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Evaluation of intramedullary rib splints for less-invasive stabilisation of rib fractures

Inga Helzel [a], William Long [a], Daniel Fitzpatrick [b], Steven Madey [a], Michael Bottlang [a,*]

[a] Biomechanics Laboratory, Legacy Research & Technology Centre, Portland, OR, USA
[b] Slocum Centre for Orthopaedics, Eugene, OR, USA

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ABSTRACT

Background: Intramedullary fixation of rib fractures with generic Kirschner wires has been practiced for over 50 years. However, this technique has not been advanced to address reported complications of wire migration and cut-out. This biomechanical study evaluated a novel rib splint designed to replicate the less-invasive fixation approach of Kirschner wires while mitigating their associated complications.

Methods: The durability, strength, and failure mode of rib fracture fixation with intramedullary rib splints were evaluated in 27 cadaveric ribs. First, intact ribs were loaded to failure to determine their strength and to induce realistic rib fractures. Subsequently, fractures were stabilised with a novel rib splint made of titanium alloy with a rectangular cross-section that was secured with a locking screw. All fixation constructs were dynamically loaded to 360,000 cycles at five times the respiratory load magnitude to determine their durability. Finally, constructs were loaded to failure to determine their residual strength and failure modes.

Results: Native ribs had a strength of 9.7 $\pm$ 5.0 N m, with a range of 3.5–19.6 N m. Fracture fixation with rib splints was uneventful. All 27 splint constructs sustained dynamic loading without fixation failure, implant migration or implant cut-out. Dynamic loading caused no significant decrease in construct stiffness ($p = 0.85$) and construct subsidence remained on average below 0.5 mm. The residual strength of splint constructs after dynamic loading was 1.1 $\pm$ 0.24 N m. Constructs failed by splint bending in 44% of specimens and by developing fracture lines along the superior and inferior cortices in 56% of specimens. Regardless of the failure mode, all rib splint constructs recoiled elastically after failure and retained functional reduction and fixation. No construct exhibited implant cut-out or migration through the lateral cortex.

Conclusions: Rib splints can provide sufficient stability to support respiratory loading throughout the healing phase, but they cannot restore the full strength of native ribs. Most importantly, rib splints mitigated the complications reported for rib fracture fixation with generic Kirschner wires, namely implant cut-out and migration through the lateral cortex. Therefore, rib splints may provide an advanced alternative to the original Kirschner wire technique for less-invasive fixation of rib fractures.

Introduction

Surgical fixation of rib fractures is increasingly being recognised as an effective yet underutilised intervention for stabilisation of flail chest injuries and serial rib fractures.[16,31,32] Growing acceptance of surgical fixation has been driven by several clinical studies which demonstrated that surgical stabilisation of a flail chest segment can reduce the incidence of pneumonia, mortality, duration of hospitalisation, and treatment cost compared to internal pneumatic stabilisation.[1,3,14,24,40] Further benefits of surgical stabilisation include a decreased likelihood of long-term respiratory dysfunction and skeletal deformity.[4,11,15,17]

Traditionally, rib fractures have been stabilised with osteosynthesis plates or with intramedullary Kirschner wires. Intramedullary fixation of rib fractures with Kirschner wires has been performed for over 50 years[20] and has several important benefits over plating. Kirschner wires can be inserted through smaller incisions in a less-invasive approach, requiring less resection of intercostal tissue than plating.[33] Kirschner wires follow the canal shape upon insertion, while plates require intra-operative contouring to match the rib surface.[8,9] Intramedullary implants are better tolerated than plates that remain prone to the rib surface and that require removal due to persistent discomfort in 5–15% of cases.[21,28] Furthermore, intramedullary implants derive fixation strength by confinement in the rib canal, while plate fixation can be prone to screw loosening and plate

* Corresponding author at: Legacy Biomechanics Laboratory, 1225 NE 2nd Ave, Portland, OR 97232, USA. Tel.: +1 503 413 5457; fax: +1 503 413 4942.
E-mail address: mbottlan@lhs.org (M. Bottlang).

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pull-off, especially in the presence of osteoporotic bone[9,12]. Most importantly, intramedullary implants allow fixation of posterior rib fracture, where access for plating is severely restricted by the scapula and latissimus dorsi.[2]

The clinical efficacy of rib osteosynthesis with Kirschner wires has been described in a number of case series that attested good to excellent results.[1,17,20,33] After two decades of experience in rib fracture fixation with Kirschner wires, Samarrai concluded that this technique has given the most satisfactory results when compared with other fixation techniques.[33] While the clinical utility of intramedullary fixation of rib fractures has been well established, there are two persistent limitations. First, the thin and circular cross-section of Kirschner wires provides poor rotational stability and is prone to cutting out through the cortex, especially in the presence of osteoporotic bone.[9,17] Second, Kirschner wires can dislodge and migrate, which may cause discomfort, loss of fixation, or harm.[1,2,18,36] Albrecht and Brug reported abandoning the use of Kirschner wires because of their migration risk and propensity for cut-out, despite their relative ease of use and sufficient stabilisation.[2] However, since its introduction half a century ago, the technique has not been improved to mitigate the reported complications.

