New insights into the pathophysiology of flail segment: the implications of anterior serratus muscle in parietal failure

Jacques Borrelly, Mathias Hossain Aazami

Medipole Gentilly-Saint Jacques, 54320 Maxeville, France
Cardio-thoracic Surgery and Thoracic Transplantation Department, Teheran University of Medical Sciences, Imam Khomeini Hospital, Boulvard Keshavarz, Teheran, Iran

Abstract

Objective: The wisdom of surgery facing multiple and multi-focal ribs fractures (flail segment) remains controversial. By the present retrospective study, we sought to determine the advisability of surgery as well as the anatomical and biomechanical features of flail segment leading to secondary dislocation.

Method: From 1970 to 2000, 127 patients underwent flail segment osteosynthesis. Clinical charts, operative reports and imaging data were reviewed retrospectively. Rib osteosynthesis was carried out with Judet staple and Kirschner wires until 1980, since then it has been undertaken with sliding-staples-struts. Postoperative chest X-ray was carried out to classify the flail segments into anterolateral and posterolateral types according to the location of anterior and posterior rib fractures. Each type was then divided into three subgroups of primary parietal, secondary parietal and retreat indications that were inferred retrospectively from final indications of rib osteosynthesis.

Results: The mean age of patients (ranging in age from 20 to 84 years) was 56.14.4 years with a male predominance (108/19). Seventy percent of flail segments was considered as posterolateral. The mean number of rib fractures per patient was 6.0.35. Rib osteosynthesis was undertaken with sliding-staples-struts in 70% of patients. The overall hospital mortality was 16%; it was subsequently reduced to 8% since sliding-staples-struts were used. The mean duration of ventilation was reduced from 5.8.0.76 days to 2.98.0.83 days with sliding-staples-struts. Seventy-seven percent of patients with posterolateral flail segment and primary parietal indication were extubated within the first 48 h postoperatively, whereas 46% of patients from other subgroups required ventilation for more than 5 days. Similarly, 83% of patients of the former subgroup returned to full previous level of activity compared with a rate of 52% for the latter subgroups. The flail segments were dislocated superoposteriorly for both anterolateral and posterolateral types, evoking the action of anterior serratus muscle.

Conclusions: The anterolateral and posterolateral flail segments are rendered susceptible to secondary dislocation through a complex set of factors, of which the action of anterior serratus muscle is obvious. Restoration of parietal mechanics by early surgical reduction/fixation is a reliable therapeutic option in selected patients and offers encouraging results.

2005 Elsevier B.V. All rights reserved.

Keywords: Flail chest; Rib fracture; Serratus anterior muscle

1. Introduction

The flail chest continues to represent a challenging clinical entity in spite of the crucial role for parietal integrity in respiratory mechanics, although anatomical restoration of traumatic flail chest remains controversial [1–6]. Consequently, surgical reduction/fixation of flail chest has not garnered wide acceptance though the encouraging results have been reported in the medical literature [3,7–13]. The surgical approach is mainly implied in view of huge thoracic deformity, of ensuing respiratory failure and as ‘retreat indication’ where thoracotomy is mandatory because of threatened associated visceral lesions [1,2,4,5,14]. The inherent propensity towards dislocation for both the anterolateral and the posterolateral flail segments is well recognised [7,8,13–15]; however, reluctance has been raised to the rationale of early surgical reduction/fixation that stems from (1) our prevailing definition for flail chest based on clinical evidence of paradoxical motion [2,4,5,16]; (2) slighting the implications of parietal mechanical failure such as flail segment dislocation in patient recovery and late outcome [5,6,12]; (3) the lack of a standardised and reliable surgical approach attempt at restoring mechanical integrity of the chest wall [2,3,4,7,8,11,12,14,17–19] and (4) the paucity of well conducted and randomised clinical trials between surgical reduction/fixation approach and conservative therapeutic options that otherwise seems difficult, if not impossible, to be ruled by in the setting of blunt thoracic trauma [5,7–10,13,15,20].

