Prospective Randomized Controlled Trial of Operative Rib Fixation in Traumatic Flail Chest

Silvana F Marasco, MSurg, FRACS, Andrew R Davies, FRACP, FCICM, Jamie Cooper, FRACP, FCICM, MD, Dinesh Varma, FRANZCR, Victoria Bennett, BNSc, CCRN, Rachael Nevill, BNurs, Geraldine Lee, MPhil, Michael Bailey, PhD, MSc (statistics), Mark Fitzgerald, FACEM

BACKGROUND: Traumatic flail chest injury is a potentially life threatening condition traditionally treated with invasive mechanical ventilation to splint the chest wall. Longer-term sequelae of pain, deformity, and physical restriction are well described. This study investigated the impact of operative fixation in these patients.

STUDY DESIGN: A prospective randomized study compared operative fixation of fractured ribs in the flail segment with current best practice mechanical ventilator management. In-hospital data, 3-month follow-up review, spirometry and CT, and 6-month quality of life (Short Form-36) questionnaire were collected.

RESULTS: Patients in the operative fixation group had significantly shorter ICU stay (hours) postrandomization (285 hours [range 191 to 319 hours] for the surgical group vs 359 hours [range 270 to 581 hours] for the conservative group; $p = 0.03$) and lesser requirement for noninvasive ventilation after extubation (3 hours [range 0 to 25 hours] in the surgical group vs 50 hours [range 17 to 102 hours] in the conservative group; $p = 0.01$). No differences in spirometry at 3 months or quality of life at 6 months were noted.

CONCLUSIONS: Operative fixation of fractured ribs reduces ventilation requirement and intensive care stay in a cohort of multitrauma patients with severe flail chest injury. (J Am Coll Surg 2013;216:924–932. © 2013 by the American College of Surgeons)

Flail chest is a severe thoracic injury associated with significant morbidity and mortality. Mortality rates of up to 33% have been reported, reflecting the severity of the injury as well as the likelihood of associated life threatening injuries such as splenic, liver, myocardial and lung lacerations.[1] Risk of death is significantly higher in both young patients (18 to 45 years) with rib fractures of Abbreviated Injury Score (AIS) of 3 or greater (odds ratio 1.4; 95% CI 1.3 to 1.6) and older patients (over 64 years) (odds ratio 2.5; 95% CI 2.3 to 2.8).[2] Patients with flail chest often have severe acute respiratory failure requiring mechanical ventilation and prolonged ICU stay. Long-term morbidity, including chronic pain, deformity, disability, and respiratory compromise, have been well documented.[3,4]

Despite some promising prospective trials, operative rib fixation of flail chest is not considered standard management and is not practiced widely. Currently, rib fixation tends to be used in specialty trauma centers and is practiced by a minority of cardiothoracic, trauma, or orthopaedic surgeons. Reasons for this include lack of familiarity with existing evidence, and until recently, a lack of specific rib fixation prostheses.[5]

We conducted a prospective randomized controlled trial involving traumatic flail chest patients receiving mechanical ventilation comparing operative rib fixation to nonoperative management. This single institution study was performed at The Alfred Hospital, 1 of 2 adult major trauma centers in Victoria, Australia.[6] More than 1,200 major trauma patients with an overall mortality of 8% are treated each year, including approximately 580 adult thoracic trauma (Maximum Abbreviated Injury Score [1998 version] >2) patients, with an overall mortality of 5%.

CME questions for this article available at http://jacscme.facs.org

Disclosure Information: Authors have nothing to disclose. Timothy J Eberlein, Editor-in-Chief, has nothing to disclose.

Support: This study was funded by a grant from the Transport Accident Commission, Victoria, Australia.

Received October 25, 2012; Revised December 3, 2012; Accepted December 11, 2012.

From the CJOB Cardiothoracic Surgery Department (Marasco, Lee), the Intensive Care Unit (Davies, Cooper, Bennet, Nevill), the Department of Radiology (Varma, Bailey), and the Trauma Service (Fitzgerald), The Alfred Hospital; the Department of Surgery (Marasco, Varma), Monash University, The Alfred Hospital; and the Department of Epidemiology & Preventive Medicine (Varma, Bailey), Monash University, Melbourne, Australia.
Correspondence address: A/Prof Silvana F Marasco, CJOB Cardiothoracic Department, The Alfred Hospital, Commercial Rd, Prahran 3181, Australia. email: s.marasco@alfred.org.au

Published by Elsevier Inc.

ISSN 1072-7515/12/$36.00
http://dx.doi.org/10.1016/j.jamcollsurg.2012.12.024

The primary aim of the study was to investigate the effect of operative rib fixation of flail chest on mechanical ventilation time and ICU stay.

