CT-lung volume estimates in trauma patients undergoing stabilizing surgery for flail chest

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A B S T R A C T

Aim: To estimate and compare lung volumes from pre- and post-operative computed tomography (CT) images and correlate findings with post-operative lung function tests in trauma patients with flail chest undergoing stabilizing surgery.
Patients and methods: Pre- and post-operative CT images of the thorax were used to estimate lung volumes in 37 patients who had undergone rib plate fixation at least 6 months before inclusion for flail chest due to blunt thoracic trauma. Computed tomography lung volumes were estimated from airway distal to each lung hilum by outlining air-filled lung tissue either manually in images of 5 mm slice thickness or automatically in images of 0.6 mm slice thickness. Demographics, pain, range of motion in the thorax, breathing movements and Forced Vital Capacity (FVC) were assessed. Total Lung Capacity (TLC) measurements were also made in a subgroup of patients (n = 17) who had not been intubated at time of the initial CT. Post-operative CT lung volumes were correlated to FVC and TLC.
Results: Patients with a median age of 62 (19–90) years, a median Injury Severity Score (ISS) of 20 (9–54), and a median New Injury Severity Score (NISS) of 27 (17–66) were enrolled in the study. Median follow-up time was 3.9 (0.5–5.6) years. Two patients complained of pain at rest and when breathing. Pre-operative CT lung volumes were significantly different (p < 0.0001) from post-operative CT lung volumes, 3.51 l (1.50–6.05) vs. 5.59 l (2.18–7.78), respectively. At follow-up, median FVC was 3.76 l (1.48–5.84) and median TLC was 6.93 l (4.21–8.42). Post-operative CT lung volumes correlated highly with both FVC [r_s = 0.75 (95% CI 0.57–0.87, p < 0.0001)] and TLC [r_s = 0.90 (95% CI 0.73–0.96, p < 0.0001)]. The operated thoracic side showed decreased breathing movements. Range of motion in the lower thorax showed a low correlation with FVC [r_s = 0.48 (95% CI 0.19–0.70, p = 0.002)] and a high correlation with TLC [r_s = 0.80 (95% CI 0.51–0.92, p < 0.0001)].
Conclusions: Post-operative CT-lung volume estimates improve compared to pre-operative values in trauma patients undergoing stabilizing surgery for flail chest, and can be used as a marker for lung function when deciding which patient with chest wall injuries can benefit from surgery.

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Introduction

Surgical management of rib fractures has received increasing attention in recent years with the development of new fixation techniques [1], although the indication for surgery is still debatable, especially in patients with non-flail rib fractures, traumatic brain injury (TBI) and severe lung contusions. Rib fractures occur in 40% of patients with thoracic trauma [2] and multiple fractures may lead to chest wall instability and thus flail chest [3]. Flail chest is associated with pulmonary contusions, respiratory insufficiency and high mortality [4] and current practice guidelines support surgical management of patients with flail chest [5] because this may be associated with decreased mortality, incidence of pneumonia and need for ventilator support [6–8]. It is still unclear, however, if rib stabilization improves chest wall healing and long-term lung function.

Computed tomography is the diagnostic tool of choice for identifying intra-thoracic and chest wall injuries as CT can detect

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the 75% of rib fractures that are missed on chest X-rays [9]. Volumetric CT images of the thorax indicating reduced lung volume may aid decision-making for rib fracture stabilization as lung function tests during the acute phase are challenging.

Different techniques that estimate lung volume using CT images have been used to assess patients with pulmonary disease [10], pre-operative size matching in lung transplant surgery [11], and post-operative lung function predictions in patients undergoing lung cancer resection [12]. In blunt thoracic trauma, pulmonary contusions have been quantified to predict Acute Respiratory Distress Syndrome (ARDS) development [13,14] and clinical outcomes [15]. Therefore, a post-trauma CT scan of the thoracic cage could potentially help the clinician to identify chest wall injuries, assess deformity and estimate lung volumes before deciding to operate. To our knowledge, however, no studies have used CT to estimate lung volumes in trauma patients undergoing stabilizing surgery for flail chest.

The aim of this study, therefore, was to estimate and compare lung volumes in trauma patients with flail chest undergoing stabilizing surgery using pre- and post-operative CT images, and to correlate these findings to post-operative lung function tests.

This study was approved by the Research Ethics Committee at Gothenburg University, Gothenburg, Sweden (Dnr 887-13). All patients gave their informed consent to participate in the study after verbal and written information.

Patients and methods

Patients

Patients (aged ≥18 years) who had undergone stabilizing surgery for flail chest at least 6 months previously were invited to participate in a follow-up study between October 2015 and January 2018. Flail chest is defined as three or more adjacent ribs each fractured in more than one location [3]. Patients with pre-existing conditions influencing lung function and movement of the thorax (e.g., previous lung resection, severe chronic pulmonary, neurological or musculoskeletal diseases or severe brain and spinal injury) were not eligible for inclusion. All patients were assessed using the ISS [16] and NISS [17] injury scoring systems. Injuries to the lungs were graded, 1–6, according to the presence and extent of contusions, lacerations and vascular injury by using the Lung injury scale (LIS) [18]. In cases of no lung injury the patient was graded LIS 0. Injuries to the chest wall were graded, 1–5, according to the presence and extent of contusions and lacerations of the soft tissues and fractures of the sternum and ribs by using the Chest Wall Injury Scale (CIS) [19].

