Characteristics of rib fractures in young abused children

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Abstract

Background The presumed mechanism of rib fractures in abuse is violent grasping of the torso causing anterior–posterior chest compression. We hypothesized an asymmetrical distribution of rib fractures in abused infants given the greater incidence of right-hand dominance within the general population.

Objective The objective of this study was to characterize rib fractures in abused children, particularly sidedness; additionally, we evaluated the sidedness of other abusive skeletal fractures.

Materials and methods We reviewed medical records from abused children (0–18 months old) with rib fractures. We also retrospectively reviewed their radiographs to determine characteristics of rib fractures (number, side, rib region, level, acuity) and other skeletal fractures (number, side, location), as well as differences in the distribution of rib and other skeletal fractures.

Results A total of 360 rib fractures were identified on 273 individual ribs involving 78 abused children. Sixty-three children (81%) had multiple rib fractures. There was a significantly greater number of left-side rib fractures (67%) than right-side fractures ($P<0.001$). Fractures were most often identified in the posterior and lateral regions and mid level of the ribcage (Ribs 5 through 8). Fifty-four percent of subjects had other skeletal fractures; these non-rib fractures were also predominantly on the left side ($P=0.006$).

Conclusion In our study of abused children, there was a higher incidence of rib fractures in the posterior, lateral and mid-level locations. Additionally, we found a predominance of left-side rib and other skeletal fractures. Further research is needed to understand whether factors such as perpetrator handedness are associated with these unequal distributions of fractures in abused children.

Keywords Child abuse · Children · Fractures · Handedness · Infants · Radiography · Ribs · Sidedness

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Introduction

Rib fractures in young children carry a high specificity for abuse [1–9]. A meta-analysis of studies comparing fractures in child abuse to other causes found that rib fractures had the highest probability of abuse (pooled probability 71%) [5]. Rib fractures in infants are particularly concerning; Pandya et al. [6] found that in children younger than 18 months, the odds ratio that a rib fracture was caused by abuse was 23.7 (compared to 9.1 in children older than 18 months). Paine et al. [8] found similar results related to age in a systematic review of rib fracture studies; the prevalence of abuse in children younger than 12 months with a rib fracture ranged between 67% and 87%, but in children 12–35 months of age, the prevalence was 28–29%. Also concerning is the strong association of rib fractures with abusive head trauma, which when combined carries a high incidence of mortality and morbidity [10–12].

The presumed mechanism of rib fractures in abuse is violent grasping of the torso causing anterior–posterior chest

compression [4, 13, 14]. In such cases of torso compression during abuse, a perpetrator might grasp the infant facing him or her with hands enveloping the chest (Fig. 1) [10, 12–14]. In this scenario, the perpetrator's right hand encircles the left side of the child's torso and vice versa for the left hand. Eighty-five percent to 90% of the general population is right-hand dominant, commonly with asymmetrical hand strength; the dominant hand can be at least 10% stronger than the contralateral hand [15]. This raises the possibility that a right-hand-dominant perpetrator might preferentially squeeze or apply greater pressure to the left side of an infant chest when grasping the torso. Hence, we hypothesized that the frequency of left-side rib fractures is greater than right-side rib fractures in abused infants given the greater prevalence of right-hand dominance within the general population. Knowledge of this association could allow for inference of perpetrator handedness in child abuse investigations.

Several studies have described rib fracture location by region (anterior, posterior and lateral) [2, 3, 9, 16, 17], but to our knowledge only two studies evaluated the distribution of rib fractures by left vs. right side [17, 18]. Love et al. [18] found no significant difference in the distribution of rib fractures occurring on the left vs. right sides. However, this study evaluated rib fractures in infant autopsies and included all manners of death, not only abuse. Barber et al. [17] reported a greater frequency of left-side rib fractures (288 left-side vs. 202 right-side rib fractures) but did not report whether this was a significant difference. Thus, the primary objective of our study was to determine whether there is a significant difference in the distribution of left- and right-side rib fractures in young abused children. A secondary objective was to describe characteristics of rib fractures in this population, focusing on location (rib region and level) and acuity.

Fig. 1 Illustration demonstrates child positioning relative to a perpetrator during abusive thoracic compression; note the hand position while the perpetrator grasps the child's torso

Materials and methods

Study design

This study was a retrospective review of chest radiographs, radiology reports and radiographic skeletal surveys obtained from Norton Children's Hospital in Louisville, KY. These cases involved infants and young children with rib fractures who were determined to have been physically abused. This study protocol was approved by the institutional review board at our institution.