METHODS

Enrolment for the study took place between January 2007 and December 2011. Informed consent was obtained from the next of kin initially and consent sought from the patient for follow-up once sufficiently recovered. Institutional ethics committee approval was obtained. The trial was registered under Clinical Trials Gov with registration number NCT00298259.

Patients were screened for enrollment into the trial on hospital admission. Forty-six patients with traumatic flail chest injury receiving invasive mechanical ventilation were enrolled in the study. Patients were enrolled only if they were ventilator dependent with no prospect of successful weaning within the next 48 hours. Inclusion criteria were the presence of a flail segment defined as 3 or more consecutive ribs fractured in more than 1 place, producing a free floating segment of chest wall. Diagnosis was made clinically with confirmation on 3-dimensional CT imaging. Exclusion criteria were age greater than 80 years (it was considered that osteoporotic bones precluded fixation with the available prostheses), spinal injuries (which precluded placement of the patient in a lateral decubitus position), open rib fractures with soiling or infection, sepsis, severe traumatic brain injury (Glasgow Coma Scale <10 at the scene of accident or at presentation to the hospital, as its management may have received priority over the study protocol), and uncorrected coagulopathy.

Randomization was via a computer generated code using block randomization with block size of 4. After consent and enrollment, an opaque envelope with the treatment assignment was opened and the time of enrollment documented.

Patients were randomized to either operative rib fixation or nonoperative management. Surgery was planned after viewing 3-dimensional CT chest reconstructions and was performed within 48 hours of enrollment. Only rib fractures between the levels of ribs 3 and 10 were fixed. Usually 1 or 2 incisions were used to achieve access to multiple ribs. Wherever possible, chest wall muscles were preserved, splitting them along the length of their fibers. The periosteum was also preserved. Ribs fractured more than once were usually addressed by fixing 1 fracture per rib, converting a flail segment to simple fractured ribs. Ribs with a single fracture were not fixed unless there was gross deformity mandating intervention. Anterior and lateral rib fractures were preferentially fixed over posterior rib fractures, due to more reliable fixation and easier access compared with posterior rib fractures.[7,8]

Inion resorbable (Inion OTPS) 6- or 8-hole plates and bicortical screws were used for every rib fixation. These plates and screws are made of a polylactide copolymer that resorbs over 18 to 24 months. The plates were applied to the external cortical surface of the rib after reducing the fracture. The screws traversed both the outer and inner cortex of the ribs and were inserted after tapping the drill hole and using a depth gauge to determine the length of screw to be used.

Patients assigned to nonoperative management were treated with current best practice mechanical ventilator management. Weaning from ventilation was via a protocol used for all patients irrespective of assigned group and irrespective of mode of ventilation. Commencing from the day after surgery, or 24 hours after enrollment in the conservative management group, patients had sedation (not analgesia) cessation considered every morning and a spontaneous breathing trial conducted if patients met appropriate criteria. If the patient was comfortable with a respiratory rate <25 breaths/minute after 4 hours of the spontaneous breathing trial, mechanical ventilation was weaned. If the patient's respiratory rate was >25 breaths/minute, appropriate sedation and mechanical ventilation were recommenced for another 24 hours. Tracheostomy insertion was also protocol driven and occurred at day 7 if it appeared to the treating physician that weaning of mechanical ventilation was not likely within the next 2 to 3 days.

The primary endpoints of the study were duration of mechanical ventilation and ICU stay. The secondary endpoints were number of respiratory complications (pneumonia, pneumothorax, intercostal catheter usage), rate of failed extubation, rate of tracheostomy, readmission to intensive care, duration of hospital stay, and cost assessment of the operation. Pneumonia was defined as a new infiltrate on chest x-ray, with positive sputum culture. Intensive care unit discharge time was recorded as the time the patient was deemed ready for discharge so that ward bed access did not affect the results.

Patients were reviewed at 3 months postoperatively for clinical assessment, spirometry, and CT scan of chest imaging with 3-dimensional reconstructions of the thoracic cage. All patients were sent a Short Form 36-item Health Status Questionnaire (SF-36) at 6 months to assess physical functioning, role limitations owing to physical problems, role limitations owing to emotional problems, social functioning, mental health, general health perceptions, vitality, and bodily pain.

Sample size estimation was based on duration of mechanical ventilation. Calculations were performed using duration of mechanical ventilation values from patients with traumatic flail chest treated at The Alfred Hospital over the 4 years before commencement of this study. Assuming an alpha of 0.05, power of 0.8, and a standard deviation of 140 hours, to detect a difference in duration of mechanical ventilation of 120 hours (5 days), 23 patients per group were required to be enrolled.

