay, lower incidence of lung infection, respiratory failure and thoracic deformity, reduced cases of tracheotomy, significantly relieved pain and improved respiratory function.^{17–22} Five meta-analyses also confirmed these clinical benefits, and reported shortened hospital stay and lower mortality in FC patients undergoing SSRF.^{23–27} Another retrospective cohort study of 625,617 patients with TRFs also showed that FC surgery can reduce patients' mortality.²⁸ CT evaluation was used to compare the lung volume before and after FC operation, and the result showed that the postoperative CT-vital capacity estimate was improved compared with preoperative value.²⁹ A logistic regression model analysis of chest wall injury dataset in the UK indicated that after controlling for related factors, the biggest predictive factor of internal fixation for rib fracture is injury type, to be specific, patients with unilateral FC, bilateral FC, and non-flail fracture involving more than 3 ribs are more likely to undergo surgery compared with those with non-flail fracture of less than 3 ribs.³⁰ A retrospective study conducted by Du et al.¹⁶ also revealed that internal fixation of FC can quickly stabilize the chest wall, improve the affected respiratory function, and restore complete shape of the chest wall, superior to conservative treatment.

In conclusion, the curative effect of surgery for FC has been generally recognized. In spite of small sample size, different methods and inconsistent results of clinical studies, general speaking, the surgical treatment of FC is better than non-surgical treatment. Based on the results of recent researches, the expert panel recommends surgery for the treatment of FC on the basis of foreign clinical guidelines.^{6–8}

Recommendation 2: SSRF should be considered for all patients with FC (level IIA)

Non-flail rib fractures

Besides surgical internal fixation of FC, many studies focus on the surgical internal fixation of non-flail rib fractures. Chien et al.³¹ conducted a retrospective cohort study involving 174 patients with rib fractures and found that more displaced bones in rib fracture led to more chest complications; the number of displaced rib fractures may be a strong predictive factor of pulmonary complications, e.g., the number of fractured ribs (≥ 3) and displacement of the fractured ends (yes/no) are the most sensitive risk factors for chest complications, independent of other risk factors or severity index. Notably, only 4 patients (2.3%) underwent surgical treatment including internal fixation, and others received non-surgical treatment. Two prospective studies and a retrospective case-control study showed that after internal fixation, the patients with non-flail MRFs (≥ 3 fractured ribs, severe displacement) had less use of analgesic drugs, less pain, less complications, shortened time of mechanical ventilation, reduced length of ICU and hospital stay, decreased mortality and significantly improved quality of life related to respiratory dysfunction compared with the non-surgical group.^{32–34} In a prospective study of 128 patients, Lin et al.³⁵ found that internal fixation of rib fracture during exploratory thoracotomy still had the aforementioned benefits. In a prospective single-center study involving 118 patients, Khandelwal et al.³⁶ gave stratified management of all patients based on pain severity: patients with mild to moderate pain received conventional treatment, and patients with severe pain underwent surgery and the result showed that internal fixation of rib fracture reduced pain to a greater extent and shortened the time of disability or time to work.

Recommendation 3: SSRF may be considered for those with non-flail rib fractures in the following situations:

- (1) Non-flail MRFs (≥ 3 fractured ribs) and the broken ends are displaced (level IIB);
- (2) Non-flail rib fractures combined with other conditions requiring exploratory thoracotomy (level III);
- (3) Non-flail rib fractures with severe pain, and early non-surgical treatment proved to be ineffective (level IIB).

Rib fractures with severe lung contusion

Approximately 20% of TRFs (≥ 2 ribs) in adults are combined with lung contusion, of which severe lung contusion (pulmonary contusion volume $\geq 20\%$) accounts for about 6%.^{37,38} Studies showed that after SSRF, patients with rib fractures and pulmonary contusions had significantly lower risk of respiratory failure and tracheotomy, less mechanical ventilation time, improved respiratory function, reduced pain and shorten hospital stay.^{21,39} However, some studies also demonstrated that there was no clear benefit from surgical treatment in patients with rib fractures combined with severe pulmonary contusion.^{40,41} In general, whether to choose surgical internal fixation for rib fractures with severe pulmonary contusion is still controversial, which needs to be clarified by further researches. It is believed that whether internal fixation of rib fractures is suitable for patients with pulmonary contusion depends on the severity of pulmonary contusion.

Recommendation 4: Severe pulmonary contusion should not be considered an absolute contraindication to SSRF, and the patient's conditions should be evaluated before SSRF (level III)

Rib fractures with severe head injury

A multicenter retrospective cohort study included 456 patients with MRFs and moderate to severe head injury, 111 of whom received SSRF treatment, and the median operation time was 3 days.⁴² Compared with the non-surgical treatment group, there was no difference in the time of avoiding mechanical ventilation between the two groups. The incidence of lung infection and 30-day mortality in the SSRF group were significantly reduced. According to the Glasgow coma scale score, the patients were divided into two subgroups. Among them, patients with MRFs and severe head injury (Glasgow coma scale score, ≤ 8 points) had a significant reduction in the 30-day mortality rate after surgery. The incidence of SSRF-related complications was only 3.6%. These data indicate that SSRF may play a role in patients with selective head injury. In addition, early SSRF can improve respiratory function, reduce positive end-expiratory pressure, lower intracranial pressure and further improve cerebral perfusion pressure. For patients with greater chance of brain function recovery or trying to wean, timely internal fixation will help reduce the application of sedation and analgesics, shorten ventilator time and improve the successful rate of weaning. Therefore, severe head injury should not be regarded as an absolute contraindication to SSRF, and individualized SSRF assessment should be carried out in patients with severe head injury. The timing of surgical intervention is a key issue.⁴¹