The inherent propensity of flail segment towards dislocation that results in parietal mechanical dysfunction can accurately be assessed at present by analysing flail segment
with thoracic CT scan, provided the pathophysiology of flail segment and factors involved in the process of flail segment dislocation are properly adopted. In the present retrospective study, our experience with surgical reduction/fixation over a 30-year period is reviewed with an aim to determine the advisability of early surgical reduction/fixation in the setting of flail segment, while focusing on the action of anterior serratus muscle in flail segment dislocation.

2. Patients and methods

During a 30-year period from 1970 to 2000, 794 patients were cared for severe blunt chest trauma. One hundred and forty-seven of 794 patients (18.5%) underwent thoracotomy during their hospitalisation. Among the 147 patients operated on, surgical reduction/fixation of a flail segment (multi-focal fractures of at least three consecutive ribs regardless of clinical evidence for paradoxical motion or initial degree of deformation) was carried out in 127 patients who are enrolled in the current study (16% of all patients).

Thoracotomy was centred on the flail area and its length adjusted according to the extension of the flail segment and associated intra-thoracic lesions. Some surgical rules were carefully observed, which include (1) expanding the ribs minimally with retractors; (2) checking carefully for associated visceral lesions and haemorrhage inside thoracic cavity; (3) proper placement of drainage tubes and (4) draining superficial ecchymosed layers (muscles and soft tissues). Rib osteosynthesis was carried out by means of Kirschner wires and Judet staples until 1980; then it has been undertaken systematically with sliding-staples-struts (SSS) [13,15,21], which are conceived especially for anatomic reconstruction of ribs and thoracic cage. Generally, the upper and lower ribs are neglected, unless there is a huge thoracic deformation as is the case with stove-in-chest fractures. Epidural analgesia was used since 1985 whenever feasible.

Clinical charts, operation reports, reports of subsequent medical visits, radiological and, whenever available, thoracic CT-scan images were reviewed retrospectively in an attempt to study the surgical outcome and determine the anatomy of flail segments. The flail segment was categorised topographically by studying postoperative chest X-rays, where the staples allowed determining the exact location of rib fractures accurately compared with preoperative X-rays. The flail segments were classified into two major categories according to two biomechanical landmarks on the thoracic cage that were represented by the lines of anterior and posterior rib angles, whichever was the initial extent of chest deformation or clinical evidence of paradoxical motion (Fig. 1). The posterolateral flail segment (PL) was considered where posterior fractures affected the line of posterior rib angle, whereas the anterolateral flail segment (AL) was considered if anterior fractures were found in the area of anterior rib angle; the overlapping lateral area comprises the insertion of the digitations of anterior serratus muscle.

For each of the two categories, the patients were subdivided into three subgroups according to final indications for surgical fixation:

- retreat indication (RIn) was defined if threatened visceral lesions were associated, where surgical fixation was carried out at the end of the operation;
- primary parietal indication (PPIn) was considered if surgical fixation was attempted to restore parietal

![Fig. 1. (A) The flail segments are classified as anterolateral if anterior fractures are found in the area of anterior rib angle (arrow) and as posterolateral if posterior fractures affect the line of posterior rib angle (dotted arrow). Postoperative chest X-ray turned to be helpful in classifying accurately the flail segment type. Compare the preoperative chest X-ray with postoperative ones: (B and C) anterolateral flail segment; (D and E) posterolateral flail segment. At present, chest CT-scan is a valuable diagnostic tool in accurately classifying flail segment type at patient admission.](image-url)
mechanical integrity within the first 2 days after initial trauma;
- secondary parietal indication (SPIn) was considered if surgical fixation was attempted to offer a better respiratory or functional outcome in view of parenchymal lesions, impossibility of pursuing conservative therapy, shrinkage of chest wall, secondary respiratory deterioration or to shorten the time on the ventilator after the first 3 days following initial trauma.

3. Results

One hundred and twenty-seven patients underwent surgical fixation following blunt chest trauma during the study period. The mean age was 56 ± 14.4 years (ranging in age from 20 to 84 years), of whom 19 were women (15%). The causes of trauma were motor vehicle and motor—pedestrian accidents: 60%, falls: 19%, crush injury: 15%, sport: 3% and miscellaneous: 3%. The mean number of fractured ribs per patient was 6 ± 0.35. Mild-to-moderate pulmonary contusion was present in 76% of the patients, and 52% of them displayed some degree of paradoxical motion. The associated lesions are listed in Table 1. The anterolateral flail segments were associated with a higher incidence of associated visceral lesions, especially in the left side compared with posterolateral ones (47% vs 23%).