Subjects

Subjects were identified using a clinical database maintained by the Kosair Charities Division of Pediatric Forensic Medicine that contained data about children evaluated for suspicion of abuse. We included children 0–18 months of age who were abused, who had a skeletal survey and who presented with rib fractures between 2008 and 2015. Determinations of plausibility between presenting injuries and caregiver-provided history were made through a comprehensive medical evaluation and review by the Kosair Charities Division of Pediatric Forensic Medicine's team, which includes board-certified child abuse pediatricians, one of whom is a co-author (M.C.) of this study. Only cases determined to be definite abuse were included in the study. Cases determined to be plausible or indeterminate were not included in the study. Postmortem exams were not intentionally excluded; however, they were not in the database from which the subjects were drawn.

Procedures

We collected data for each child from skeletal survey radiographs stored on the hospital's picture archiving and communication system (PACS) and the radiology report. Only radiographs were evaluated; no CT or bone scintigraphy was used. These radiographic data were reviewed by two board-certified pediatric radiologists. The first was the original reader on the radiology report, and the second was a co-author (V.M.) with 24 years of experience reading the images; any discrepancy in interpretation resulted in the removal of that case from the study. The subsequent concordant interpretations were recorded in a custom searchable research database. Abstracted data included age, gender, number of rib fractures, location of each rib fracture (side, region within rib, and rib number), and acuity of each fracture. Ribs were divided into upper (Ribs 1, 2, 3 and 4), middle (Ribs 5, 6, 7 and 8) and lower (Ribs 9, 10, 11 and 12) levels. Rib region was divided into four distinct sections on each side: posterior, posterolateral, lateral, and anterolateral (Fig. 2). Acuity of fracture was determined by the presence of periosteal reaction/callus as seen on the radiograph.
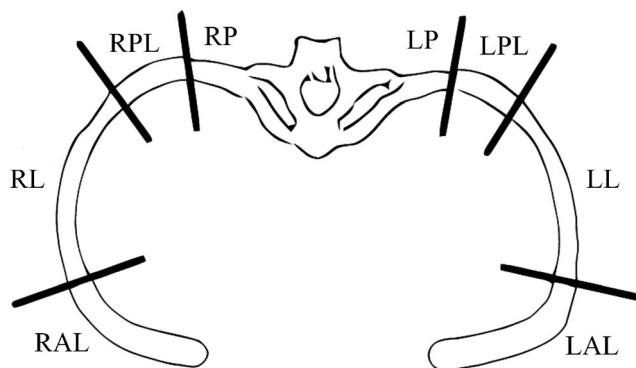
Fig. 2 Regions of rib (four per side) used to identify fracture location within the rib. *LAL* left anterolateral, *LL* left lateral, *LP* left posterior, *LPL* left posterolateral, *RAL* right anterolateral, *RL* right lateral, *RP* right posterior, *RPL* right posterolateral

Fractures were either recorded as acute (no periosteal reaction) or healing (periosteal reaction). Additionally, using skeletal surveys, any other skull and long bone skeletal fractures were recorded and described by number and location (side and bone), including presence of classic metaphyseal lesions. Repeat skeletal surveys were evaluated when available and any newly identified fractures were recorded for the child. If fractures were identified on both initial and follow-up skeletal surveys, they were only counted once, and acuity was recorded based on the initial survey.

Data analysis

We performed descriptive statistics of rib fracture characteristics and other skeletal fracture characteristics. To test the null hypothesis that the proportion of total rib fractures occurring on the left and right side were equal, we performed a two-side binomial test. Additionally, we determined the number of left- and right-side rib fractures for each child and performed a paired *t*-test to determine whether the mean number of left-side rib fractures differed from the mean number of right-side rib fractures.

To determine whether there were differences in fracture distribution by thoracic cage level and within rib region, we used chi-square tests. We also conducted a 3-way loglinear analysis to determine whether there were interactions between age and fracture region or fracture level. Other skeletal fractures were also evaluated by side; we performed a binomial test to determine whether there was a difference in the distribution. Significance for all statistical tests was set at $P \leq 0.05$.

Results

We included 78 children with rib fractures and a determination of abuse. Sixty-five percent (*n*=51) of the study sample was male. Subject age ranged 0.5–18 months, with a mean age of

4.4 (±3.9) months. Eighty-one percent (*n*=63) of the children were 6 months and younger.

We identified a total of 360 rib fractures in 273 individual ribs among the 78 children (mean 4.6, range 1–18 fractures per child); 63 children (81%) had multiple rib fractures. Of the 360 rib fractures, 241 (67%) were left-side fractures, while 119 (33%) presented on the right side of the thoracic cage. This distribution differed significantly from the null hypothesis of 50% (*P*<0.001).