Methods

Surgical procedure

Rib fractures were stabilized using the MatrixRIB[TM] Fixation System (DePuy Synthes, West Chester, USA) consisting of pre-shaped angular locked plates and intra-medullary splints, as described previously [20,21].

Computed tomography

All CT images of the thorax were obtained using one of the following 64-slice scanners: LightSpeed VCT, Discovery CT750HD, and Optima CT660 from GE Healthcare (Waukesha, USA) or Somatom Force Dual 192 from Siemens Medical Healthcare (GmbH, Erlanger, Germany). Computed tomography was done pre-operatively with a tube voltage of 120 kV and intravenous contrast medium (often as part of a whole-body CT post trauma), and 6-months post-operatively with a tube voltage of 80–100 kV and without intravenous contrast medium.

The effective radiation dose for post-operative CT was estimated by multiplying the indicated dose length product (DLP) by the conversion factor $0.017 \, mSv/(Gy \times cm)$ [22]. Patients were instructed to inhale deeply without exhaling during CT scanning.

Transverse images of 0.6 mm thickness were available for 3 months after scanning, whilst transverse images of 5 mm thickness were saved long term in radiological archives. The CT images were evaluated by a single radiologist with 20 years of experience in thoracic radiology. The mediastinal and parenchymal window settings were used in AW Volume Share[TM] 5 software (Advantage Workstation 2.0; GE Healthcare, Waukesha, USA). The number and side of rib fractures, and concomitant sternal, clavicle, scapular and thoracic spine fractures were assessed in pre-operative CT images. Signs of lung changes, non-united fractures, plate or splint dysfunction, and rib healing patterns were assessed in post-operative CT images.

Thoracic VCAR (Volume Computer Assisted Reading) Parenchyma Analysis imaging software (GE Healthcare, Waukesha, USA) was used to calculate CT lung volume for air-filled lung tissue in patients (n = 18) with 0.6 mm thick CT images available pre- and post-operatively (Fig. 1a and b). Lung volume was calculated manually by outlining air-filled lung tissue in each CT image in patients with CT images of 5 mm thickness available pre- and post-operatively (n = 19) (Fig. 1c). Automatic and manual CT-lung volume were measured from airway distal to each lung hilum. Atelectasis, haemothorax and pneumothorax were excluded from the estimated volumes. Minimal pneumothoraces were disregarded, but volumes of pneumothorax ≥10 mm were estimated in the same way as lung volumes. All manual estimations were done twice to assess reliability. In nine patients both automatic and manual measurements were performed for comparison. The correlation and agreement between repeated manual measurements and manual and automatic measurements was estimated.

Clinical follow-up

A clinical follow-up was done 6 months post-operatively at the earliest. Patients answered a standardized questionnaire concerning demographics, pain at rest and when breathing, local discomfort, local sensation, dyspnoea, and analgesia usage. The range of motion in the thorax was assessed by measuring thoracic excursion (at the level of the fourth costae and the xiphoid process) [23]. Breathing movements were measured at rest and during maximal breathing with the patient lying in a supine position using a Respiratory Movement Measuring Instrument, RMMI® (ReMo Inc. Keldnaholt, Reykjavik, Iceland) [24]. Laser sensors were placed along a sagittal line, approximately 1/3 the length of the clavicle from the sternal notch, at the level of the fourth rib (upper thorax), xiphoid process (lower thorax) and umbilicus (abdomen) bilaterally. Changes in distance between the sensors and the skin surface were registered during one minute and the average movement for each site was calculated. The median difference in movement between the operated and non-operated side was calculated.