Statistical analysis

Statistical analysis was performed using SAS version 9.2 (SAS Institute Inc). All variables were initially assessed for normality. Group comparisons of proportions were made using chi-square tests or Fishers exact tests where numbers were small and were reported as numbers (%). Continuously normally distributed variables were compared using Student *t*-tests and reported as mean (standard deviation); non-normally distributed data were compared using Wilcoxon rank sum tests and reported as medians (interquartile range). To ensure that all observed results were not due to baseline imbalances, multivariate modelling was used, adjusting for the covariate of "other surgical interventions." In order to facilitate this, duration variables were log-transformed and analyzed using generalized linear modelling, with results reported as geometric means (95% CI). The need for noninvasive ventilation was assessed using logistic regression, with results reported as odds ratios (95% CI). Analysis was performed on an intention-to-treat basis. A 2-sided p value of 0.05 was considered statistically significant.

RESULTS

There were 5,036 major trauma patients (Injury Severity Score [1998 version] >15) treated at The Alfred Hospital over the 5-year period of enrollment, including 2,940 patients with thoracic trauma Maximum Abbreviated Injury Score [1998 version] >2. Over that period 230 patients were coded as having a flail chest, with less than half requiring invasive mechanical ventilation. Screening and enrollment numbers are outlined in the Consort diagram (Fig. 1). One patient assigned to the operative group did not have surgery due to the development of sepsis, but was analyzed in the operative group on an intention-to-treat basis. One patient assigned to the nonoperative group died before hospital discharge. Patient demographics are outlined in Table 1. There was a significantly lower proportion of nonsmokers in

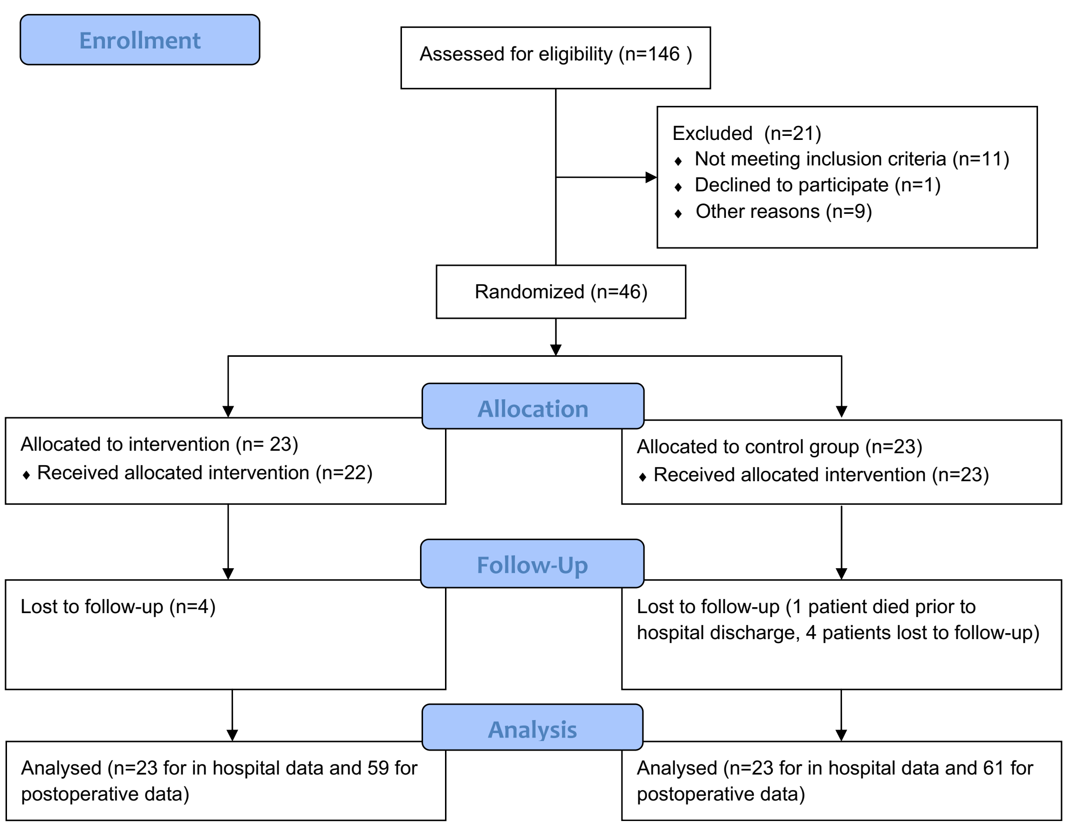

Figure 1. CONSORT 2010 flow diagram.