One hundred and nine patients were operated in view of resuming parietal mechanics, deemed as parietal indication (Pin), resulting in surgical fixation in 108 patients (Fig. 2). The inspection of thoracic cavity allowed the discovery of overlooked associated visceral lesions in 19 of the patients operated on the basis of parietal indication. Conversely, rib osteosynthesis was undertaken in 19 of 38 patients who were taken for operation because of associated visceral lesions, considered as retreat indication.

Rib osteosynthesis was feasible in all cases except one because of agglutinated fractures, and the median number of ribs surgically fixed was 4.9 ± 0.32. The first 36 (30%) patients were operated with Judet staples and Kirschner wires and the remaining with sliding-staples-struts (70%). The overall hospital mortality was 16%, 25% for the first 36 patients and 8% for patients who were operated with sliding-staples-struts. None of the hospital deaths was related to rib osteosynthesis; the hospital attrition was related with septicaemia, stress ulcer, renal failure, multi-organ failure, acute respiratory distress syndrome, pneumonia and mesenteric ischaemia. Four patients developed wound suppuration that was handled conservatively with antibiotics without removing the materials.

Accordingly, 89 patients (70% of operated patients) were classified as displaying a posterolateral flail segment. The remaining 38 patients (30%) were considered as having anterolateral flail segment. The distribution of patients according to final indications for surgical reduction/fixation is reported in Table 2.

With our growing experience, there was a trend for earlier operation. In doing so, the patients were operated on before thoracic shrinkage sets in or prior to the onset of respiratory failure. All the 14 patients in AL-PPIn subgroup were operated on the day of admission because of huge chest wall deformation and stove-in-chest fractures.

Seventy-seven percent of patients with posterolateral flail segment who were operated on for primary parietal indication were extubated within first 48 h after the surgical procedure, whereas 47% of patients belonging to other subgroups required a prolonged period of ventilation (more than 5 days), of whom 13% underwent a subsequent tracheostomy. The mean duration of ventilation was 5.8 ± 0.76 days for the patients operated on with Judet staples and Kirschner wires compared with a mean duration of 2.98 ± 0.83 days since sliding-staples-struts have been used, reflecting the continual progress in respiratory care protocols and importance of the quality of rib osteosynthesis material.

Eighty-three percent of patients of PL-PPIn subgroup returned to their previous full employment or to their previous level of activity versus 52% of the survivors for other subgroups. Therefore, the subgroup of PL-PPIn provided better overall outcome.

---

Table 1

<table>
<thead>
<tr>
<th>Injury</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemothorax</td>
<td>93</td>
</tr>
<tr>
<td>Pneumothorax</td>
<td>60</td>
</tr>
<tr>
<td>Extremity fractures</td>
<td>52</td>
</tr>
<tr>
<td>Head injury</td>
<td>30</td>
</tr>
<tr>
<td>Diaphragmatic rupture</td>
<td>11</td>
</tr>
<tr>
<td>Abdominal visceral injury</td>
<td>6</td>
</tr>
<tr>
<td>Cardiac wound</td>
<td>3</td>
</tr>
<tr>
<td>Pericardial rupture</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Table 2

<table>
<thead>
<tr>
<th>Final indications</th>
<th>AL (%)</th>
<th>PL (%)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>PPIn</td>
<td>14 (11%)</td>
<td>58 (46%)</td>
<td></td>
</tr>
<tr>
<td>SPIn</td>
<td>18 (14%)</td>
<td>18 (14%)</td>
<td></td>
</tr>
<tr>
<td>Rin</td>
<td>6 (5%)</td>
<td>13 (10%)</td>
<td></td>
</tr>
<tr>
<td>Total flail</td>
<td>38 (30%)</td>
<td>89 (70%)</td>
<td>127</td>
</tr>
</tbody>
</table>