Recommendation 5: Severe head injury should not be considered as an absolute contraindication to SSRF; the patient's conditions should be evaluated before SSRF (level III)

Timing of surgery

SSRF at early stage is recommended. Tanaka et al.¹⁷ enrolled 37 patients in a randomized clinical trial and SSRF was performed within 5 days of mechanical ventilation. In a randomized clinical trial conducted by Marasco et al.,¹⁹ all 46 cases underwent SSRF within 2 days after mechanical ventilation. A recent retrospective comparative study of 33 patients showed that the patients who underwent SSRF for FC within 3 days after injury had significantly shorter time of mechanical ventilation, ICU and hospital stay, and less medical cost.⁴³ Pieracci et al.⁴⁴ analyzed 551 cases in a multi-center study and compared the outcomes of SSRF at different stage (<1 day, 1–2 days, 3–10 days post-injury); they found that SSRF within 24 h after admission showed shorter operation time and better outcome. In general, it is technically feasible to perform SSRF within 72 h after injury, and the international guidelines for rib fractures also advocate surgery within this time window.^{6,8} For FC combined with pulmonary contusion or more fatal injuries such as severe head injury, abdominal organ injury and severe pelvic fracture and hemorrhage, Gao et al.⁴⁵ adopted the principle of damage control surgery, i.e., at emergency, firstly use simple suspension/traction to correct the floating chest interfering with breathing, deal with fatal injuries and improve the hemodynamics, and then gave internal fixation, achieving good results. He et al.⁴⁶ retrospectively analyzed 794 patients underwent surgery for simple rib fracture and found that 3–7 days after injury was the best time for rib fracture surgery. However, the limitation lies that this is a retrospective study with large time span.

Recommendation 6:

- (1) SSRF should be performed within 72 h after injury (level IIB);
- (2) For rib fractures combined with other fatal injuries, the principle of damage control surgery should be adopted: manage fatal injuries and give primary resuscitation, and then perform SSRF within 3–7 days after injury if possible (level IIB).

Surgical methods

Open surgery

The principles of incision design for open surgery are as follows: full exposure of surgical area, small injury, occult incision, good cosmetic effect, to cut the chest wall but not to enter the thoracic cavity. The preoperative location of fracture is considered a prerequisite for surgical incision design and treatment plan. Rib fracture locations can be divided into front (from anterior thorax to anterior axillary line), lateral (between anterior axillary line and posterior axillary line) and back (from posterior thorax to posterior axillary line),⁴⁷ and no incision is suitable for all types of fractures in SSRF. In clinic, the surgical approaches include standard posterolateral thoracic incision, incision on inframammary fold, sub-axillary incision and subscapular incision.^{15,41,48} Based on the frequent locations of rib fractures and the anatomical structure of the chest wall, in order to reduce trauma, Greiffenstein et al.⁴⁹ designed 3 surgical incisions for rib fractures (anterolateral longitudinal incision, posterolateral auscultation triangle longitudinal incision, and subscapular incision), which were suitable for most of rib fracture surgery using muscle-sparing technique.

Anterolateral longitudinal incision: make a longitudinal incision at the lower edge of the tail of the axillary hairy area, dissect and lift the latissimus dorsi along the anterior edge of the latissimus dorsi,

dissect the serratus anterior muscle and protect the long thoracic nerve.

Posterolateral auscultation triangle longitudinal incision: make a longitudinal incision inside the scapula to expose the auscultation triangle, dissect the trapezius, latissimus dorsi and scapula and lift them, and dissect the paraspinous muscles (stereoliac ribs) if necessary.

Subscapular incision: make an incision along the medial arc of the scapula until the lower corner of the scapula to expose the auscultation triangle, dissect the trapezius, platys, and scapula and lift them, partially cut-open the trapezius and/or latissimus dorsi if necessary. A retrospective case study showed that the internal fixation of rib fractures using muscle-sparing technique is conducive to the recovery of shoulder function and strength.⁵⁰ If the pleural rupture is found during open internal fixation of the ribs and preoperative imaging demonstrated pleural effusion (blood) or coagulated hemothorax, the surgeon can use a suction device to enter the thoracic cavity through the pleural rupture and clear the pleural effusion, even perform a thoracoscopy or appropriately extend the pleural rupture to detect damage of visceral organs in the thoracic cavity, completely remove the blood and blood clots in the thoracic cavity, and place a closed thoracic drainage tube after internal fixation.

Recommendation 7:

- (1) The surgical incision should be selected according to the rib fracture site and the anatomical structure of chest wall (level IIB);
- (2) The muscles of chest wall should be spared as much as possible (level IIB).

Thoracoscopic surgery

There are two methods of thoracoscopic reduction and internal fixation for rib fractures: auxiliary use of a thoracoscope in open SSRF and total thoracoscopic SSRF. Thoracoscopic reduction and internal fixation for rib fractures has the following advantages: small surgical incision, improved visualization of rib fractures, especially subscapular and posterior fractures, reduced damage to chest wall muscle and nerves, minimized damage to the lungs and heart, avoiding discomfort caused by plate displacement, palpable plate and scapula contact, removal of residual hemothorax, placement of chest drainage tubes and local analgesic catheters, thoracic exploration and repair of intrathoracic injuries, less postoperative pain, and shortened time back to work.^{51,52}

Thoracoscopic SSRF refers to the positioning, reduction and internal fixation of rib fractures under a thoracoscope. Theoretically, thoracoscopic SSRF is superior to thoracotomy of SSRF in the following aspects: a wide surgical field of view, no scapular retraction, no touching on chest wall plate after cortical internal fixation, less structural damage in the pleural cavity, and expanding surgical indications for posterior rib fracture (near the spine). Total thoracoscopic SSRF is clinically applicable, which has been reported in the literature at home and abroad.^{52–55} In China, the devices and instruments designed for total thoracoscopic SSRF have been developed, by which sufficient reduction and fixation can be achieved.