Table 1. Patient Demographics

Variable	Operative group (n = 23)	Nonoperative group (n = 23)	p Value
Age, y, mean ± SD	57.8 ± 17.1	59.3 ± 10.4	0.72
Sex male/female, n	20/3	20/3	1.00
Body mass index, kg/m^2, mean ± SD	27.9 ± 4.6	29.0 ± 6.8	0.55
Smoking history, n (%)			
Ex smoker	5 (22)	2 (9)	0.22
Current smoker	8 (35)	3 (13)	0.08
Nonsmoker	10 (43)	18 (78)	0.02
Underlying lung disease, n (%)			
Asthma	3 (13)	1 (4)	
COPD	2 (9)	1 (4)	
Mechanism of injury, n (%)			0.86
Motor vehicle accident	17 (74)	14 (61)	
Pedestrian vs car	2 (9)	3 (13)	
Crush injury	1 (4)	2 (9)	
Fall from height	3 (13)	4 (17)	
NISS, mean ± SD	36.4 ± 10.3	42.9 ± 13.3	0.07
ISS, mean ± SD	35.0 ± 11.4	30.0 ± 6.3	0.13
TRISS, mean ± SD	0.8 ± 0.2	0.8 ± 0.2	0.77
GCS at scene, mean ± SD	13.4 ± 2.8	13.6 ± 2.6	0.74
Best GCS within first 48 h, mean ± SD	11.0 ± 4.5	9.9 ± 4.7	0.43
Head injury AIS code 2 or above, n (%)	0 (0)	2 (9)	0.49
Bony spinal injury, n (%)	15 (65)	14 (61)	0.76

AIS, Abbreviated Injury Score; GCS, Glasgow Coma Scale; ISS, Injury Severity Score; NISS, New Injury Severity Score; TRISS, Trauma and Injury Severity Score.

the operative group (43% vs 78%; p = 0.02), but otherwise, both groups were adequately matched.

There were no differences between groups in the number of ribs fractured or the degree of underlying lung contusion (measured at time of enrollment) (Table 2). There was a difference between groups in terms of other nonthoracic surgical interventions performed. The nonoperative group had a higher number of orthopaedic and general surgical operative procedures (74% vs 48%; p = 0.07) (Table 2).

Twenty-two patients underwent operative rib fixation. Most (13 of 22; 59%) patients had 4 ribs fixed (range 2 to 7 ribs). Two (9%) patients had bilateral rib fixation. Anterior and lateral fractures were most commonly fixed. Only 1 patient had posterior rib fractures fixed.

The early postoperative outcomes are outlined in Table 3. There was no difference between groups in the duration of invasive mechanical ventilation, but noninvasive ventilation was used in a greater number of patients and for a longer duration in the nonoperative management group. The nonoperative group had a longer duration of ICU stay. More patients in the nonoperative group required tracheostomy. There was a trend toward more patients in the nonoperative group developing pneumonia (p = 0.07; Table 3). There were no significant differences between groups in packed cell transfusion requirements or total blood products transfused during their inpatient stay (Table 3). Although the median packed cell volume transfused in the nonoperative group appears to be twice that of the operative group, this was largely driven by a single patient who required 58 units of packed cells during his inpatient stay. He was also the only mortality in the entire cohort, which occurred due to sepsis, at day 92 postinjury.

Multivariate modelling was used to adjust for the covariate of "other surgical interventions," which, although not significantly different on univariate analysis, showed a higher incidence in the nonoperative group (Table 2). For all of the significantly different outcomes reported earlier, statistical significance remained after adjustment: duration of ICU stay postrandomization (mean hours [95% CI], 255 [201 to 323] vs 372 [294 to 470], p = 0.03); total ICU stay (mean hours [95% CI], 317 [257 to 390] vs 456 [371 to 562], p = 0.02); duration of noninvasive ventilation postextubation, (mean hours [95% CI], 22 [11 to 45] vs 67 [37 to 121], p = 0.03); received noninvasive ventilation postextubation, (odds ratio [95% CI] 4.4 [1.04 to 18.6], p = 0.04).

The difference between groups in the ICU of 124 hours equates to a saving of 5.17 days in the operative group.

Table 2. Injury Description

Variable	Operative group (n = 23)	Nonoperative group (n = 23)	p Value
Total no. fractured ribs, mean ± SD	11.0 ± 3.1	11.3 ± 4.7	0.79
No. of ribs in flail segment, mean ± SD	5.1 ± 1.7	5.5 ± 2.0	0.43
No. of patients with bilateral vs unilateral rib fractures	12:11	13:10	
Underlying lung contusion, n (%)*			
None	3 (13)	2 (9)	1.00
Mild	16 (70)	16 (70)	1.00
Moderate	4 (17)	4 (17)	1.00
Severe	0 (0)	1 (4)	1.00
Pneumothorax, n (%)	20 (90)	21 (91)	0.64
Other surgical interventions required, n (%)†	11 (48)	17 (74)	0.07
Thoracotomy, n	0	2	
Laparotomy, n	1	2	
ORIF clavicle, n	3	5	
Pelvic external fixation, n	0	2	
Spinal fusion, n	2	0	
ORIF limb fracture, n	5	6	
Plastics, n	2‡	4	

*Determined on chest x-ray on day of enrollment into trial.
†Some patients underwent more than 1 surgical intervention.
‡Includes ORIF facial fractures in 1 patient.
ORIF, open reduction internal fixation.