Lung function tests

Forced vital capacity was performed in a standardized manner [25] at follow-up using an EasyOne® Spirometer (ndd Medical Technologies Inc., MA, Us). Total Lung Capacity with body plethysmograph was measured in a subgroup of 17 patients who had not been intubated at initial CT using the TLC Sensormedics Vmax® Encore system (Yorba Linda CA, USA) and SentrySuite[TM] v. 2.21 software (Intramedic AB, Sweden). The correlation and agreement between post-operative CT lung volume and FVC and TLC was estimated.
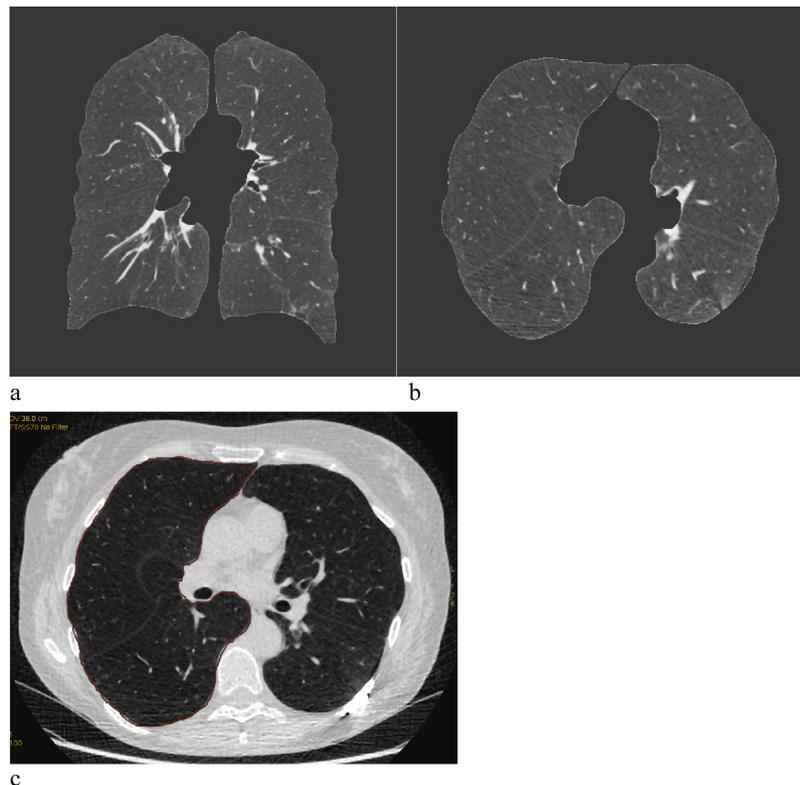
Fig. 1. Shows examples of CT images used for lung volume estimates using a) automatic measurements in coronal thoracic sections, b) automatic measurements in transverse thoracic sections, and c) manual measurements in transverse thoracic sections.

Statistical analyses

All statistical analyses were done using SPSS v21 software (IBM® 2012). Mainly non-parametric methods were used for data analysis, as the sample size was considered small and the data were not normally distributed. Results are shown as median with range for continuous variables, and n and % for categorical variables. The Wilcoxon Signed Rank Test was used to assess variability in paired samples and for comparisons over time. The Mann-Whitney Test was used to compare subgroups. Bivariate correlation was calculated with Spearman's Two-Tailed Correlation Coefficient and a 95% Confidence Interval (CI) was calculated using Fisher's Z. Bland-Altman diagrams were created to compare manual and automatic lung volume measurements and CT-lung volumes with FVC and TLC, respectively. Significance was considered to be $p < 0.05$.

Results

Patient demographics

Of the thirty-seven patients enrolled, 26 (70%) and 11 (30%) were male and female, respectively, with a median age of 62 (19–90) years. The mechanism of injury was road traffic accidents in 18 (49%) patients: motor vehicle accidents (MVA) (n = 11); pedestrian vehicle accidents (PVA) (n = 3); and bicycle accidents (n = 4). The mechanism of injury in the remaining 19 (51%) patients was due to falls (n = 14); horse riding (n = 2); jet-skiing (n = 1), parasailing (n = 1); and assault (n = 1). Patients had a median ISS 20 (9–54), NISS 27 (17–66), CIS 4.0 (3–4) and LIS 2.0 (0–4). Median follow-up time was 3.9 (0.5–5.6) years post trauma. Patients complained of pain at rest and when breathing (n = 2), breathlessness (n = 6), local discomfort (n = 14), and decreased local sensation (n = 10). Three patients used analgesia at follow-up.

Clinical assessment

Pre- and post-operative CT results are shown in Table 1. The estimated effective radiation dose for post-operative CT ranged from 0.3 to 1.25 mSv. Approximately 43% of fractured ribs were operated on and 34% of all rib fractures were stabilized. The median CT lung volume on the left side increased from 1.46 (0.45–3.67), pre-operatively, to 2.69 (0.71–3.87), post-operatively, and the median lung volume on the right side increased from 1.90 (0.77–2.95), pre-operatively, to 2.94 (1.47–4.19), post-operatively. Pre-operative CT estimates of median total lung volume were 3.51 l (1.50–6.05) and post-operative radiological estimates of total lung volume were 5.59 l (2.18–7.78) (Fig. 2). The difference between CT lung volumes estimated pre- and post-operatively was statistically significant ($p < 0.0001$), even when excluding patients with pneumothorax ($p < 0.0001$) or lung contusions ($p < 0.0001$) at initial CT. Pre- and post-operative CT estimates of median total lung volume, according to operated side and whether or not the patient had unilateral or bilateral rib fractures, are shown in Table 1.

Post-operative lung volumes were higher than pre-operative lung volumes in the four patients who were intubated at initial CT. There were too few patients in this subgroup, however, to perform a separate statistical analysis. The distribution of pre- and post-operative CT lung volumes comparing intubated and non-intubated patients was not significantly different ($p > 0.05$). Intubated patients had significantly higher ISS, NISS and LIS values, but there was no difference in age, CIS and pneumothorax volume compared to non-intubated patients.