Recommendation 8:

- (1) The auxiliary use of a thoracoscope in open SSRF is advised (level III)
- (2) The total thoracoscopic SSRF is advised (level III)

Rib fracture sites for surgical fixation

The anatomy in periphery of rib fracture sites should be considered in surgical internal fixation. The first and second ribs are deep inside the body, hard to expose, with low mobility, involving with important blood vessels and nerves around, so the risk of surgery is relatively high. The 11th and 12th ribs are floating ribs, with little effect on breathing after fractures. Unless the ribs are significantly displaced, causing damage to blood vessels, nerves, thoracic or abdominal organs, organ incarceration, lung hernia, or obvious chest wall deformities, surgical internal fixation is not recommended.^{8,56,57} If the fracture brings remarkable physiological hazards, fixation should be the top priority and the side-injury caused by operation should be evaluated in order to reduce or eliminate the hazards. It is important to find a balance between fixation effect and injury caused by surgery. The lateral and lower rib fracture is the first choice for fixation since it brings great pain.⁴¹ The ribs move continuously with breathing, and the fractured parts are particularly prone to shearing movement. Once the fractured rib is completely displaced, it will shear due to the inevitable movement during breathing. In addition, the dislocation and movement of ribs are also the main causing factors of pain. Therefore, displaced rib fracture is the top priority of surgical fixation. For the FC, the management of fixation on each fractured end as simple rib fracture cannot avoid deformity and displacement, especially for the posterior rib fracture. Although it has been confirmed in imaging studies, there are no reports on its effect on function or quality of life. The literature showed that the incidence of bone bridges between adjacent ribs in non-fixed fractures (54%) was twice that of fixed fractures (23%). It is speculated that bone bridges are related to the periosteum tearing at the rib fracture site, and the formation of bone bridges may affect compliance of thorax. Therefore, all palpable fractures should be fixed as much as possible under ideal conditions.⁵⁸ However, Gao⁵⁹ figured out that rib fixation surgery is to improve chest wall compliance, rather than increase chest trauma and destroy chest wall compliance. It is not recommended to arbitrarily increase the number of internal fixed ribs and excessively strip chest wall.

When there is sufficient rib length at both ends of the fracture line (≥ 2.5 cm), the existing rib repair system can achieve good fixation and ensure sufficient stability. It is difficult to fix the posterior back rib fracture near the transverse process and the anterior chest rib fracture near the sternum. The thoracic approach can expand the surgical indications for the posterior back rib fracture adjacent to the transverse process.⁵² The anterior-wall FC can be fixed with steel plates, steel wires, and sutures. It is reported that the fractured ends of the costal cartilage near the sternum are fixed to the sternum, but there is a risk of affecting the compliance of thorax, which has not been confirmed yet. In literature, there are some reports on plate and screw fixation for rib fracture combined with sternum fracture,⁶⁰ or costal cartilage fracture.⁶¹

Recommendation 9:

- (1) For rib fractures (non-FC), all displaced ribs should be fixed (level IIB);
- (2) For rib fractures (FC), it is recommended to fix different fractured segments of multiple ribs (level III);
- (3) Surgery is not recommended for fractures of the 1st, 2nd, 11th and 12th ribs. In cases of significant displacement, vascular injury, risk of local organ damage, or local intractable pain, rib fracture fixation can be performed (level III).
- (4) Surgical internal fixation is not recommended for rib fractures within 2.5 cm from the transverse process, without significant displacement (level III).

- (5) Costal cartilage fractures can be repaired by fixing to the cartilage or sternum (level III)

Internal fixation method and material selection

There are usually 2 types of internal fixation for rib fractures: cortical fixation and intramedullary fixation. The corresponding materials should be selected according to the internal fixation method.

Cortical fixation

Cortical fixation is divided into outer and inner cortical fixation based on different positions of fixators, or encircling fixation and plate and screw fixation based on different fixation methods, or single cortical fixation and double cortical fixation according to the depth of screw fixation. There is no clinical evidence to demonstrate the advantages and disadvantages of encircling fixation and plate and screw fixation. Most of fixators in clinic are steel plates, especially the rib-like internal fixation system designed according to the biomechanical properties of the ribs introduced by Bottlang et al.⁶² The anatomical plate is suitable for severe comminuted rib fractures. Two adjacent rib fractures of FC can be bridged using a single long anatomical plate, which is the key to stabilizing the FC.⁶³ Due to the complex geometry of the ribs, it may be difficult to prepare a steel plate that fits the rib contour during the operation. Some study reported screw loosening and pullout in the cases of plate fixation,⁶⁴ so intraoperative shaping is important. In clinical practice, the choice of plate and screw fixation is based on whether a multi-segment fracture of single rib exists. Usually, for multi-segment fracture of single rib, a long-span steel plate is more conducive to the recovery of the thoracic shape. In addition, if the fractured ends are located next to the sternum or spine, a steel plate and screws are more conducive to fixation across the ribs. The fixation using shape memory alloy encircling device and the claw-shaped bone plate are easy to operate. During the operation, after fully dissecting the periosteum, the fractured ends are precisely reduced and fixed. Those fixators are suitable for patients with multiple fractures, but there is a risk of chronic postoperative pain because of compression on intercostal nerves, so they are not suitable for costal cartilage fractures or fractures near the spine.^{15,65–67} Small incision or auxiliary thoracoscopic surgery can be adopted using the Rib Minimally Invasive Plate System (MatrixRIB-MIPO), which can accurately build the shape of fractured ribs, and firmly fix multi-segment fractures, especially for costal cartilage fractures or fractures near the spine.⁶³ Compared with the standard anterior fixation plate, the U-shaped plate has the advantages of significantly shorter length, less time to expose broken ends of fractured ribs, and higher durability, which is conducive to minimally invasive rib fracture repair.⁶⁸