The cost of running an ICU bed in our hospital is estimated to be $4,109 per day. This potential cost saving of $21,243 per operatively managed patient is offset by the average cost of the operation, which, in this cohort was $6,800 per patient. The breakdown of these costs are $4,200 for the prostheses ($1,050 per fracture fixed) and $2,600 for approximately 2.5 hours of operating room time. This equates to a cost saving of $14,443 per patient who underwent rib fixation.

Follow-up at 3 months showed no significant differences between groups in spirometry results (Table 4). Clinical review at 3 months revealed 2 patients with a visible flail segment. Both had an anterior flail segment and were in the nonoperative group. The flail segment

Table 3. Outcomes

Outcomes	Operative group (n = 23)	Nonoperative group (n = 23)	p Value
Duration of ICU stay prerandomization, h, mean ± SD	61.6 ± 36.1	81.3 ± 84.2	0.31
Duration of ICU stay between randomization and surgery, h, mean ± SD	49.4 ± 35.9	N/A	
Duration of IMV postrandomization, h, mean ± SD	151.8 ± 83.1	181.0 ± 130.2	0.37
Duration of ICU stay postrandomization, h, median (IQR)	285 (191–319)	359 (270–581)	0.03
Total ICU stay, h, median (IQR)	324 (238–380)	448 (323–647)	0.03
Failed extubation, n (%)	3 (13)	1 (4)	0.61
Received NIV postextubation, n (%)	13 (57)	19 (83)	0.05
Duration of NIV postextubation, h, median (IQR)	3 (0–25)	50 (17–102)	0.01
Tracheostomy, n (%)	9 (39)	16/23 (70)	0.04
Patients requiring blood product transfusion, n	18	19	0.78
Packed cell transfusion during inpatient stay, mL, median (IQR)	620 (0–3,100)	1,240 (620–3,100)	0.39
Total blood products transfused, mL, median (IQR)	930 (620–1,860)	900 (500–1,395)	0.57
Readmission to ICU, n (%)	2/23 (9)	2/23 (9)	0.99
ICCs required, n, median (IQR)	2 (1–4)	2 (1–4)	0.99
Pneumonia, n (%)	11/23 (48)	17/23 (74)	0.07
Duration of hospital stay, d, median (IQR)	20 (18–28)	25 (18–38)	0.24
In hospital mortality, n	0	1	0.87

ICC, intercostal catheter; IMV, invasive mechanical ventilation; IQR, interquartile range; NIV, noninvasive ventilation.

Table 4. Spirometry Results at 3-Month Follow-Up

Percent predicted value	Operative group (n = 17)	Nonoperative group (n = 17)	p Value
FEV1	74.3 ± 15.0	80.2 ± 18.3	0.31
FVC	77.9 ± 15.7	84.8 ± 14.0	0.19
MMEF	76.2 ± 36.9	82.1 ± 35.0	0.64
PEF	62.8 ± 28.5	68.1 ± 36.5	0.63
TLC	84.0 ± 24.4	88.2 ± 23.4	0.61
FEV1/FVC	95.6 ± 9.8	95.0 ± 17.3	0.92

Data are reported as mean ± SD.
FEV1, forced expiratory volume in one second; FVC, forced vital capacity; MMEF, maximal mid expiratory flow; PEF, peak expiratory flow; TLC, total lung capacity.

was not causing either patient any pain or restriction of activity. Most (60%) patients complained of ongoing limitation in their daily work and home lives (15 of 21 [71%] in the nonoperative group vs 10 of 21[48%] in the operative group). However, the majority of these restrictions were due to injuries other than the flail chest injury. Only 2 patients (1 in each group) reported concerns about the cosmetic appearance of their chest at follow-up. Chest CTs with 3-dimensional reconstructions performed at 3 months were analyzed for degree of healing and residual deformity in the fixed ribs (Table 5). Short Form-36 quality of life questionnaire at 6 months showed no differences between groups in any of the domains or the component summary scores (Table 6).