Based on recent biometric data,[19] we have designed a rib splint for intramedullary fixation of rib fractures to maintain the less-invasive nature and simplicity of intramedullary pinning with Kirschner wires while avoiding the reported limitations. Specifically, the rib splint has a flat, rectangular cross-section for rotational stability and improved resistance to cut-out in osteoporotic bone. Furthermore, it provides a fixation screw to prevent migration and loss of fixation. This biomechanical study evaluated the durability, strength and failure mode of rib splint constructs in human ribs. It tested the hypothesis that rib splint constructs can provide sufficient durability and strength to support dynamic respiratory loading throughout the fracture healing period without exhibiting implant migration or cut-out.

Methods

The durability, strength, and failure mode of intramedullary fixation of rib fractures with rib splints were evaluated in human cadaveric ribs. Intact ribs were loaded to failure to determine the strength of intact ribs and to induce realistic rib fractures. Subsequently, fractures were stabilised with intramedullary rib splints. All fixation constructs were subjected to prolonged dynamic loading to assess their durability under exaggerated respiratory forces. Finally, constructs were loaded to failure to determine their residual strength and failure modes.

Specimens

Twenty-nine ribs of levels four through nine were harvested from two male cadavers (62 and 65 years, $n = 11$ ribs) and one female cadaver (82 years, $n = 18$ ribs). Human cadavers were non-embalmed and were selected to represent a range of bone properties for construct evaluation in strong and weak ribs. Ribs were shortened to harvest specimens of the posterolateral rib diaphysis with a consistent arc height l (Fig. 1a). For this purpose, ribs were sectioned posteriorly midway between the angle and the tubercle. Ribs were then sectioned anteriorly to yield diaphyseal specimens with an arc height l of nominally 30 mm. Harvesting specimens with a consistent arc height rather than with a consistent length ensured that all specimens were tested under the same bending loads despite variations in anatomic curvature. For load induction, polymer spheres of 25 mm diameter with a cylindrical mounting recess were cemented to both ends of the diaphyseal specimens (Fig. 1b).

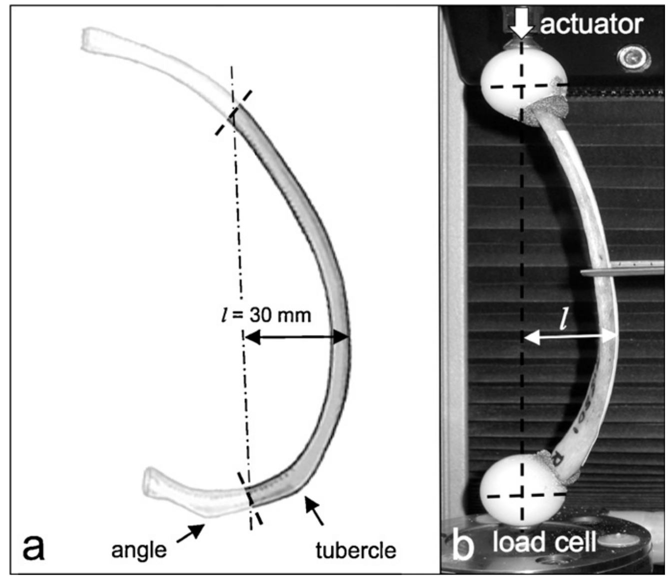

Fig. 1. (a) Harvesting of posterolateral specimens of the rib diaphysis with an arc height of $l = 30$ mm. (b) Spheres were applied to specimen ends for load induction.

Implants

Rib splints were 97 mm long and had a rectangular cross-section of 1 mm × 4 mm for provision of rotational stability and cut-out resistance (Fig. 2a). To prevent implant migration, rib splints had a threaded screw hole for fixation of the splint to the rib with a locking screw. The front section was tapered to reduce insertion forces (Fig. 2b). The splint tip was sloped to guide the splint along the medullary canal without penetrating the lateral cortex (Fig. 2c). Implants were inserted through a 5 mm diameter entry portal in the lateral cortex, drilled at a 30 mm distance to the fracture site (Fig. 2d). This location is consistent with that recommended for Kirschner wire insertion.[1,20] To facilitate insertion through the entry portal toward the fracture, the front portion of the rib splint was straight. The remainder of the rib splint had a curvature of 200 mm radius that approximated the average curvature of ribs[19] to minimise residual stress after

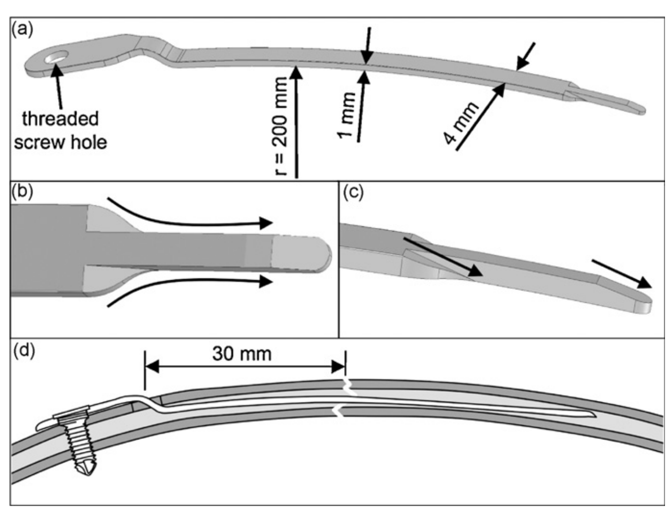

Fig. 2. (a) Rib splints with rectangular cross-section and a screw hole for fixation. (b) Tapered front section to reduce insertion forces. (c) Sloped splint tip to guide the splint along the medullary canal without penetrating the lateral cortex. (d) Implants were inserted through a 5 mm diameter entry portal at 30 mm distance to the fracture site.