Forty-seven of the 78 children presented with unilateral rib fractures. Thirty-three of these children (70%) had only left-side fractures, and the other 14 (30%) had only right-side fractures. The remaining 31 (40%) children presented with bilateral rib fractures. Chest radiographs for representative children with left-side, right-side and bilateral rib fractures are shown in Figs. 3, 4, 5, 6 and 7. Twenty-two (71%) of the 31 children with bilateral fractures had more left- than right-side rib fractures, 2 (6.5%) had more right- than left-side rib fractures, and 7 (22.5%) had an equal number of rib fractures on both sides. Overall, the mean number of left-side rib fractures (3.09) was significantly greater than the mean number of right-side rib fractures (1.53) (*P*<0.001); 55 children (71%) had only left-side or left-predominant rib fractures. Sixteen children (21%) had only right-side or right-predominant rib fractures.

The region within each rib where the fracture occurred is an important characteristic when considering fracture mechanism. In our sample, most rib fractures occurred either laterally (43% of all fractures) or posteriorly (29%) (Fig. 8). An additional 8% of fractures occurred in the posterolateral region. There was a significant association between the rib region and fracture incidence (X^2 (df=3) = 28.38, *P*<0.001). Fractures in the lateral regions (left lateral and right lateral)
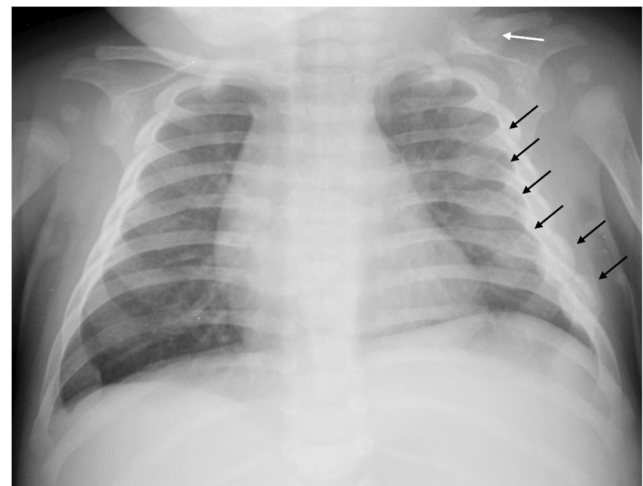

Fig. 3 Slightly rotated anteroposterior chest radiograph of six healing rib fractures in a 2-month-old abused boy. All fractures are located on the left side of the thoracic cage. These lateral rib fractures (*black arrows*) are located predominantly at the mid level of the thoracic cage, with multiple fractures of Ribs 6 and 7. This infant also sustained a left clavicular fracture (*white arrow*)
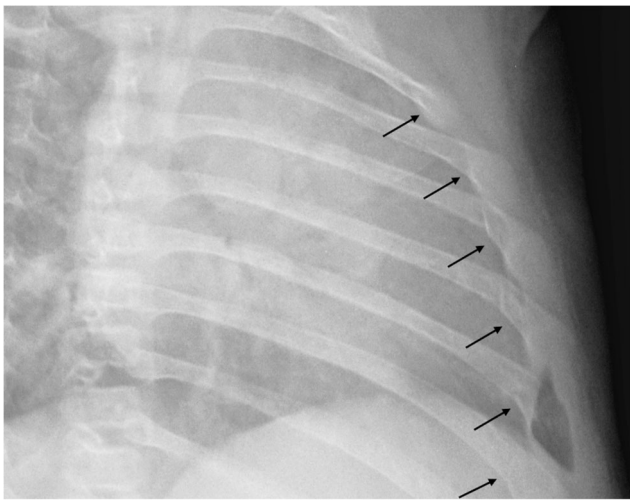
Fig. 4 Oblique radiograph of six healing rib fractures in a 4-month-old abused girl. All fractures are on the left side of the thoracic cage. These anterolateral rib fractures (*arrows*) are located at the upper and mid levels of the thoracic cage. This infant also sustained a left radial fracture (not pictured)

Fig. 6 Slightly rotated anteroposterior chest radiograph of three healing rib fractures in a 1-month-old abused girl all found on the right side of the thoracic cage; these three posterior rib fractures (*black arrows*) are located at the mid level of the thoracic cage. This infant also sustained a right humeral fracture (*thin white arrow*) with periosteal reaction (*thick white arrow*)

were most common (present in 50% of children), followed by the posterior regions (left posterior and right posterior). Twenty children (26%) had anterolateral fractures and 12 children (15%) had fractures identified in the posterolateral regions. Thirty-seven children (47%) had fractures in multiple rib regions (mean number of rib regions 1.7, range 1–4). Loglinear analysis did not reveal a significant relationship between subject age and rib region.