DISCUSSION

In this prospective randomized trial comparing operative rib fixation and nonoperative management for traumatic flail chest, we demonstrated reduced duration of ICU stay and reduced use of noninvasive ventilation and tracheostomy in the operative group. The duration of invasive mechanical ventilation (IMV) from randomization was not significantly different between groups, although it did trend to a lesser duration in the conservative management group. If the duration of IMV in the surgical group is analyzed from the time of operation, the differences between groups becomes quite marked, with significantly less requirement for IMV in the surgical group. Although the treating intensivists were not blinded to the treatment group, ventilatory weaning and requirement for tracheostomy were protocol driven. A spontaneous breathing trial was considered in every patient on a daily basis. After day 7 postintubation, tracheostomy was considered if it appeared the patient would not reach extubation within the next 2 to 3 days. Although IMV time between groups was not significantly different, it was 30 hours shorter in the surgical group, which helps to explain why those

Table 5. Three-Dimensional CT Results at 3 Months

3D CT appearance	Operative group, n (n = 21)	Nonoperative group, n (n = 17)	p Value
Complete healing	11	8	0.50
Partial healing	7	8	0.51
Nonhealing	3	1	0.38
Preoperative overlapping rib ends	14	10	0.86
Residual overlapping rib ends	8	10	0.35
Improvement in overlapping bone ends	6	0	0.72
Preoperative displacement (>1 rib >rib width)	9	13	0.05
Residual displacement (>1 rib >rib width)	4	7	0.16
Improvement in rib displacement	5	6	0.12
Preoperative angulation (>5 degrees >1 rib)	9	12	0.09
Residual angulation (>5 degrees >1 rib)	3	9	0.01
Improvement in angulation	6	3	0.15

patients were less likely to receive a tracheostomy. Further, the increased requirement for noninvasive ventilation in the nonoperative group indicates that the tracheostomy protocol was appropriately followed because those patients did require ongoing ventilatory support, albeit noninvasive.

The duration of hospital stay was 5 days shorter in the surgical group, which reflects the 5-day shorter ICU stay. However, the difference in overall hospital stay (20 days vs 25 days) was not significantly different between groups. It is also possible that this length of stay was affected by

Table 6. Short Form-36 Quality of Life Questionnaire Results at 6 Months Postinjury

SF-36 domains	Operative group (n = 19)	Nonoperative group (n = 18)	p Value
Physical functioning	33.4 ± 13.0	38.4 ± 12.0	0.24
Physical role	32.1 ± 7.9	35.1 ± 11.4	0.36
Bodily pain	42.2 ± 9.4	37.9 ± 11.0	0.22
General health	45.2 ± 11.8	44.0 ± 12.2	0.77
Vitality/energy	44.1 ± 10.8	46.3 ± 8.2	0.49
Social functioning	36.0 ± 15.0	37.2 ± 12.5	0.79
Emotional role	37.6 ± 14.5	37.8 ± 13.5	0.97
Mental health	45.9 ± 13.2	46.5 ± 9.1	0.87
PCS	33.6 ± 9.8	35.2 ± 10.7	0.65
MCS	45.1 ± 13.8	45.2 ± 9.2	0.98

Scores are reported as mean ± SD.
MCS, mental component summary score; PCS, physical component summary score.

a delay in transfer to rehabilitation hospitals due to bed block, which often tends to occur in our area. However, this would occur equally between groups, so does not explain the difference in length of stay seen in this study cohort. The reduction in ICU stay in the operative group reduced the ICU costs by more than $14,000 per patient, (a considerable cost savings to the health system) and saved 5 ICU bed days per patient.

Short-term follow-up of our patients demonstrated no significant differences in spirometry at 3 months between groups. This result contrasts with previous studies that have demonstrated improvements in percent predicted forced vital capacity, total lung capacity, and forced expiratory flow at 75% of vital capacity from 2-month follow-up.[4,9]

We were unable to demonstrate any difference between groups in terms of Short Form-36 quality of life questionnaire outcomes at 6 months postinjury. The physical summary score was lower in both groups than the mental summary score. This finding suggests that the patients made appropriate psychological adjustments to their injuries, as has been previously reported.[10] Normative data from the Australian population show a mental health summary score of 50.8, which is similar to the scores in our study population. The reported physical summary score in the general Australian population is 49.8, which is quite a bit higher than the scores in the groups in this study.[11]

We did not specifically assess pain in this study because all of the enrolled patients were sedated and ventilated at the time of enrollment. So the main indication for surgery was mechanical stabilization, not pain. Further, because these patients were a true multitrauma cohort with multiple system injuries, it was thought that any assessment of analgesic requirement would be confounded by the many other injuries also requiring analgesia. Indeed, that is what we found at 3-month follow-up. As outlined in the results, patients who complained of ongoing physical limitation reported that they were limited by pain and stiffness from other injuries, particularly shoulder girdle injuries, rather than rib injuries themselves.