Manual measurements of CT lung volumes were done twice per patient (n = 21 pre-operatively and n = 19 post-operatively, respectively) to assess reliability. The median difference between manual measurements from same image was 0.03 l (0–0.29), but this was not statistically significant ($p = 0.303$). A strong correlation

Table 1
Shows results of pre-operative and post-operative CT imaging in 37 patients with flail chest and unilateral or bilateral thoracic injuries, operated on the left and right side, respectively.

	Rib stabilization on left side (n = 19)		Rib stabilization on right side (n = 18)	
	Unilateral rib fractures (n = 12)	Bilateral rib fractures (n = 7)	Unilateral rib fractures (n = 15)	Bilateral rib fractures (n = 3)
Pre-Operative CT				
Total CT lung volume (l)	4.26 (1.83–5.31)	2.75 (1.54–4.34)	2.68 (1.50–6.05)	2.96 (2.25–4.01)
Pneumothorax (n)	5 (5L)	4 (4L)	7 (6R and 1B)	3 (1R and 2B)
Total pneumothorax volume (l)	0 (0–0.067)	0 (0–0.106)	0 (0–1.504)	0.157 (0–0.499)
Lung contusion (n)	5 (5L)	5 (2L, 1R and 2B)	8 (7R and 1B)	3 (1R and 2B)
Fractured ribs (n)	7 (5–10)	14 (9–19)	8 (4–12)	12 (9–16)
Rib fractures (n)	11.5 (9–18)	21 (14–36)	13 (7–22)	15 (12–24)
Clavicle fracture (n)	1 (1L)	1 (1L)	3 (3R)	0
Scapula fracture (n)	1 (1L)	1 (1L)	5 (4R and 1B)	1 (1R)
Sternal fracture (n)	2	4	2	1
Thoracic spine fracture (n)	0	2	5	2
Post-Operative CT				
Total CT lung volume (l)	5.43 (3.97–7.78)	5.59 (3.15–7.47)	5.73 (2.18–7.53)	5.30 (4.12–6.56)
Lung pathology (n)	0	0	1 (1B)	0
Fractured ribs operated (n)	3.5 (2–6)	4 (3–5)[a]	4 (2–5)	5 (4–5)[a]
Rib fractures operated (n)	4 (2–7)	6 (3–11)[a]	4 (2–8)	5 (4–7)[a]
Implant dysfunction (n)	0	1 (1L)	0	0
Rib synostosis (n)	1 (1L)	3 (3L)	6 (6R)	1 (1R)
Non-union (n)	0	1 (1B)[b]	2 (1R and 1B)[b]	1 (1R)[b]
Clavicle fracture operated (n)	0	0	2 (2R)	0
Scapula fracture operated (n)	0	0	1 (1R)	0
Sternal fracture operated (n)	0	1	0	0
Thoracic spine fracture operated (n)	0	0	1	0

Median values are shown with range in parenthesis.
L = left side, R = right side and B = bilateral.
[a] Despite the presence of bilateral rib fractures, there were no bilateral rib stabilizations done.
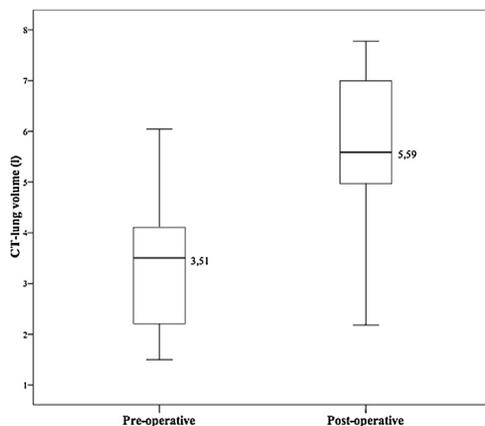[b] Non-union occurred only in non-operated rib fractures.

Fig. 2. Box plots of pre- and post-operative CT-lung volumes in 37 patients with flail chest.

($r_s = 0.995$) and agreement between the first and second manual measurements are shown in Fig. 3a, with a wider dispersion of, results in the range of lower values. The median difference between manual and automatic measurements in the same patient (n = 9) was 0.04 l (0–0.21) and also not significant (p = 0.066). A strong correlation [$r_s = 0.99$ (95% CI 0.94–0.997; p < 0.0001)] between automatic and manual measurements is shown in Fig. 3b, although there was a tendency for overestimation of lung volume when performing manual measurements.

Lung function tests were performed on the same day as post-operative CT and showed a median FVC of 3.76 l (1.48–5.84) with a predicted FVC of 96% (60–114). Post-operative CT lung volumes correlated highly with FVC [coefficient $r_s = 0.75$ (95% CI 0.57–0.87,

p < 0.0001)]. Values obtained by CT-lung volume estimation were higher than FVC (Fig. 4a).