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insertion of the implant. Prototypes of rib splints for biomechanical testing were manufactured by Synthes CMF (West Chester, PA, USA) from medical grade titanium alloy (Ti–6Al–4VELI). Titanium alloy was chosen over stainless steel since it has comparable yield strength but greater flexibility, accommodating elastic deformation during splint insertion with less force. Rib splint insertion was facilitated by a custom insertion tool that was attached to the threaded hole of the splint. Splints were gradually inserted by impacting the insertion tool shaft with a small hammer. The tool handle provided control of splint orientation during insertion. Once fully inserted, the splint was secured with one bi-cortical locking screw in the extramedullary splint segment.

Test setup

Specimens were evaluated under two-point-bending with a servo-hydraulic material test system (Instron DynaMight 8841, Canton, MA). This loading mode has typically been used to simulate physiologic loading as well as injury mechanisms in ribs.[10,29,32] The anterior and posterior spheres of each specimen were supported in spherical cups attached to the actuator and load cell of the test system (Fig. 3a). These specimen constraints resembled physiological degrees of freedom at the costro-vertebral articulation and the sterno-costal articulation (Fig. 3b). Consequently, axial load F by the actuator induced a rib bending moment $M = F^{*}l_{(F)}$, with $l_{(F)}$ being the arc height of the specimen at a given load F. The arc height $l_{(F)}$ was continuously recorded during specimen loading using a non-contact laser displacement sensor (ANR12821, Matsushita, Osaka, Japan) with 100 Hz sampling frequency and a resolution of better than 0.01 mm. To ensure adequate surface reflective properties for laser-based assessment of $l_{(F)}$, a thin strip of perforated adhesive tape was applied to the lateral cortex of each rib. Based on the recordings of $l_{(F)}$ and F, the rib bending moment M was assessed during each test.

Test procedures

Specimens were subjected to a sequence of three tests to determine the strength of intact ribs, the durability of fixation constructs under prolonged dynamic loading, and the residual strength and failure mode after dynamic loading.

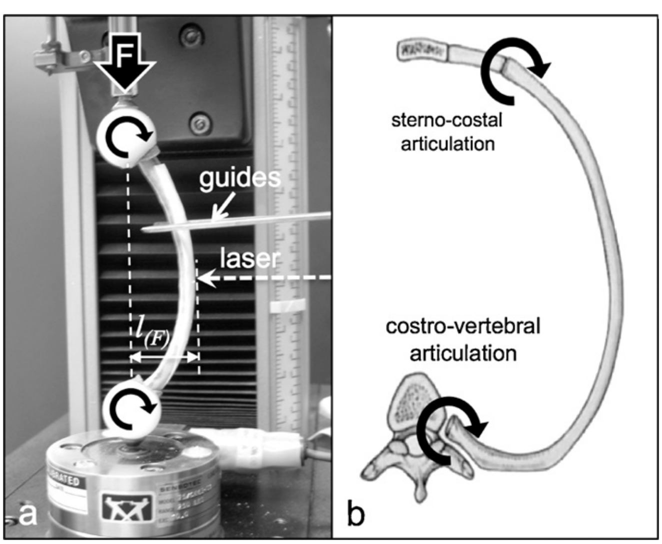

Fig. 3. (a) Axial load (F) induced two-point-bending with a bending moment $M = F^{*}l_{(F)}$, where $l_{(F)}$ is the arc height at a given load F. Guides prevented specimen rotation and $l_{(F)}$ was traced with a laser displacement sensor. (b) Specimen constrains resembled anatomical constraints of the costro-vertebral and sterno-costal articulations.

First, all ribs were loaded quasi-statically to failure at a rate of 10 N/s to determine the strength of intact ribs. Strength was extracted in terms of the bending moment M_{INTACT} at the peak load observed during quasi-static loading. This failure test furthermore served to induce a clinically relevant fracture pattern.

Subsequently, splint constructs were dynamically loaded for 360,000 cycles to simulate a respiratory loading history until fracture stabilisation by callus formation can be expected. This cycle number is based on average reports of respiration rates (14 min^{-1})[13,27] and times to rib fracture stabilisation by callus formation (17.3 days).[3,5] Dynamic loading was applied at 3 Hz with an exaggerated respiratory loading magnitude of 200 N/mm, representing five times the bending moment measured *in vivo* on human ribs during physiologic respiration.[29] A static pre-load of 2 N was retained throughout dynamic loading to secure the specimen during the unloading phase. Subsidence d_{SUB} of rib fixation constructs was measured to quantify non-recoverable, plastic deformation caused by dynamic loading. For assessment of d_{SUB}, dynamic loading was paused every 20,000 cycles and the change in actuator position at 2 N pre-load relative to the start of dynamic loading was assessed. Additionally, the axial stiffness S of rib fixation constructs was measured before and after dynamic loading to detect any decrease in construct stiffness caused by dynamic loading.

After dynamic loading, rib fixation constructs were quasi-statically loaded to failure to determine their residual strength in terms of the construct bending moment M_{CON} at the peak load observed during quasi-static loading. Finally, the failure mode was analysed for the presence of implant bending, fixation failure, and rib fracture.

Outcome parameters M_{INTACT}, M_{CON}, d_{SUB}, and S were reported in terms of their mean ± one standard deviation. Statistical analysis was performed with two-tailed, paired Student's t-test at a level of significance of $\alpha = 0.05$.