Only 2 other prospective randomized trials have been reported investigating the impact of operative fixation of flail chest injury.[4,9] Both studies, slightly smaller than this one, demonstrated significantly reduced mechanical ventilation time, ICU stay, incidence of pneumonia, and improved spirometry at follow-up in the operative group. Tanaka and colleagues[4] also demonstrated earlier return to work in the surgical cohort at 6-month follow-up. The average age of the patients in our study (58 years) was older than that reported in both previous randomized controlled trials of 45 years[4] and 38 years.[9] This is likely to explain the seemingly slower recovery in our patients and the lower rates of return to work (many of our patients were retired). Our failure to identify differences in spirometry results at 3 months may also be related to the older age cohort in our study.

The study by Grantezny and associates[9] also had a cohort of patients with much lower Injury Severity Scores (ISS) (average 17.4) compared with those in our study group (average 33.3). Again, this reflects a seemingly different study population—younger patients with single system injuries—compared with our population of older patients with multiple system injuries (as evidenced by the number of nonthoracic operations required). We have also reported the New Injury Severity Score (NISS) and the Trauma and Injury Severity Scores (TRISS) to give a more comprehensive picture of the injury severity of this group of patients. The higher ISS scores and multisystem nature of the injuries in our cohort of patients may explain our failure to identify any differences in quality of life between groups.

Other previous research on operative fixation of fractured ribs has consisted of retrospective reviews and case reports. The retrospective review by Voggenreiter and coworkers[12] was the only one to subdivide the treatment groups into those with and without significant contusion. Although they found benefits in the operative treatment group, they also found that these benefits were negated by the presence of significant pulmonary contusion. In our study, the majority of patients had only mild contusion on chest x-ray at the time of enrollment.

Almost all of the published studies have used metal implants for operative fixation of the ribs. Granetzny and colleagues[9] used Kirschner and stainless steel wires; Tanaka and associates[4] used Judet struts. In contrast, we used a polylactide copolymer prosthesis applied as a 6- or 8-hole plate and screws. These prostheses degrade by hydrolysis and are metabolized by the body into carbon dioxide and water. They maintain at least 40% of their strength at 3 months, by which time the fractures would be expected to have completely healed, and are completely absorbed without toxicity over 1 to 3 years. Animal models using these absorbable plates have shown faster and stronger healing compared with traditional metal plates, which may actually slow bone healing.[13] This occurs because the metal plate protects the bone from any load, but in doing so it removes the stimulus for new bone growth (known as stress-shielding). In contrast, the absorbable plates allow gradual transfer of stress loads to the bone, stimulating faster bone growth.[13]

Because the plates and screws are absorbable there is no need to remove plates, which confers a potential cost savings to this procedure. Also, it minimizes the sequelae of possible prosthesis-related complications such as migration, palpability (especially in thin patients), or thermal sensitivity. Metal prostheses usually require removal if these complications occur, while a more conservative approach can be adopted with absorbable prostheses. Furthermore, there is no contraindication to future MRI in patients who have had absorbable plates implanted.

Despite the existing evidence of patient and hospital benefits with operative fixation of flail chest injury, clinical equipoise within the Western surgical community has persisted (operative rib fixation seems to have been taken up more readily in East Asia[14]). This study is now the third study (in 3 different countries) to show similar benefits in this patient population, and we hope that it will influence management change in these critically ill trauma patients. Another reason why surgeons have been slow to embrace this type of surgery is probably related to the lack of specific prostheses designed for rib fixation. In this study we used a prosthesis designed for the fibula. However, over the last few years, a number of products have come onto the market specifically designed for rib fixation.[15] This demonstrates the increasing awareness and interest in this type of surgery and also acknowledges that in the past, surgical results when using nonspecific prostheses have been very variable.[16-18]

Ribs present a number of surgical difficulties not encountered with other bony injuries. Ribs are subject to continual movement with breathing as well as sudden more forceful movements during coughing and sneezing. Ribs have a thin inner and outer cortex, making prosthesis fixation difficult and at times unreliable. Typical rib fractures often involve splintering of the ribs, mandating that bone fixation be undertaken at a site further away from the fracture. Each rib differs slightly in its shape, and in particular, in the radius of its curvature, which means that a "one size fits all" approach, particularly, with less malleable prostheses, is unlikely to be successful.[19]