A subgroup of patients (n = 17) who had not been intubated at time of initial CT also underwent TLC measurement with body plethysmograph with a TLC of 6.93 l (4.21–8.42) and a predicted TLC of 93% (72–111) at follow-up. There was a significant high correlation between post-operative CT lung volumes and TLC with $r_s = 0.90$ (95% CI 0.73−0.96, p < 0.0001). The TLC values were higher than CT-lung volume estimations (Fig. 4b). The median time lapse between post-operative CT and TLC was 45 (0–483) days. When comparing patients who had undergone TLC measurement (n = 17) with those who had not (n = 20), no significant differences in ISS, NISS, CIS, and LIS values; pneumothorax volume; pre- and post-operative lung volumes; breathing movements; or lower thoracic excursions were seen. The median age of patients who had undergone TLC measurement was 10 years less than that of those who had not undergone TLC (p = 0.012).

Post-operative CT showed non-united fractures in three patients; these only occurred in non-operated ribs. One patient had implant dysfunction with two loose screws, and one patient showed signs of lung fibrosis and usual interstitial pneumonia (UIP). Heterotopic ossification with rib synostosis was seen in 4 patients on the left side and 7 patients on the right side.

Breathing movements were measured in 36 patients (Table 2). Ten patients had bilateral rib fractures but none of the patients were operated on both sides. Patients with unilateral rib fractures had decreased breathing movements on the operated side compared with the non-operated side in the lower thorax and during maximal breathing in the upper thorax. Median differences, however, were small (0.13–2.04 mm). There was no difference in breathing movements between the operated and non-operated side in patients with bilateral rib fractures, except for the abdomen at rest, where breathing movements were decreased on the operated side.
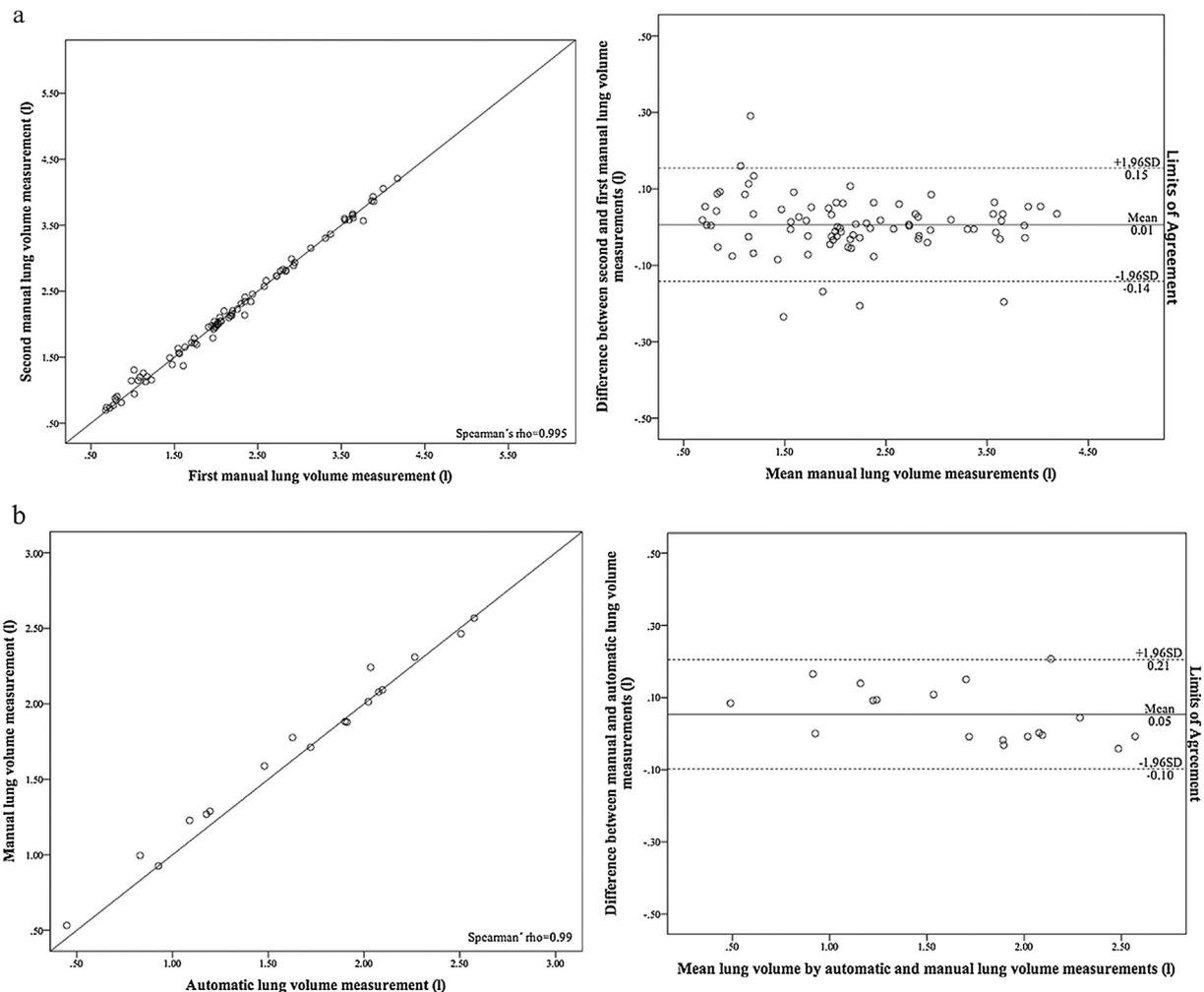
a

b

Fig. 3. Shows the correlation and a Bland-Altman diagram of a) manual lung volume measurements pre-operatively (n = 21) and post-operatively (n = 19), and b) automatic and manual lung volume measurements (n = 9).