Results

All 29 ribs failed by a single fracture in the diaphysis. Two specimens were excluded from further testing due to rib fracture adjacent to the polymer sphere in one specimen, and pathologic occlusion of the medullary canal in the other. The remaining 27 ribs had an average strength of $M_{INTACT} = 9.7 \pm 5.0$ N m, range 3.5–19.6 N m.

Fracture fixation with rib splints yielded functional reduction of all fractures (Fig. 4a). During splint insertion, the sloped and

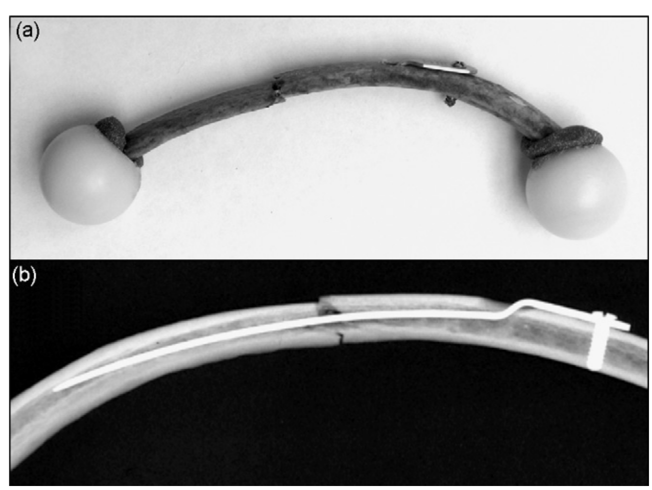

Fig. 4. (a) Reduction of fracture with rib splint. (b) Radiograph, visualising splint position in rib after insertion and fixation with locking screw.

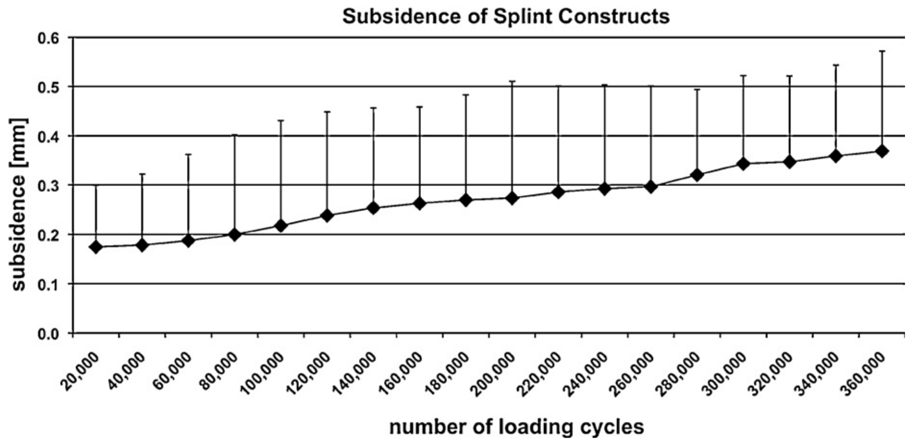

Fig. 5. All splint constructs sustained 360,000 loading cycles, whereby subsidence progressed linearly and reached on average less than 0.4 mm.

tapered splint tip traced the intramedullary canal without penetrating through the lateral cortex (Fig. 4b). All 27 splint constructs sustained 360,000 loading cycles. Subsidence progressed linearly and reached on average $d_{SUB} = 0.37 \pm 1.9$ mm (range 0.1–0.7 mm) at the end of dynamic loading (Fig. 5). The stiffness of splint constructs decreased by less than 1% from 2.65 ± 2.3 to 2.64 ± 2.3 N/mm over the dynamic loading period ($p = 0.85$).

The residual strength of splint constructs after 360,000 loading cycles was $M_{CON} = 1.1 \pm 0.24$ Nm, range 0.7–1.5 N m. Splints provided equal amounts of construct strength in osteoporotic and strong ribs, as a decrease in rib strength did not correlate with a decrease in construct strength ($R^2 = 0.003$) (Fig. 6).

In 15 of 27 rib splint constructs, failure occurred primarily by development of fracture lines along the superior and inferior cortices, starting from the original fracture site (Fig. 7). In the remaining 12 rib constructs, failure occurred primarily by splint bending at the fracture site. Regardless of the failure mode, all rib splint constructs recoiled elastically after failure and retained functional reduction and fixation in both sides of the fracture. None of the rib splint constructs failed catastrophically by implant cut-out or migration through the lateral cortex.

Discussion

Surgical stabilisation of rib fractures has primarily been indicated for flail chest injuries. A flail chest is defined as double fracture of three or more consecutive ribs.[34] These rib fractures

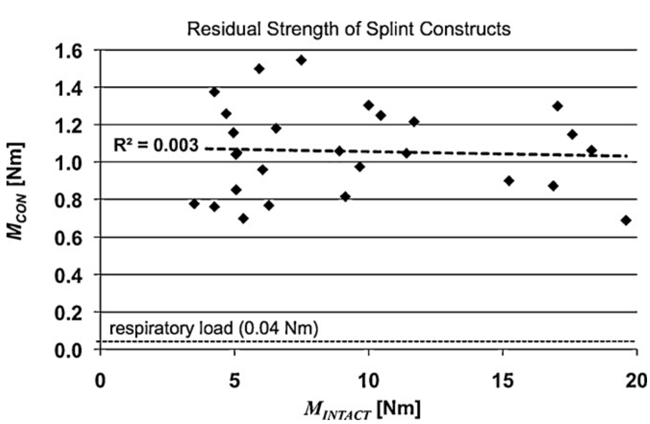

Fig. 6. Failure loads of intact ribs and splint constructs for each of the 27 specimens. Splints provided equal amounts of stabilisation in weak and strong ribs since there was no correlation between rib strength and construct strength ($R^2 = 0.003$).