Although the SSRF system approved by the Food and Drug Administration does not specify where to place the plate (outer cortex or inner cortex), all studies related to structural strength, metal fatigue, plate flexibility and screw strength are conducted on the system placed on the outer cortex. The contours of all plates are located on the outer cortex, so the plates should be placed on the outer cortex of the ribs. A commercially available inner cortex fixation system was reported to obtain good fixation effect and early follow-up result was beneficial.⁵² The inner cortex of ribs is 33% thicker than the outer cortex, and the density of the inner cortex is twice that of the outer cortex. Theoretically, any rib fracture can be fixed on the inner cortex, which is thicker and denser, so the fixation is firmer.⁶⁹ However, Choke et al.⁷⁰ studied biomechanics of monocortical and bicortical plate fixation for rib fractures in a

cadaveric model and found no difference in the stability of fixation. Monocortical fixation is recommended to avoid complications such as potential pleural injury and thoracic organ damage.

At present, the commonly used plates are made of titanium alloy, including remodeling plates, titanium microplates, U-shaped plates, etc. Most of encircling devices are made of nickel-titanium memory alloy. The bone plate is widely used, easy to use, reliable and compatible, but it cannot firmly fix costal cartilage fractures, and it needs to be removed by a second operation because it is made of non-degradable materials. When choosing fixation material, the following aspects: easy-to-use, biomechanical properties, complication risk and cost of implant, should be the surgeon's top concerns.²⁴ At present, most of the SSRF evidence supports the use of outer cortex plate and bicortical screw fixation.^{3,19,21,22,35,63} Claw-shaped plates such as shape memory alloy rib encircling device and claw-shaped bone plates are also commonly used in China.^{71–73}

Intramedullary fixation

At present, no clinical evidences prove that intramedullary fixation is superior or inferior to cortical fixation. However, in biomechanics, the intramedullary rod only provides a fixed point, and the distal rib has no fixed point, which cannot prevent the separation of the fracture line theoretically. Intramedullary fixation has advantages of small incision, less trauma and avoiding periosteal dissection.

The intramedullary rib splint is commonly used for minimally invasive fixation of simple, non-comminuted fractures. It can replace reduction and fixation of ribs using Kirschner wire. This intramedullary fixation method is good for posterior rib fractures, but cannot be used for paravertebral fractures.^{63,74} Absorbable rib nails are made of polylactic acid polymer and have been successfully used in traumatic FC surgery.⁶⁴ However, rib nails are of limited use in patients with anterior rib fractures or comminuted fractures, rib stenosis and small bone marrow cavity.⁷⁵

Recommendation 10:

- (1) Rib fractures can be fixed with anatomical plates and claw-shaped plates (level IIA)
- (2) No enough evidences demonstrate whether bicortical or monocortical fixation is superior in SSRF (level IIB)
- (3) Compared with absorbable plates, permanent plates can provide better strength and reliability (level III).
- (4) Intramedullary rib splints and rib nails can be used to fix simple, non-comminuted fractures (level III)

Treatment of combined injuries in rib fractures

Lung injury and hemopneumothorax

The number of rib fractures is significantly correlated with the incidence of hemothorax and/or pneumothorax. The more rib fractures, the higher incidence of concurrent hemothorax and/or pneumothorax. The incidence of concurrent hemothorax and/or pneumothorax (339 cases) was 6.7%, 24.9%, and 81.4% in blunt chest injury patients without rib fractures, with 1–2 rib fractures, and with >2 rib fractures, respectively; 76.7% of patients (226 cases) required closed drainage of thoracic cavity.⁷⁶ Lin et al.⁷⁷ made a similar conclusion in a retrospective cohort study of 1621 patients with chest trauma. Hemothorax patients are in risk of empyema. A multi-center, prospective study conducted by the American Association of Trauma Surgery showed that in 328 hemothorax patients from 20 medical centers, including 167 patients with penetrating chest injuries (stab wounds/gunshot wounds), the incidence of

empyema was 26.8%; rib fractures, injury severity score ≥ 25 , and interventions for pleural hemorrhage were independent predictors of post-traumatic hemothorax combined with empyema.⁷⁸ Therefore, intraoperative thoracic exploration is recommended for rib fracture patients with hemothorax (>300 mL) and/or pneumothorax and with indications for internal fixation.³⁵ Its purpose is to remove residual pleural hemorrhage, repair lung injury/intrapulmonary hematoma/hematocele, assist in positioning the fractured ends of ribs, place a closed thoracic drainage tube and give necessary analgesia.⁴⁷ If the displacement of fractured ends and comminuted fracture involve the pleura, and a clear pleural rupture is found during the operation, closed drainage of thoracic cavity should be given in principle. For patients with clear thoracic organ damage, a closed thoracic drainage tube should be routinely placed after pleural cavity exploration.