Median upper and lower thoracic excursions were 2.8 (0.5–6.7) cm and 3.2 (0.5–9.1) cm, respectively. Upper thoracic excursion did not correlate with CT-lung volume estimates [r_s = 0.12 (95% CI -0.22–0.42, p = 0.493)], FVC [r_s = 0.20 (95% CI -0.13–0.49, p = 0.235)] or TLC [r_s = 0.31 (95%, -0.20–0.69, p = 0.227)]. In contrast, lower thoracic excursion showed a low correlation with FVC [r_s = 0.48 (95% CI 0.19–0.70, p = 0.002)] and a high correlation with TLC [r_s = 0.80 (95% CI 0.51–0.92, p < 0.0001)], but not with post-operative CT-lung volume estimates [r_s = 0.28 (95% CI -0.05–0.55, p = 0.097)].

Discussion

In this cross-sectional study of 37 patients with blunt thoracic trauma who had undergone stabilizing surgery for flail chest, we found a significant increase in CT-lung volume estimates when comparing pre- and post-operative CT images of the thorax. This increase was independent of pneumothorax or lung contusions on initial CT. It is possible that there could be a difference in results between intubated and non-intubated patients in pre-operative lung volume measurements as intubated patients have improved ventilation and reduced atelectasis formation. In contrast, non-intubated patients are awake, in pain and may be unable to inhale deeply before examination.

Intubated patients had significantly higher ISS, NISS and LIS values, suggesting a higher physiological burden. There was no significant difference in CT lung volumes pre- and post-operatively when comparing intubated and non-intubated patients. There were, however, too few patients who were intubated at initial CT to separately analyse potential differences between pre- and postoperative lung volumes.

We found a strong correlation between post-operative CT lung volume and FVC and TLC. To our knowledge, this is the first ever study to assess CT lung volumes in patients undergoing rib fracture stabilization. Since pain and/or inability to follow instructions hampers acute phase lung function testing in patients with acute thoracic trauma, information on CT lung volumes aids assessment of such patients. Moreover, CT lung volume can serve as a marker for lung function and provide the clinician with information to improve informed decision-making concerning surgery for rib fractures. Such information can also be extracted from pre-existing CT images, thereby requiring no additional invasive procedures; for example, if a patient has had previous CT of the thorax, the radiologist could compare images and calculate potential lung volume reduction on the affected side. In addition, the lungs can be assessed independently, in contrast to lung function tests where TLC is measured.