cause ineffective respiration by pain-related hyperventilation and paradoxical movement of the chest wall. The majority of patients with flail chest requiring mechanical ventilatory support develop significant respiratory complications.[39] Conservative management by internal pneumatic stabilisation requires long-term respiratory support, which increases the risk of pneumonia and associated mortality. Additionally, in the absence of anatomic reconstruction and surgical stabilisation, 64% of flail chest patients experience long-term sequelae, including persistent chest pain, chest wall deformity, and dyspnoea on exertion.[4] In order to reduce the morbidity, mortality and long-term sequelae, five indications for surgical stabilisation of flail chest have been established in the literature: (1) inability to wean a patient from mechanical ventilation, (2) severe chest wall instability causing paradoxical respiration, (3) "stabilisation on retreat" subsequent to thoracotomy, (4) persistent or progressive loss of pulmonary function due to chest wall deformation or over-riding ribs, and (5) persistent pain secondary to fracture mal-union.[25,26] While some controversy remains on the benefits of surgical stabilisation of flail chest injuries in the presence of extensive pulmonary contusion, there is clear consensus for these indications in the absence of severe pulmonary contusion.[40]

The benefits of surgical stabilisation of a flail chest have been demonstrated in a number of comparative studies.[1,3,14,24,38,40] In these studies, surgical stabilisation yielded on average a 41% decrease in ventilation time, a 69% decrease in pneumonia, a 71% decrease in mortality, and a 38% shorter hospitalisation time compared to conservative treatment by internal pneumatic stabilisation. The strongest level of evidence for benefits of surgical stabilisation has been provided by Tanaka et al. in a prospective randomised trial in 37 consecutive flail chest patients.[38] Surgical stabilisation shortened the ventilatory period from 18.3 to 10.8 days, lowered the incidence of pneumonia from 77% to 24%, decreased the total medical expense by 43%, and increased the percentage of return to full-time employment after 6 months from 5% to 61%. Surgical stabilisation of a flail chest should ideally be accomplished within 24 to 48 h after injury to facilitate reduction, to prevent fibrosis, and to minimise duration of respirator use,[30] especially since the risk of pulmonary complications and acute respiratory distress syndrome (ARDS) increases significantly over time.[26,40]

In addition to flail chest stabilisation, several case studies have recommended further indications in which patients with rib fractures have benefited from surgical stabilisation. These indications include management of acute pain in patients with multiple rib fractures,[6] chronically painful non-unions,[23,37] reconstruction of congenital deformities and reduction of overriding ribs.[31] Most

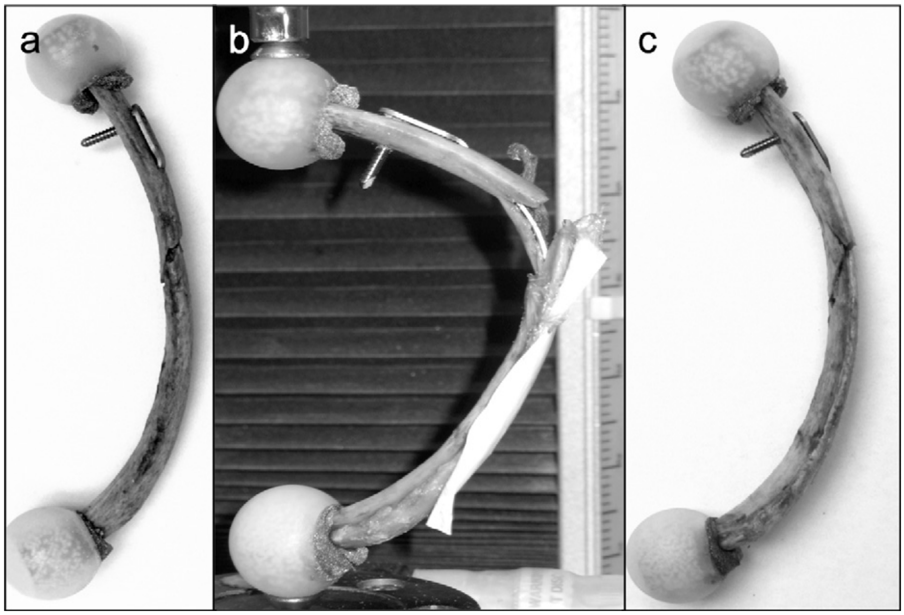

Fig. 7. Failure of rib splint construct by fracture along the superior and inferior cortex: (a) construct after dynamic loading. (b) Construct shown in stressed position during failure test, shown with white tape for laser-tracking of rib bending. (c) Construct recoiled elastically after failure and retained functional reduction and fixation.

recently, Richardson et al. reported on primary stabilisation of multiple rib fractures with overlying bone fragments that may produce severe pain, respiratory compromise and that are prone to non-union.[31] Based on excellent outcomes, they suggested that operative fixation is a useful yet underused treatment for patients with sever chest wall deformities. Nevertheless, some controversy remains regarding indications of operative stabilisation, as the benefits may not generally outweigh the risks inherent to surgery.[21]