A wide variety of prostheses have been tried in rib fixation. Many have flaws. Kirschner wires provide little rotational stability, and are prone to migration. Metal plates borrowed from other applications are able to be curved in one direction only. Because rib curvature is quite complex, these metal plates are prone to "lifting off" the rib. Although the ribs do not carry a heavy load, they are affected by torque in multiple directions due to the layers of intercostal muscles inserting onto the ribs, as well as multiple chest wall muscles. Few authors have commented on the impact of the chest wall musculature on the dislocation and distraction of fractured ribs. Borrelly and Aazami,[20] in their retrospective review of flail chest patients, noted that the actions of serratus anterior tend to distract anterolateral fractures while impacting the ribs in posterolateral fractures. Analysis of the effect of intercostal muscle forces on rib fractures and fixation method has recently been analyzed and could assist in development of specific rib prostheses.[7,8]

CONCLUSIONS

This study shows clinical benefit and cost savings to the health system for flail chest patients who undergo rib fixation. Hopefully this study will help to change operative management protocols for these critically ill patients. Further trials into nonventilator-dependent patients also need to be performed to assess in more detail potential patient benefits of pain reduction and functional improvements.

Author Contributions

Study conception and design: Marasco, Davies, Cooper, Fitzgerald

Acquisition of data: Marasco, Bennet, Nevill, Lee

Analysis and interpretation of data: Marasco, Davies, Cooper, Varma, Lee, Bailey, Fitzgerald,

Drafting of manuscript: Marasco, Davies, Cooper, Varma, Bennet, Nevill, Lee, Bailey, Fitzgerald

Critical revision: Marasco, Davies, Cooper, Varma, Bennet, Nevill, Lee, Bailey, Fitzgerald

REFERENCES

1. Ciraulo DL, Elliott D, Mitchell KA, et al. Flail chest as a marker for significant injuries. J Am Coll Surg 1994;178:466−470.
2. Kent R, Woods W, Bostrom O. Fatality risk and the presence of rib fractures. Annu Proc Assoc Adv Automot Med 2008;52: 73−82.
3. Kerr-Valentic MA, Arthur M, Mullins RJ, et al. Rib fracture pain and disability: can we do better? J Trauma 2003;54: 1058−1063.
4. 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.
5. Mayberry JC, Ham LB, Schipper PH, et al. Surveyed opinion of American trauma, orthopaedic and thoracic surgeons on rib and sternal fracture repair. J Trauma 2009;66:875−879.
6. Atkin C, Freedman I, Rosenfeld JV, et al. The evolution of an integrated state trauma system in Victoria, Australia. Injury 2005;36:1277−1287.
7. Marasco SF, Šutalo ID, Bui AV. Mode of failure of rib fixation with absorbable plates: a clinical and numerical modelling study. J Trauma 2010;68:1225−1233.
8. Marasco SF, Liovic P, Sutalo ID. Structural integrity of intramedullary rib fixation using a single bioresorbable screw. Acute Care Surg 2012;73:668−673.
9. Granetzny A, El-Aal MA, Emam E, et al. Surgical versus conservative treatment of flail chest. Evaluation of the pulmonary status. Interact Cardiovasc Thorac Surg 2005;4:583−587.

10. Singer MA, Hopman WM, MacKenzie TA. Physical functioning and mental health in patients with chronic medical conditions. Qual Life Res 1999;8:687—691.
11. Australian Bureau of Statistics. National health survey: SF-36 population norms, Australia. Canberra, ACT: Australian Bureau of Statistics; 1995.
12. Voggenreiter G, Neudeck F, Aufmkolk M, et al. Operative chest wall stabilisation in flail chest — outcomes of patients with or without pulmonary contusion. J Am Coll Surg 1998;187: 130—138.
13. Viljanen J, Pihlajamaki H, Kinnunen J, et al. Comparison of absorbable poly-L-lactide and metallic intramedullary rods in the fixation of femoral shaft osteotomies: an experimental study in rabbits. J Orthop Sci 2001;6:160—166.
14. 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.
15. Marasco SF. Open surgical fixation of fractured ribs. Recent Patents Biomed Eng 2010;3:1—6.
16. Balci AE, Eren S, Cakir O, Eren MN. Open fixation in flail chest: review of 64 patients. Asian Cardiovasc Thorac Ann 2004;12:11—15.
17. Mayberry JC, Terhes JT, Ellis TJ, et al. Absorbable plates for rib fracture repair: preliminary experience. J Trauma 2003;55: 835—839.
18. Marasco S, Cooper J, Pick A, Kossmann T. Pilot study of operative fixation of fractured ribs in patients with flail chest. ANZ J Surg 2009;79:804—808.
19. Mohr M, Abrams E, Engel C, et al. Geometry of human ribs pertinent to orthopaedic chest-wall reconstruction. J Biomech 2007;40:1310—1317.
20. Borrelly J, Aazami MH. New insights into the pathophysiology of flail segment: the implications of anterior serratus muscle in parietal failure. Eur J Cardiothorac Surg 2005;28:742—749.