One goal of surgery is to normalise lung function. Two randomized-controlled trials (RCTs) showed improved lung function in patients managed surgically compared to those managed conservatively [6,7], whereas a third RCT showed no difference [8]. Reducing chest wall deformity and returning the
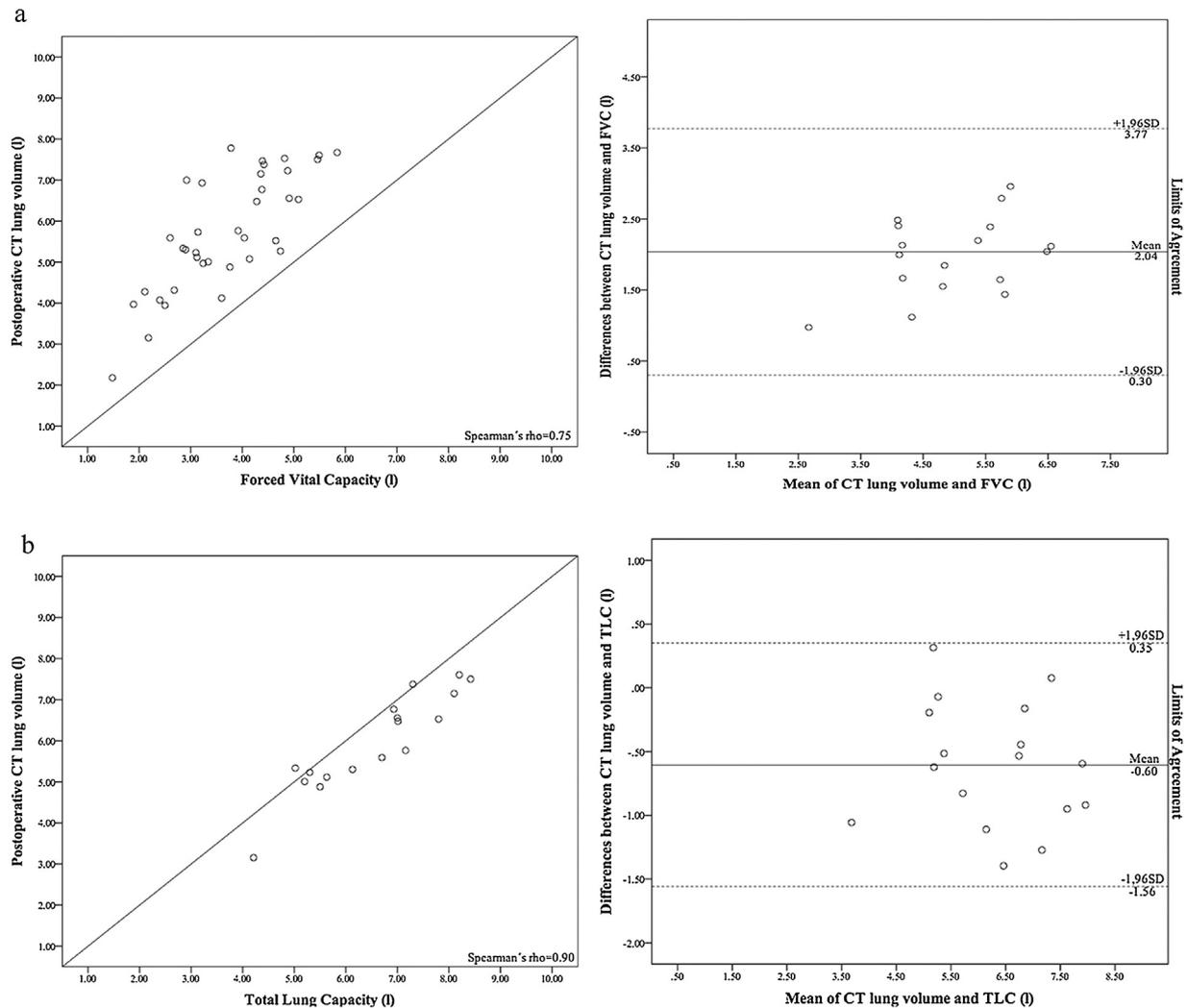
a

b

Fig. 4. Shows the correlation and a Bland-Altman diagram of post-operative CT-lung volume and a) Forced Vital Capacity (FVC) (n = 37 patients), and b) Total Lung Capacity (TLC) (n = 17 patients).

thoracic cage to its anatomical form may optimize lung function. When assessing chest wall function, the clavicles, scapula, sternum, and thoracic spine must be evaluated in addition to the ribs because concomitant injuries often exist, as shown here. In our study, 43% of fractured ribs had been operated on and 34% of rib fractures had been stabilized. Converting a flail segment to a non-flail segment by stabilizing only one fracture per rib may not always prevent deformity [26]. Stabilizing all fractures may cause rigidity and stiffness in the chest wall and stabilizing too few may be inadequate.

We found that chest wall healing was good, with only three patients having non-united fractures in non-operated ribs. Moreover, breathing movements were reduced on the operated side in the upper and lower thorax in patients with unilateral rib fractures. Although these differences were small and of questionable clinical significance, this contrasts with our earlier study where breathing movements were better on the operated side one year post surgery [20]; however, follow-up time differed and— despite a median time from trauma of 3.9 (0.5–5.6) years—some patients had been examined less than one year post surgery. Our earlier study also showed a gradual improvement even one year post surgery [20].

In this study, lower thoracic excursion correlated with FVC and TLC, but not with CT lung volumes, which may reflect the difference

between the anatomical and dynamic aspects of the chest wall. Better movement in the lower thorax of operated patients compared to non-operated patients has been shown previously [27]. Patients can complain of chest tightness after surgery, although this appears to be more prevalent in conservatively managed patients [6]. We found two patients had persisting pain when breathing and 38% experienced local discomfort, which is less than in our previous study where 47% of patients complained of local discomfort one year post-surgery [20]. Different implants cause different levels of stiffness, which may be necessary to avoid implant failure and breakage [28] and thus may cause greater chest wall rigidity in operated patients. However, since we found no difference in breathing movements in the thorax between the operated and non-operated side in patients with bilateral fractures, the stiffness experienced may also be due to the healing process. Tissue scarring cannot be seen on CT. Although heterotopic ossification with rib synostosis was seen in 30% of the patients it is unclear if this is more prevalent in patients undergoing rib fracture surgery. It is possible that rib synostosis, rather than implant rigidity is the cause of perceived chest wall stiffness.

This study has several limitations. Different CT scanners, 64-slice and dual 192-slice, were used. Computed tomography images of either 0.6 mm or 5 mm slice thickness were evaluated, and atelectasis, haemothorax and pneumothorax may have been

Table 2

Breathing movements measured post-operatively on the operated and non-operated side, at rest and during maximal breathing, in 26 patients with unilateral and 10 patients with bilateral rib fractures. Differences between operated and non-operated sides are shown as median with range and 25 (Q1) and 75 (Q3) percentiles, respectively.