Intramedullary fixation enables less-invasive stabilisation of rib fractures and is the only viable option for fixation of posterior rib fractures where accessibility is limited. Generic Kirschner wires remain the standard of care for intramedullary fixation of rib fractures, despite persistent complications related to implant migration and breakout. Intramedullary Rehbein plates with a rectangular cross-section were introduced in 1972 to improve rotational stability and to prevent migration reported with Kirschner wires.[35] One end of the Rehbein plate remained outside the rib canal, was bent onto the rib surface, and was sutured to the periosteum to prevent migration. Despite encouraging clinical results,[17] Rehbein plates remained the only attempt at improving intramedullary fixation of rib fractures to date. The rib splint tested in the present study was designed to retain the benefits of Kirschner wires, while eliminating their reported complications. The splint cross-section was based on a recent biometric study that described the cross-sectional dimensions of human ribs, including the width, height and cortex thickness along the diaphyseal canal.[19] In order to replace the need for bending and suture fixation of early Rehbein plates, rib splints were anatomically contoured and were applied with a locking screw that provides angle-stable fixation to resist implant migration.

Results of the present study provide the first biomechanical evaluation of an intramedullary implant for rib fracture fixation. The tested rib splint is the first intramedullary implant that has been specifically designed for ribs based on biometric data to address the persistent complications associated with Kirschner wires. Implant performance was assessed in ribs that ranged in bending strength from 3.5 to 19.6 N m. Cormier et al. reported a bending strength of 0.8–4.8 N m for osteoporotic ribs with a *T*-score range of -1.9 to -3.3.[7] Therefore, results of the present study encompass rib splint performance in both osteoporotic and strong ribs.

Splint insertion did not require implant bending since the 1 mm thick titanium splints were sufficiently flexible to conform to the rib curvature upon insertion. Rib splints were designed with a 75 mm long intramedullary segment for stabilisation of a single fracture. In case of flail chest injury with multiple fractures per rib, multiple implants will be required. The sloped and tapered splint tip in combination with the high flexibility of the intramedullary splint segment enabled the splint tip to glide along the rib canal without penetrating the outer cortex. However, it was essential to insert the splint parallel to the rib in order to prevent the splint from advancing into the inferior or superior cortices.

Splint constructs endured dynamic loading without failure in strong or osteoporotic specimens. The rectangular cross-section of rib splints confined the collapse at the fracture zone to axial displacement along the splint shaft and thereby limited subsidence to less than 1 mm in all specimens. Construct durability was further evident by the negligible decrease in construct stiffness of less than 1% in response to dynamic loading. Using a similar test set-up, Sales et al. evaluated the durability of rib plating constructs by assessing their change in stiffness during dynamic loading.[32] They found that the stiffness of rib plate constructs and novel U-plate constructs deteriorated by 9.9% and 1.9%, respectively, in response to 50,000 loading cycles at an axial load magnitude that was approximately three times less than in the present study.

The dynamic loading was likely more aggressive than what can be expected *in vivo* for several reasons. First, the dynamic load amplitude (200 N/mm) was five times greater than the bending moment of 39 ± 15 N/mm measured *in vivo* during normal respiration in six patients.[29] Second, the duration of dynamic loading (360,000 cycles) simulated the entire loading history until fracture union. Dynamic loading therefore did not account for load sharing by progressive formation of a fracture callus during the healing phase. Furthermore, ribs were tested in isolation without accounting for secondary stabilisation provided by neighbouring ribs and the surrounding soft tissue envelope. Results therefore demonstrated that rib splint constructs are sufficiently durable to support respiration at an exaggerated level throughout the fracture-healing period. This conclusion is further supported by the fact that rib splint constructs retained a strength after dynamic loading that was on average 26 times greater than the bending loads under physiologic

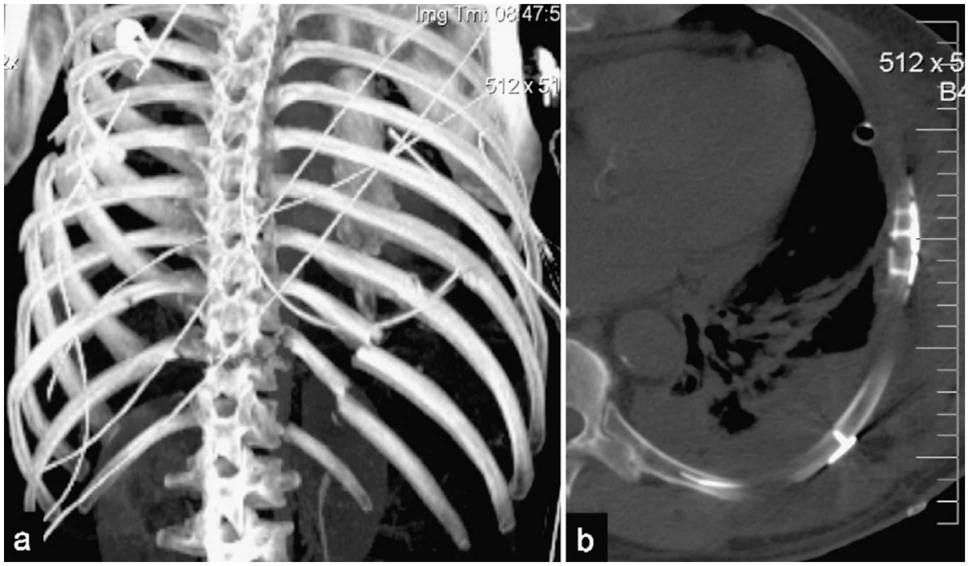

Fig. 8. Clinical case: (a) lateral and posterior fractures of flail chest injury. (b) Posterior fracture stabilisation with rib splint; lateral fracture stabilisation with osteosynthesis plate.