Bone defects

Anatomical reduction is the basic principle of orthopedic surgery, and it is also applicable to SSRF. Free rib fragments should be reduced and fixed during SSRF. In generally speaking, small gap (<10 mm) between fractured end of rib can be managed by anatomical reduction, and ribs with defects larger than 10 mm should be bridged with plates and bone grafting is considered if necessary. Autologous and non-autologous grafts are equally effective for bone grafting surgery, but autologous bone is regarded as the gold standard.⁷⁹ The iliac bone is mostly used for bone grafting. No matter which technology is used, all grafts should meet the following criteria: structural integrality, osteoinductivity, osteoconductivity and osseointegration. Usually, single rib defect has little effect on respiratory function, demanding no surgical reconstruction.

Injury and defect of chest wall muscles

If remarkable chest wall muscle damage or defect is found during the operation, indicating existence of lung herniation or high risk of lung herniation, it is recommended to repair the muscle defect by pericostal fixation. The adjacent ribs are fixed using absorbable suture to close or minimize intercostal defect. If the defect cannot be repaired by suture, a pedicled myocutaneous flap and/or other materials (patch, mesh, etc.) can be used.⁸⁰

Recommendation 11:

- (1) For rib fracture patients with hemothorax and/or pneumothorax (>300 mL) and indication for internal fixation, it is recommended to perform routine thoracic exploration in SSRF (level IIA);
- (2) If thoracic viscera injury is definite, the thoracic cavity should be explored before SSRF (level III);
- (3) If the pleural cavity damage is found during SSRF, a closed pleural drainage tube (level III) should be placed;
- (4) If remarkable chest wall muscle damage or defect is found during the operation, indicating existence of lung herniation or high risk of lung herniation, it is recommended to repair the muscle defect by pericostal fixation. If the defect cannot be repaired by suture, a pedicled myocutaneous flap and/or other materials (patch, mesh, etc.) can be used (level IIA).

Statement

The purpose of this consensus is to provide standardized guidance for the SSRF. The recommendations are based on evidence-based medicine principles and multidisciplinary experts' opinions. However, the current consensus may be updated as research on the

SSFR continues and more high-quality clinical evidence emerges. This consensus is only for academic guidance and not for legal basis. In actual clinical work, individual differences exist in patients' conditions and the clinical situation is complex and changeable, so this consensus should be applied according to the specific situation.

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Ethical statement

Not applicable.

Declaration of competing interest

All authors declare that there is no conflict of interests.

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Appendix B. Supplementary data

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References

- Martin TJ, Eltorai AS, Dunn R, et al. Clinical management of rib fractures and methods for prevention of pulmonary complications: a review. *Injury*. 2019;50:1159–1165. <https://doi.org/10.1016/j.injury.2019.04.020>.
- He WW, Yang Y, Wu WM, et al. Chest wall stabilization (CWS) in China: current situation and prospect. *J Thorac Dis*. 2019;11:S1104–S1148. <https://doi.org/10.21037/jtd.2019.03.31>.
- Majercik S, Cannon Q, Granger SR, et al. Long-term patient outcomes after surgical stabilization of rib fractures. *Am J Surg*. 2014;208:88–92. <https://doi.org/10.1016/j.amjsurg.2013.08.051>.
- Bemelman M, Poeze M, Blokhuis TJ, et al. Historic overview of treatment techniques for rib fractures and flail chest. *Eur J Trauma Emerg Surg*. 2010;36:407–415. <https://doi.org/10.1007/s00068-010-0046-5>.
- Brasel KJ, Moore ER, Albrecht RA, et al. Western Trauma Association critical decisions in trauma: management of rib fractures. *J Trauma Acute Care Surg*. 2017;82:200–203. <https://doi.org/10.1097/TA.0000000000001301>.
- Kasotakis G, Hasenboehler EA, Streib EW, et al. Operative fixation of rib fractures after blunt trauma: a practice management guideline from the Eastern Association for the Surgery of Trauma. *J Trauma Acute Care Surg*. 2017;82:618–626. <https://doi.org/10.1097/TA.0000000000001350>.
- Qiao GB, Chen G. Treatment of traumatic rib fractures: guangdong thoracic surgery industry consensus (2017 Edition). *Chinese Journal of Clinical Thoracic and Cardiovascular Surgery*. 2018;25:362–367.
- Pieracci FM, Majercik S, Ali-Osman F, et al. Consensus statement: surgical stabilization of rib fractures rib fracture colloquium clinical practice guidelines. *Injury*. 2017;48:307–321. <https://doi.org/10.1016/j.injury.2016.11.026>.
- Demetriades D, Inaba K. *The Initial Assessment Management of Trauma*. seventh ed. Beijing: China Science Publishing & Media Ltd; 2021:47–49.
- Henry TS, Donnelly EF, Boiselle PM, et al. ACR appropriateness Criteria® rib fractures. *J Am Coll Radiol*. 2019;16:S227–S234. <https://doi.org/10.1016/j.jacr.2019.02.019>.
- Battle C, Hayward S, Eggert S, et al. Comparison of the use of lung ultrasound and chest radiography in the diagnosis of rib fractures: a systematic review. *Emerg Med J*. 2019;36:185–190. <https://doi.org/10.1136/emmermed-2017-207416>.