PPIn: primary parietal indication; SPIn: secondary parietal indication; Rin: retreat indication.
Six patients had residual parietal pain after surgical procedure, which cannot be formally ascribed to osteosynthesis per se. Two patients were reoperated: one was reoperated after 8 months in view of delayed false aneurysm of the aortic isthmus (the patient was operated emergently on the basis of abdominal haemorrhage, therefore, without initial chest CT-scan; splenectomy was carried out through classic laparatomy, then separate thoracotomy was effected in view of rib osteosynthesis, which showed no peri-aortic haematoma at that time); the other patient was reoperated 10 years after initial rib osteosynthesis for overlooked diaphragmatic rupture related with new chest trauma due to fall (roofer); the sliding-staples-struts were uneventfully removed at the time of reoperation in both the cases.

The retrospective analysis of X-rays and chest CT-scan imaging disclosed a constant posterosuperior direction for flail segment dislocation, if present; the latter is speculated to be resultant to the action of anterior serratus muscle, the digitations of which in the lateral area would pull on flail segment.

4. Comments

The reluctance to the widespread application of rib osteosynthesis is partly due to our incomplete understanding of flail segment pathophysiology. Although considered as one of the criteria for our prevailing definition of flail chest, paradoxical motion is not, however, unequivocally related per se with ensuing respiratory failure in the setting of flail chest as well as its occurrence is not exclusive to the traumatic context [22]. Furthermore, the fractured ribs splinted by scapular osteomuscular coverage do not necessarily display paradoxical motion, yet sustaining the possibility for threatening secondary respiratory deterioration, which can occur independently from the degree of underlying pulmonary contusion [14,15,20]. To address the above mentioned restrictions, we concur with Ahmed and Mohyuddin [7] in preferring the term flail segment that is defined as a parietal segment comprising more than three ribs detached from the adjacent chest wall by multi-focal fractures over the term flail chest that would imply clinical evidence of paradoxical motion. Nevertheless, the classification of the different types of flail segment in the available literature seems to be conflicting [5,7,8,14,16]. Our retrospective analysis was based on postoperative chest X-ray carried out to categorise the flail segments into two major types according to two biomechanical landmarks on the chest wall. The anterolateral flail segment is defined as that in which the anterior fractures are found in the area of the anterior rib angle, while a flail segment is considered as posterolateral if posterior fractures comprise the line of posterior rib angle (Fig. 1). Both the types share the lateral area, the importance of which in respiratory mechanics is reflected by the insertion of the digitations of inspiratory serratus anterior muscle.

The strength of our rationale for early surgical reduction/fixation in the setting of anterolateral and posterolateral flail segments is based on recognising the importance of parietal mechanics integrity in respiratory function, especially when

![Diagram](image.png)

Fig. 3. (A) A schematic view of a drawer-like mechanism underlying flail segment dislocation. When involved in inspiration or shoulder movements, the digitations of anterior serratus muscle pull on flail segment in a posterior and superior direction. (B and C) Right-sided and left-sided anterolateral flail segments respectively. Plain arrows show insertion of the digitations of anterior serratus muscle on flail segment; dotted arrow displays the drawer-like mechanism. Note the internal impaction in B due to scapular osteomuscular splitting.
the action of inspiratory muscles is called for, thereby, underscoring the crucial contribution of the lateral area in respiratory mechanical reserve. Together with the latter, the possible secondary dislocation of flail segment, which is well documented as a possible evolving pathway [3,4,15], perpetuates a vicious circle of morbidities resulting in decreased patient functional capacity [4,19]. Although the lack of well-conducted randomised clinical trials compels to be affirmative, the implications of mechanical disturbances in patient respiratory aptitude and overall morbidity can be inferred from the available reported data. In a series of 64 patients with a flail segment, Ahmed and Mohyuddin [7] documented faster recovery and a decreased rate of hospital complications among those patients operated on with surgical fixation, though surgical indication attempted at primarily restoration of parietal mechanics was carried out only for 38.5% of patients (10/26). Voggenreiter et al. [9] also demonstrated significant benefits of primary surgical fixation for patients sustaining flail chest without underlying pulmonary contusion. In addition, these authors emphasised the usefulness of secondary surgical fixation for patients with pulmonary contusion when a progressive collapse of the chest wall occurs at the time of weaning from the ventilator. The authors’ conclusions can be backed up by the series of Clark et al. [20] wherein 57% of patients with isolated flail chest required mechanical ventilation as opposed to 31% with an isolated pulmonary contusion, again underscoring the role of parietal factors.