respiration. Conversely, rib stabilisation with splints restored on average only 11.4% of the bending strength of intact ribs. These results indicate that native rib strength is not restored until fractures heal. Given that the medical condition of patients recovering from flail chest trauma precludes rigorous activities that pose a risk of traumatic impacts to the chest wall, the transient deficiency in rib strength may be of minor concern. The highest forces in ribs during recovery are likely to occur during coughing and sneezing. Coughing can generate thoracic pressure of up to 40 kPa.[22] Converting this peak pressure into a rib bending moment by data extrapolation from Rehm[29] would suggest a peak bending moment of 0.9 N m, which remains just below the average residual strength of rib splint constructs. However, adjacent ribs and connective tissues provide additional structural support *in vivo* that have not been accounted for in the present study.

The observed failure modes did not resemble implant migration or implant cut-out from the lateral cortex, as has been reported for Kirschner wires. Shah reported that Kirschner wires sometimes shatter ribs longitudinally and can penetrate out of the rib into the soft tissue.[36] Others have reported that Kirschner wires may dislodge and migrate to just below the skin, requiring removal.[1,2,18] In contrast, none of the splint constructs failed catastrophically. All rib splint constructs retained functional reduction and fixation of rib fractures after failure. In 15 specimens, fracture lines along the superior and inferior cortices triggered a decrease in the apparent bending moment, which was detected as implant failure. The remaining 12 specimens failed primarily by splint bending. However, the high flexibility of titanium alloy enabled elastic recoil after failure, whereby the residual plastic deformation was sufficiently small to retain functional reduction and stabilisation. The locking screw retained stable fixation of the extramedullary splint segment. Furthermore, it prevented implant lift-off and migration through the lateral cortex that has been reported for Kirschner wires. No fracture occurred at the locking screw or the splint insertion portal. The absence of fractures at the splint insertion portal demonstrated that the splint effectively transferred load from the locking screw across the fracture while bridging and shielding the entry portal from excessive loading.

The present evaluation of rib splints has several limitations. Constructs were tested in bending only. This simplified bending mode represented the principal loading of ribs *in vivo* and has strong precedence for biomechanical testing of ribs and rib fixation constructs.[10,29,32] Instead of rib osteotomies, realistic rib fractures were induced by loading of native ribs to failure. This resulted in poor control of the fracture location, for which reason one specimen had to be eliminated. It yielded simple transverse or oblique fractures, whereby comminuted fractures may be more difficult to stabilise. However, the majority of rib fractures caused by blunt trauma are simple and transverse.[20] Splints were not tested in specimens younger than 62 years, which could be stronger than the ribs of this study. However, since the failure mode in strong ribs was splint bending, the same failure mode will likely occur in even stronger ribs from younger specimens. While the present results suggest that rib splints provide sufficient stabilisation to support respiration, these findings should be confirmed in a future clinical study that accounts for the realistic variances in splint insertion, fracture reduction, and post-operative loading histories. A prospective clinical study is currently being conducted by the authors to document surgical stabilisation of flail chest injuries with rib splints (Fig. 8). However, unlike the present biomechanical study, this clinical study will not be able to assess construct strength, subsidence, and failure modes.

In conclusion, results of this study suggest that rib splints can provide sufficient stability to support respiratory loading throughout the healing phase, but they do not restore the full strength of native ribs. Most importantly, rib splints mitigated the complications reported for rib fracture fixation with generic Kirschner wires, namely implant cut-out and migration through the lateral cortex. Therefore, rib splints may provide an advanced alternative to the original Kirschner wire technique for less-invasive fixation of rib fractures. This intramedullary fixation approach holds particular merit for fixation of posterior rib fractures where access for plating is limited.

Conflict of interest

Michael Bottlang, Daniel C. Fitzpatrick, William B. Long, and Steven M. Madey receive licensing and consulting income from Synthes CMF, West Chester, PA, USA.