12. Zhou XT, Zhang DS, Yang Y, et al. Analysis of the advantages of 3D printing in the surgical treatment of multiple rib fractures: 5 cases report. *J Cardiothorac Surg.* 2019;14(1):105. <https://doi.org/10.1186/s13019-019-0930-y>.
13. Zhou XT, Zhang DS, Xie ZX, et al. Application of 3D printing and framework internal fixation technology for high complex rib fractures. *J Cardiothorac Surg.* 2021;16(1):5. <https://doi.org/10.1186/s13019-020-01377-8>.
14. Pedraza R, Chan EY, Meisenbach LM, et al. Using electromagnetic navigation for intraoperative rib fracture localization during rib plating: a case report. *Int J Surg Case Rep.* 2018;53:386–389. <https://doi.org/10.1016/j.ijscr.2018.11.029>.
15. Zhang Q, Song L, Ning SN, et al. Recent advances in rib fracture fixation. *J Thorac Dis.* 2019;11:S1070–S1077. <https://doi.org/10.21037/jtd.2019.04.99>.
16. Du DY, Su HJ, Tan YK, et al. Comparison between surgical and conservative treatment for flail chest. *J Trauma Surg.* 2009;11:196–199.
17. Tanaka H, Yukioka T, Yamaguti Y, et al. Surgical stabilization of internal pneumatic stabilization? A prospective randomized study of management of severe flail chest patients. *J Trauma.* 2002;52:727–732. <https://doi.org/10.1097/00005373-200204000-00020>.
18. Granetzny A, Abd El-Aal M, Emam E, et al. Surgical versus conservative treatment of flail chest. Evaluation of the pulmonary status. *Interact Cardiovasc Thorac Surg.* 2005;4:583–587. <https://doi.org/10.1510/icvts.2005.11.1807>.
19. Marasco SF, Davies AR, Cooper J, et al. Prospective randomized controlled trial of operative rib fixation in traumatic flail chest. *J Am Coll Surg.* 2013;216:924–932. <https://doi.org/10.1016/j.jamcollsurg.2012.12.024>.
20. Jayle CPM, Allain G, Ingrand P, et al. Flail chest in polytraumatized patients: surgical fixation using staplers reduces ventilator time and hospital stay. *BioMed Res Int.* 2015;2015:624723. <https://doi.org/10.1155/2015/624723>.
21. Pieracci FM, Lin Y, Rodil M, et al. A prospective, controlled clinical evaluation of surgical stabilization of severe rib fractures. *J Trauma Acute Care Surg.* 2016;80:187–194. <https://doi.org/10.1097/TA.0000000000000925>.
22. Liu T, Liu P, Chen JJ, et al. A randomized controlled trial of surgical rib fixation in polytrauma patients with flail chest. *J Surg Res.* 2019;242:223–230. <https://doi.org/10.1016/j.jss.2019.04.005>.
23. Leinicke JA, Elmore L, Freeman BD, et al. Operative management of rib fractures in the setting of flail chest: a systematic review and meta-analysis. *Ann Surg.* 2013;258:914–921. <https://doi.org/10.1097/SLA.0b013e3182895bb0>.
24. Slobogean GP, MacPherson CA, Sun T, et al. Surgical fixation vs nonoperative management of flail chest: a meta-analysis. *J Am Coll Surg.* 2013;216:302–311. <https://doi.org/10.1016/j.jamcollsurg.2012.10.010>.
25. Coughlin TA, Ng JWG, Rollins KE, et al. Management of rib fractures in traumatic flail chest: a Meta-Analysis of Randomised Controlled Trials. *Bone Joint Lett J.* 2016;98-B:1119–1125. <https://doi.org/10.1302/0301-620X.98B.37282>.
26. Swart E, Laratta J, Slobogean G, et al. Operative treatment of rib fractures in flail chest injuries: a meta-analysis and cost-effectiveness analysis. *J Orthop Trauma.* 2017;31:64–70. <https://doi.org/10.1097/BOT.0000000000000750>.
27. Liang YS, Yu KC, Wong CS, et al. Does surgery reduce the risk of complications among patients with multiple rib fractures? A meta-analysis. *Clin Orthop Relat Res.* 2019;477:193–205. <https://doi.org/10.1097/CORR.0000000000000495>.
28. Tignanello CJ, Rix A, Napolitano LM, et al. Association between adherence to evidence-based practices for treatment of patients with traumatic rib fractures and mortality rates among US trauma centers. *JAMA Network Open.* 2020;3:e201316. <https://doi.org/10.1001/jamaetworkopen.2020.1316>.
29. Caragounisa EC, Olsén MF, Granhed H, et al. CT-lung volume estimates in trauma patients undergoing stabilizing surgery for flail chest. *Injury.* 2019;50:101–108. <https://doi.org/10.1016/j.injury.2018.10.016>.
30. Ingoe HM, Eardley W, McDaid C, et al. Epidemiology of adult rib fracture and factors associated with surgical fixation: analysis of a chest wall injury dataset from England and Wales. *Injury.* 2020;51:218–223. <https://doi.org/10.1016/j.injury.2019.10.030>.
31. Chien CY, Chen YH, Han ST, et al. The number of displaced rib fractures is more predictive for complications in chest trauma patients. *Scand J Trauma Resuscitation Emerg Med.* 2017;25:19. <https://doi.org/10.1186/s13049-017-0368-y>.
32. Pieracci FM, Leasia K, Bauman Z, et al. A multicenter, prospective, controlled clinical trial of surgical stabilization of rib fractures in patients with severe, nonflail fracture patterns (Chest Wall Injury Society NONFLAIL). *J Trauma Acute Care Surg.* 2020;88:249–257. <https://doi.org/10.1097/TA.0000000000002559>.
33. Wu WM, Yang Y, Gao ZL, et al. Which is better to multiple rib fractures, surgical treatment or conservative treatment? *Int J Clin Exp Med.* 2015;8:7930–7936.
34. Kane ED, Jeremitsky E, Bittner KR, et al. Surgical stabilization of rib fractures: a single institution experience. *J Am Coll Surg.* 2018;226:961–966. <https://doi.org/10.1016/j.jamcollsurg.2017.11.008>.
35. Lin HL, Tarnng YW, Wu TH, et al. The advantages of adding rib fixations during VATS for retained hemothorax in serious blunt chest trauma-A prospective cohort study. *Int J Surg.* 2019;65:13–18. <https://doi.org/10.1016/j.ijsu.2019.02.022>.
36. Khandelwal G, Mathur RK, Shukla S, et al. A prospective single center study to assess the impact of surgical stabilization in patients with rib fracture. *Int J Surg.* 2011;9:478–481. <https://doi.org/10.1016/j.ijsu.2011.06.003>.
37. Choi J, Tennakoon L, You JG, et al. Pulmonary contusions in patients with rib fractures: the need to better classify a common injury. *Am J Surg.* 2021;221:211–215. <https://doi.org/10.1016/j.amjsurg.2020.07.022>.