In a unique randomised trial, Tanaka et al. [10] showed the advantages of even delayed surgical fixation (at least 5 days on the ventilator) over internal stabilisation, especially in terms of ventilator duration (10.8 ± 3.4 days vs 18.3 ± 7.4 days) and severe infectious complications such as pneumonia (24% vs 77%). But, this study is open to criticism with regard to its high rate of excluded patients and the systematically delayed nature of surgical indication. In our experience, 57% of the patients were operated on the basis of primary parietal indication with a trend for earlier operation as our experience grew. Our hospital results were better when sliding-staples-struts were used with a hospital mortality of 8% and a mean time of required ventilation of 2.98 ± 0.83 days for all related subgroups. Similarly, 77% of the patients of PL-PPIn subgroup were extubated within the first 48 h postoperatively, whereas 47% of patients from other subgroups needed a prolonged period of ventilation (more than 5 days). This difference is ascribed to a higher incidence of associated lesions and a more severe degree of underlying pulmonary contusion in the setting of anterolateral flail segment or retreat indications; it also casts light on the detrimental effect of postponing operation in patient outcome, especially when the operation is a secondary attempt to rescue the ongoing respiratory deterioration.

![Image](image-url)

**Fig. 4.** (A) The posterolateral flail segment (arrow) is dislocated due to a drawer-like mechanism and it is impacted inward the thoracic cavity due to the scapula osteomuscular covering. (B) Tri-dimensional CT-chest reconstruction showing the posterior fractures in the area of posterior rib angle. Note the internal impaction under scapula. (C) Coronal view of a posterolateral flail segment. The final result is internal impaction and overriding ribs resulting in mechanical failure of the chest wall. Arrows: flail segment; dotted arrow: scapula osteomuscular splitting.
As for the long-term outcome, the data reported in the series by Ahmed and Mohyuddin [7] and by Tanaka et al. [10] suggested advantages favouring surgical fixation, such as a better pulmonary functional capacity and a higher return-to-work rate (61% vs 5% for Tanaka et al. [10]). In the series of Beal and Oreskovich [23], patients sustaining severe flail chest wall who were treated conservatively were more susceptible to having perpetuated thoracic symptoms and developing a worsening exertional dyspnoea. Similarly, Slater et al. [11] reported a case of surgical stabilisation, 6 years after a traumatic flail chest. The indications for stabilisation were chronic pain, dyspnoea associated with ribs malunion and loss in the volume of the hemithorax due to a hugely dislocated posterolateral flail segment. After resection of the rib segments involved in pseudo-arthrosis and restoration of the ribs’ continuity using malleable plates, the authors reported a dramatic relief in the patient symptoms, resuming his full-time physical activity painlessly. In this context many authors [11,18,19] recommend a wider application of rib stabilisation in selected patients. Our results showed that the subgroup of PL-PPIn offered better outlook in terms of the rate of returning to previous level of activity compared with other subgroups (83% vs 52%). This difference was not influenced by the age of patients and should be related with sequel attendant to associated lesions. These results agree with our initial intuition according to which wisdom of early surgical reduction/fixation comes to rationale by offering a better overall outcome [15,21].

Thus, in essence early surgical reduction/fixation is thought to be of benefit to reduce overall morbidity through resuming parietal mechanics and breaking the vicious circle initiated by dislocation of the flail segment. The inherent propensity of the posterolateral and anterolateral flail segments towards dislocation, which is of particular relevance to flail segment pathophysiology, is completed by a complex set of factors governing the intricate relationship between the flail segment and the chest wall that includes (1) asynchronous tri-dimensional respiratory shifting of the flail segment in relation to its adjacent chest wall, (2) the action of extra-thoracic muscular covering, especially that of the serratus anterior muscle through a
drawer-like movement and (3) the consequences of therapeutic interventions on respiratory drive forces.