Acknowledgements

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References

1. Ahmed Z, Mohyuddin Z. Management of flail chest injury: internal fixation versus endotracheal intubation and ventilation. J Thorac Cardiovasc Surg 1995;110:1676–80.
2. Albrecht F, Brug E. Stabilisation of the flail chest with tension band wires of ribs and sternum (author's transl). Zentralbl Chir 1979;104:770–6.
3. Balci AE, Eren S, Cakir O, Eren MN. Open fixation in flail chest: review of 64 patients. Asian Cardiovasc Thorac Ann 2004;12:11–5.
4. Beal SL, Oreskovich MR. Long-term disability associated with flail chest injury. Am J Surg 1985;150:324–6.
5. Bulger EM, Arneson MA, Mock CN, Jurkovich GJ. Rib fractures in the elderly. J Trauma 2000;48:1040–6.
6. Cacchione RN, Richardson JD, Seligson D. Painful nonunion of multiple rib fractures managed by operative stabilisation. J Trauma 2000;48: 319–21.
7. Cormier JM, Stitzel JD, Duma SM, Matsuoka F. Regional variation in the structural response and geometrical properties of human ribs. Annu Proc Assoc Adv Automot Med 2005;49:153–70.
8. Di Fabio D, Benetti D, Benvenuti M, Mombelloni G. Surgical stabilisation of post-traumatic flail chest. Our experience with 116 cases treated. Minerva Chirurgica 1995;50:227–33.
9. Engel C, Krieg JC, Madey SM, et al. Operative chest wall fixation with osteosynthesis plates. J Trauma 2005;58:181–6.
10. Granik G, Stein I. Human ribs: static testing as a promising medical application. J Biomech 1973;6:237–40.
11. Haasler GB. Open fixation of flail chest after blunt trauma. Ann Thorac Surg 1990;49:993–5.
12. Hellberg K, de Vivie ER, Fuchs K, et al. Stabilisation of flail chest by compression osteosynthesis—experimental and clinical results. Thorac Cardiovasc Surg 1981;29:275–81.
13. Ho JD, Dawes DM, Bultman LL, et al. Respiratory effect of prolonged electrical weapon application on human volunteers. Acad Emerg Med 2007;14: 197–201.
14. Karev DV. Operative management of the flail chest. Wiad Lek 1997;50(Suppl 1 (Pt 2)):205–8.
15. Landercasper J, Cogbill TH, Lindesmith LA. Long-term disability after flail chest injury. J Trauma 1984;24:410–4.
16. Mayberry JC, Terhes JT, Ellis TJ, et al. Absorbable plates for rib fracture repair: preliminary experience. J Trauma 2003;55:835–9.
17. Meier P, Schupbach P. Therapy of the unstable thorax in serial fractures of the ribs. Schweiz Med Wochenschr 1978;108:608–13.
18. Menard A, Testart J, Philippe JM, Grise P. Treatment of flail chest with Judet's struts. J Thorac Cardiovasc Surg 1983;86:300–5.
19. Mohr M, Abrams E, Engel C, et al. Geometry of human ribs pertinent to orthopedic chest-wall reconstruction. J Biomech 2007;40:1310–7.
20. Moore BP. Operative stabilisation of nonpenetrating chest injuries. J Thorac Cardiovasc Surg 1975;70:619–30.
21. Mouton W, Lardinois D, Furrer M, et al. Long-term follow-up of patients with operative stabilisation of a flail chest. Thorac Cardiovasc Surg 1997;45:242–4.
22. Murray JF, Nadel JA. Textbook of respiratory medicine, 2nd ed., London: Saunders; 1994.
23. Ng AB, Giannoudis PV, Bismil Q, et al. Operative stabilisation of painful non-united multiple rib fractures. Injury 2001;32:637–9.
24. Nirula R, Allen B, Layman R, et al. Rib fracture stabilisation in patients sustaining blunt chest injury. Am Surg 2006;72:307–9.
25. Pettiford BL, Luketich JD, Landreneau RJ. The management of flail chest. Thorac Surg Clin 2007;17:25–33.
26. Quell M, Vecsei V. Surgical stabilisation of thoracic wall fractures. Unfallchirurg 1991;94:129–33.
27. Reber P, Ris HB, Inderbitzi R, et al. Osteosynthesis of the injured chest wall. Use of the AO (Arbeitsgemeinschaft fur Osteosynthese) technique. Scand J Thorac Cardiovasc Surg 1993;27:137–42.
28. Reber PU, Kniemeyer HW, Ris HB. Reconstruction plates for internal fixation of flail chest. Ann Thorac Surg 1998;66:2158.
29. Rehm KE. Die Osteosynthese der Thoraxwandinstabilitaeten. Hefte zur Unfallheilkunde 1986;175.
30. Richardson JD, Adams L, Flint LM. Selective management of flail chest and pulmonary contusion. Ann Surg 1982;196:481–7.
31. Richardson JD, Franklin GA, Heffley S, Seligson D. Operative fixation of chest wall fractures: an underused procedure? Am Surg 2007;73:591–6.
32. Sales JR, Ellis TJ, Gillard J, et al. Biomechanical testing of a novel, minimally invasive rib fracture plating system. J Trauma 2008;64:1270–4.
33. Samarrai AR. Costosynthetic stabilisation of massive chest wall instability. Int Surg 1990;75:231–3.
34. Schmit-Neuerburg KP, Weiss H, Labitzke R. Indication for thoracotomy and chest wall stabilisation. Injury 1982;14:26–34.
35. Schupbach P, Meier P. Indications for the reconstruction of the unstable thorax due to serial rib fractures and respiratory insufficiency. Helv Chir Acta 1976;43:497–502.
36. Shah TJ. On internal fixation for flail chest. J Thorac Cardiovasc Surg 1996;112:849–50.
37. Slater MS, Mayberry JC, Trunkey DD. Operative stabilisation of a flail chest six years after injury. Ann Thorac Surg 2001;72:600–1.
38. Tanaka H, Yukioka T, Yamaguti Y, et al. Surgical stabilisation of internal pneumatic stabilisation? A prospective randomized study of management of severe flail chest patients. J Trauma 2002;52:727–32 [discussion 32].
39. Velmahos GC, Vassiliu P, Chan LS, et al. Influence of flail chest on outcome among patients with severe thoracic cage trauma. Int Surg 2002;87:240–4.
40. 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;187:130–8.