38. Miller C, Stolarski A, Ata A, et al. Impact of blunt pulmonary contusion in polytrauma patients with rib fractures. *Am J Surg.* 2019;218:51–55. <https://doi.org/10.1016/j.amjsurg.2019.01.027>.
39. Jiang YH, Wang X, Teng LX, et al. Comparison of the effectiveness of surgical versus nonsurgical treatment for multiple rib fractures accompanied with pulmonary contusion. *Ann Thorac Cardiovasc Surg.* 2019;25:185–191. <https://doi.org/10.5761/atcs.0a.18-00295>.
40. Vana PG, Neubaue DC, Luchette FA. Contemporary management of flail chest. *Am Surg.* 2014;80:527–535. <https://doi.org/10.1177/000313481408000613>.
41. He Z, Zhang DS, Xiao HP, et al. The ideal methods for the management of rib fractures. *J Thorac Dis.* 2019;11:S1078–S1089. <https://doi.org/10.21037/jtd.2019.04.109>.
42. Prins JTH, Lieshout EMMV, Ali-Osman F, et al. Outcome after surgical stabilization of rib fractures versus nonoperative treatment in patients with multiple rib fractures and moderate to severe traumatic brain injury (CWIS-TBI). *J Trauma Acute Care Surg.* 2021;90:492–500. <https://doi.org/10.1097/TA.0000000000002994>.
43. Su YH, Yang SM, Huang CH, et al. Early versus late surgical stabilization of severe rib fractures in patients with respiratory failure: a retrospective study. *PLoS One.* 2019;14, e0216170. <https://doi.org/10.1371/journal.pone.0216170>.
44. Pieracci FM, Coleman J, Ali-Osman F, et al. A multicenter evaluation of the optimal timing of surgical stabilization of rib fractures. *J Trauma Acute Care Surg.* 2018;84:1–10. <https://doi.org/10.1097/TA.0000000000001729>.
45. Gao JM, Du DY, Liu CP, et al. Damage control surgery for treatment of flail chest combined with multiple trauma. *Chin J Traumatol.* 2013;29:343–347.
46. He WW, Yang Y, Wu WM, et al. Optimal operation timing and combined surgery of concomitant injury in patients with multiple rib fractures. *Shanghai Med J.* 2020;43:407–412.
47. Edwards JG, Clarke P, Pieracci FM, et al. Taxonomy of multiple rib fractures: results of the chest wall injury society international consensus survey. *J Trauma Acute Care Surg.* 2020;88:e40–e45. <https://doi.org/10.1097/TA.0000000000002282>.
48. Taylor BC, French BG, Fowler TT, et al. Surgical approaches for rib fracture fixation. *J Orthop Trauma.* 2013;27:e168–e173. <https://doi.org/10.1097/BOT.0b013e318283fa2d>.
49. Greiffenstein P, Tran MQ, Campeau L. Three common exposures of the chest wall for rib fixation: anatomical considerations. *J Thorac Dis.* 2019;11:S1034–S1043. <https://doi.org/10.21037/jtd.2019.03.33>.
50. Taylor BC, Fowler TT, Reddy H, et al. Functional outcomes after muscle-sparing fixation of flail chest injuries. *J Orthop Trauma.* 2019;33:366–369. <https://doi.org/10.1097/BOT.00000000000001456>.
51. Schots JPM, Vissers YLJ, Hulsewe KWE, et al. Addition of video-assisted thoracoscopic surgery to the treatment of flail chest. *Ann Thorac Surg.* 2017;103:940–944. <https://doi.org/10.1016/j.athoracsurg.2016.09.036>.
52. Pieracci FM. Completely thoracoscopic surgical stabilization of rib fractures: can it be done and is it worth it? *J Thorac Dis.* 2019;11:S1061–S1069. <https://doi.org/10.21037/jtd.2019.01.70>.
53. Pieracci FM, Johnson J, Stoval RT, et al. Completely thoracoscopic, intra-pleural reduction and fixation of severe rib fractures. *Trauma Case Rep.* 2015;1:39–43. <https://doi.org/10.1016/j.tcr.2015.10.001>.
54. Su ZY, Zhang YL, Wei F, et al. Clinical application of SU's total thoracoscopic intrathoracic implantation and fixation with bone plates and nails for rib fractures. *Chin J Clin Thorac Cardiovasc Surg.* 2013;20:362–364.
55. Ke S, Duan H, Cai Y, et al. Thoracoscopy-Assisted minimally invasive surgical stabilization of the anterolateral flail chest using nuss bars. *Ann Thorac Surg.* 2014;97:2179–2182. <https://doi.org/10.1016/j.athoracsurg.2013.08.066>.
56. Marasco S, Saxena P. Surgical rib fixation-Technical aspects. *Injury.* 2015;46:929–932. <https://doi.org/10.1016/j.injury.2014.12.021>.
57. Pieracci FM, Rodil M, Stovall RT, et al. Surgical stabilization of severe rib fractures. *J Trauma Acute Care Surg.* 2015;78:883–887. <https://doi.org/10.1097/TA.0000000000000581>.
58. Marasco S, Liew S, Edwards E, et al. Analysis of bone healing in flail chest injury: do we need to fix both fractures per rib? *J Trauma Acute Care Surg.* 2014;77:452–458. <https://doi.org/10.1097/TA.0000000000000375>.
59. Gao JM. Progress and controversy in management of traumatic flail chest. *J Trauma Surg.* 2011;13:187–188.
60. Gao EJ, Li Y, Zhao TC, et al. Simultaneous surgical treatment of sternum and costal cartilage fractures. *Ann Thorac Surg.* 2019;107:e119–e120. <https://doi.org/10.1016/j.athoracsurg.2018.06.044>.
61. Sollender GE, White TW, Pieracci FM. Fracture of the costal cartilage: presentation, diagnosis, and management. *Ann Thorac Surg.* 2019;107:e267–e268. <https://doi.org/10.1016/j.athoracsurg.2018.08.076>.
62. Bottlang M, Walleiser S, Noll M, et al. Biomechanical rationale and evaluation of an implant system for rib fracture fixation. *Eur J Trauma Emerg Surg.* 2010;36:417–426. <https://doi.org/10.1007/s00068-010-0047-4>.
63. Bottlang M, Long WB, Phelan D, et al. Surgical stabilization of flail chest injuries with MatrixRIB implants: a prospective observational study. *Injury.* 2013;44:232–238. <https://doi.org/10.1016/j.injury.2012.08.011>.
64. Lafferty PM, Anavian J, Will RE, et al. Operative treatment of chest wall injuries: indications, Technique, and outcomes. *J Bone Joint Surg Am.* 2011;93:97–110. <https://doi.org/10.2106/JBJS.1.00696>.
65. Xu FY, Wang N, Ren J, et al. Comparison of the therapeutic effect between anatomical plates and claw-type bone plates in fixation of multiple rib fractures. *Chin J Emerg Med.* 2019;28:232–235.
66. Zhang XF, Guo ZQ, Zhao CC, et al. Management of patients with flail chest by surgical fixation using claw-type titanium plate. *J Cardiothorac Surg.* 2015;10:145. <https://doi.org/10.1186/s13019-015-0363-1>.
67. Yang Y, Dong LW, Wang J. Memory alloy embracing fixator in treatment of multiple fractured ribs and flail chest. *World J Emerg Med.* 2010;1:212–215.