4.1. Extra-thoracic considerations and drawer-like movement

In addition to asynchronous tri-dimensional respiratory movements of the flail segment causing an insidious shifting, extra-thoracic muscles commit the flail segment to initiate or increase the likelihood of dislocation. The serratus anterior muscle also has a crucial contributing role in the complex pathophysiology of flail segment dislocation. When involved in the shoulder movements or as an inspiratory muscle, the individual insertion of the digitations of the serratus anterior muscle on each rib pulls as an arm on a drawer to dislocate the flail segment (Figs. 3 and 4). This explains the common tendency of flail segment towards a posterosuperior shifting, thereby producing overriding ribs. Because of a prominent muscular covering, internal impaction into the thoracic cage is commonplace in the posterolateral area, resulting in an ‘apple-pie bed’ chest wall (Figs. 3B and 4). However, external avulsion is more frequent in the anterolateral area (Fig. 3C) and with inferior ribs of a postero-lateral flail segment because of a diminished muscular splinting.

4.2. Intra-thoracic considerations

The role of intra-thoracic factors, such as intra-thoracic pressures and thoracic drainage, has been spuriously brought to the fore [6,24,25]. Although these may imply some role, the witnessed effects are due rather to an alteration in the tone of the respiratory muscles. When effecting internal pneumatic stabilisation, the requisite sedation, analgesia or muscle relaxants can diminish the respiratory drive force, thereby minimising the shifting effects of muscular covering. Furthermore, as previously quoted by Lardinois et al. [8], even after a prolonged period of intubation, not all cases with flail chest wall turnout to be stable; this may result in malunion and pseudo-arthritis of involved ribs that perpetuate chronic symptoms through a vicious circle [7,8,14,19,23] (Fig. 5).

In spite of the available bulk of evidence in favour of rib osteosynthesis provided by the medical literature and present study, the part coming to flail segment dislocation in patient recovery and long-term outcome remains to be further investigated. Besides mechanical dysfunction of the chest wall, loss of thoracic volume, spasm, pain and fibrosis have been assigned as the factors involved in residual suboptimal functional capacity [8,14]. All these factors are nevertheless addressed effectively by surgical reduction/fixation (Fig. 5).

The patient selection process in view of early surgical reduction/fixation seems to be the salient point and is mainly based on anticipating the predominant role of mechanical disruption of chest wall in ongoing respiratory failure or when a high degree of suspicion for secondary dislocation of flail segment is raised; the latter can be reliably evaluated at present by thoracic CT-scan, provided the pathophysiology and natural history of the flail segment are adopted. Our data showed that primary restoration of parietal mechanics provides better results, especially in the setting of posterolateral flail segment. Therefore, our policy is to undertake rib osteosynthesis within the first 48 h following admission. Nevertheless, severe pulmonary contusion, emergence of multi-organ failure or associated traumatic lesions that portend a poor prognosis take precedence over surgical stabilisation. When attempted to rescue patients whose respiration deteriorates in spite of optimal conservative management, the indication of delayed rib osteosynthesis should be tailored and individualised to each clinical scenario; however, secondary restoration of the chest volume is justified in view of shuffling patient recovery, perpetuated symptoms, chest shrinkage and aesthetic prejudice.

5. Conclusion

The implications of complex pathophysiology of flail segment should be taken into account in early therapeutic modalities. Whenever feasible, chest CT scan can provide crucial details, which are helpful in classifying flail segment types and assessing their propensity towards dislocation. When properly adopted, the pathophysiology of flail segment is of paramount relevance in the therapeutic decision-making process. As surgical reduction/fixation is the most reliable treatment in avoiding or breaking the vicious cycle of dislocation, it should be recommended in selected patients. Nevertheless, further multi-centric clinical trials are needed to support our retrospective results; it is hoped that the present classifications and proposed new insights in flail segment pathophysiology will be incentive enough to conduct further retrospective and prospective trials in a normalised way.

References