Location		Median movement operated side (mm)	Median movement non-operated side (mm)	Difference between operated vs. non-operated side (mm)			p-value
				Median	Q1	Q3	
Upper Thorax							
Rest	Unilateral fractures	2.14 (0.23–10.16)	2.65 (0.34–9.64)	−0.21 (−2.19 to 3.76)	−0.84	0.11	0.077
	Bilateral fractures	3.37 (1.12–6.68)	3.17 (1.18–7.85)	−0.09 (−1.17 to 1.22)	−0.77	0.76	0.959
Max	Unilateral fractures	16.74 (1.70–29.34)	20.08 (1.38–34.70)	−2.04 (−11.86 to 10.42)	−4.67	0.20	**0.005**
	Bilateral fractures	10.75 (3.36–23.07)	9.35 (4.14–26.69)	−0.60 (−4.31 to 2.29)	−0.92	1.05	0.508
Lower Thorax							
Rest	Unilateral fractures	2.05 (0.25–8.03)	2.28 (0.30–10.11)	−0.13 (−2.84 to 1.53)	−0.54	0.20	**0.026**
	Bilateral fractures	2.35 (1.19–6.66)	2.09 (1.43–7.23)	−0.15 (−3.10 to 0.36)	−0.38	0.32	0.721
Max	Unilateral fractures	12.41 (1.06–26.69)	16.39 (1.10–34.65)	−1.04 (−9.75 to 21.33)	−3.40	0.24	**0.003**
	Bilateral fractures	8.26 (4.03–28.66)	9.81 (3.02–25.92)	−0.64 (−3.66 to 2.74)	−1.62	2.27	0.959
Abdomen							
Rest	Unilateral fractures	8.01 (1.00–19.53)	7.78 (0.87–18.25)	0.05 (−3.18 to -1.28)	−1.56	0.69	0.187
	Bilateral fractures	6.87 (3.86–14.91)	8.03 (2.86–16.77)	−0.71 (−7.65 to 1.00)	−4.22	−0.15	**0.037**
Max	Unilateral fractures	19.02 (3.15–38.86)	19.25 (2.85–36.90)	−0.47 (−8.37 to 5.40)	−3.78	1.61	0.178
	Bilateral fractures	19.24 (4.76–33.51)	19.63 (4.39–35.93)	−1.45 (−7.92 to 0.66)	−2.84	0.40	0.074

Bold values signifies p < 0.05.

underestimated in the 5 mm images. The major limitation of CT-lung volume estimation in pre-operative CT images is a lower degree of inspiration during CT scanning due to pain with atelectasis formation in the dorso-basal region of lung parenchyma. Computed tomography-lung volume estimates were made using two different methods, although the same method was used for individual patients. Estimating CT lung volumes by manual segmentation is time consuming with inherent difficulty in outlining the poorly air-filled lung tissue and discriminating against non air-filled lung tissue. In contrast, CT lung volumes are easily estimated automatically and for which several computerized programmes are available. Manual measurements were done twice and although the inter-test variation ranged from 0 to 0.29 l, this was statistically insignificant. Results from CT lung volumes acquired manually and automatically were compared in nine patients; findings were highly correlated with no significant difference.

Total lung capacity was measured in a subgroup of 17 patients and there was a time lapse between CT and body plethysmography. The reason for this being that several patients had undergone post-operative CT imaging and we did not want to subject them to unnecessary additional radiation at the time of TLC measurement. These patients were significantly younger and may have had better lung function than the other patients. Fifty seven per cent of patients had lung contusions, but these were not graded except when estimating LIS, ISS and NISS values. Since the median LIS was 2 (range 0–4), several patients had no visible contusions despite severe chest wall injuries. Lung contusions are not always prominent at initial CT, but develop within 24–48 h [29] and can influence clinical outcomes [13,15].

Conventional treatment of flail chest with analgesics and ventilator support can entail long hospitalization [30], pulmonary infections and long-term disability with chronic pain [31,32]. Estimating the CT lung volume aids assessment of patients with thoracic trauma in the immediate post-trauma phase when pain and/or inability to follow instructions make lung function testing challenging. Reduced CT lung volume is valuable information for clinicians who must decide whether or not a patient may benefit from chest wall surgery.

Further studies comparing CT lung volumes in operated versus conservatively managed patients with chest wall injuries are required to determine if chest wall surgery and chest wall healing

improves long-term lung function. Also, the differences seen between intubated and non-intubated patients in this study mandate further assessment.

Conclusions

Estimates of CT lung volumes in patients with flail chest undergoing stabilizing surgery improve significantly post-operatively regardless of the presence of pneumothorax or lung contusions at initial CT, and can be used as a marker for lung function.

Conflict of interest

None.

Data statement

The data supporting the conclusions of this study are included within the article. Additional group data, in order to maintain patient confidentiality, can be shared on request.

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