68. Sales JR, Ellis TJ, Gillard J, et al. Biomechanical testing of a novel, minimally invasive rib fracture plating system. *J Trauma*. 2008;64:1270–1274. <https://doi.org/10.1097/TA.0b013e31804a7fd5>.
69. Casha AR, Camilleri L, Manche A, et al. Internal rib structure can be predicted using mathematical models: an anatomic study comparing the chest to a shell dome with application to understanding fractures. *Clin Anat*. 2015;28:1008–1016. <https://doi.org/10.1002/ca.22614>.
70. Choke A, Wong YR, Joethy JV. Biomechanical comparison of monocortical and bicortical plate fixation for rib fractures in a cadaveric model using a locking plate system. *J Thorac Dis*. 2019;11:4966–4971. <https://doi.org/10.21037/jtd.2019.12.31>.
71. Wu WM, Zhang JP, Jiang MY, et al. Internal fixation with claw-shaped rib plate for traumatic floating chest wall. *Chin J Thorac Cardiovasc Surg*. 2005;21:23.
72. Xu EW, Qiao GB, Peng XF, et al. Indications and surgical techniques of fixation of rib fractures with memory alloy osteosynthesis plates. *Chin J Traumatol*. 2012;28:533–536.
73. Liu Y, Yu Q, Zhu J, et al. Pure titanium rib plate for treatment of flail chest and multiple rib fractures. *Chin J Traumatol*. 2013;9:650–652.
74. Helzel I, Long W, Fitzpatrick D, et al. Evaluation of intramedullary rib splints for less-invasive stabilisation of rib fractures. *Injury*. 2009;40:1104–1110. <https://doi.org/10.1016/j.injury.2009.06.004>.
75. Marasco SF, Sutalo ID, Bui AV. Mode of failure of rib fixation with absorbable plates: a clinical and numerical modeling study. *J Trauma*. 2010;68:1225–1233. <https://doi.org/10.1097/TA.0b013e3181d27cab>.
76. Liman ST, Kuzucu A, Tastepe IA, et al. Chest injury due to blunt trauma. *Eur J Cardio Thorac Surg*. 2003;23:374–378. [https://doi.org/10.1016/s1010-7940\(02\)00813-8](https://doi.org/10.1016/s1010-7940(02)00813-8).
77. Lin FC, Li RY, Tung YW, et al. Morbidity, mortality, associated injuries, and management of traumatic rib fractures. *J Chin Med Assoc*. 2016;79:329–334. <https://doi.org/10.1016/j.jcma.2016.01.006>.
78. DuBose J, Inaba K, Okoye O, et al. Development of posttraumatic empyema in patients with retained hemothorax: results of a prospective, observational AAST study. *J Trauma Acute Care Surg*. 2012;73:752–757. <https://doi.org/10.1097/TA.0b013e31825c1616>.
79. Wang WH, Yeung KWK. Bone grafts and biomaterials substitutes for bone defect repair: a review. *Bioact Mater*. 2017;2:224–247. <https://doi.org/10.1016/j.bioactmat.2017.05.007>.
80. Sanna S, Brandolini J, Pardolesi A, et al. Materials and techniques in chest wall reconstruction: a review. *J Vis Surg*. 2017;3:95. <https://doi.org/10.21037/jovs.2017.06.10>.