Level of rib fracture within the thoracic cage is an additional characteristic needed when attempting to understand injury mechanism. The majority of rib fractures (67%) occurred at the mid level between the 5th and 8th ribs (Fig. 9). There was a significant association between the rib level and fracture incidence (X^2 (df=2) = 56.91, $P<0.001$). Of the three thoracic cage

levels, children presented with fractures most often at the mid level (Ribs 5, 6, 7 or 8); 70 of the 78 children (90%) sustained a rib fracture between Ribs 5 and 8, and most of these children had fractures of the 6th and 7th ribs (63% and 68% of children, respectively). The greatest percentage of fractures also occurred on Ribs 6 and 7 (20% and 19% of the total fractures, respectively). The majority of children ($n=41$, 53%) had fractures at multiple rib levels (i.e. a combination of upper, middle or lower levels). A substantial number of the children also had fractures in multiple rib regions ($n=28$, 36%). Loglinear analysis did not reveal a significant relationship between subject age and rib level.

Determination of fracture acuity is crucial in forensic assessments. Most children in our sample ($n=71$, 91%) were
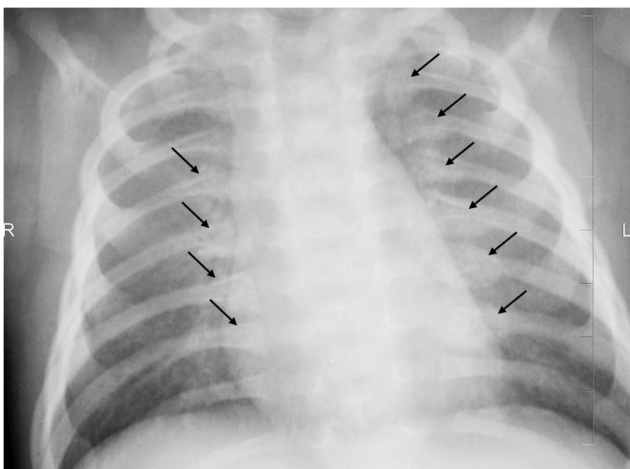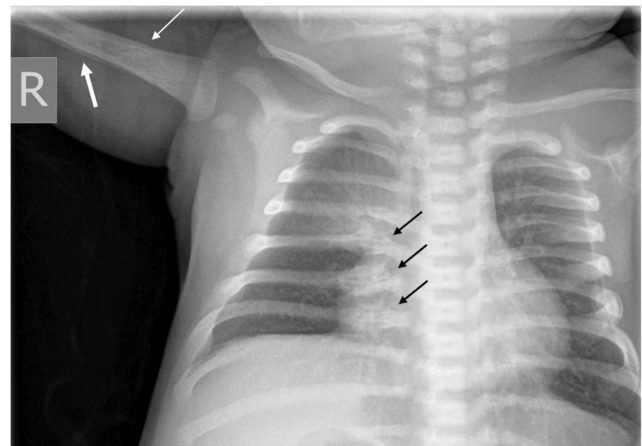

Fig. 5 Anteroposterior chest radiograph of 10 healing rib fractures in a 1-month-old abused boy, with 6 found on the left and 4 on the right of the thoracic cage. These posterior fractures (*arrows*) are located at the upper and mid levels of the thoracic cage. This infant also sustained a left humeral, left tibial, left femoral, and right tibial fracture (not pictured)
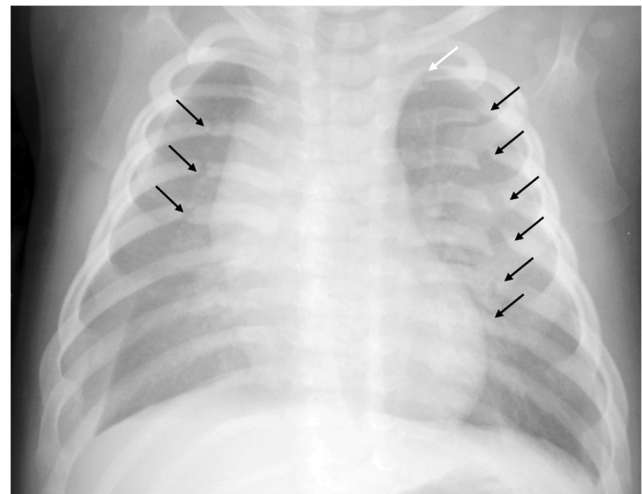

Fig. 7 Anteroposterior chest radiograph of 10 acute rib fractures in a 2-month-old abused boy, with 7 found on the left and 3 on the right of the thoracic cage. All of these fractures are posterolateral (*black arrows*) with the exception of a posterior fracture of the left 2nd rib (*white arrow*) and are located at the upper and mid levels of the thoracic cage
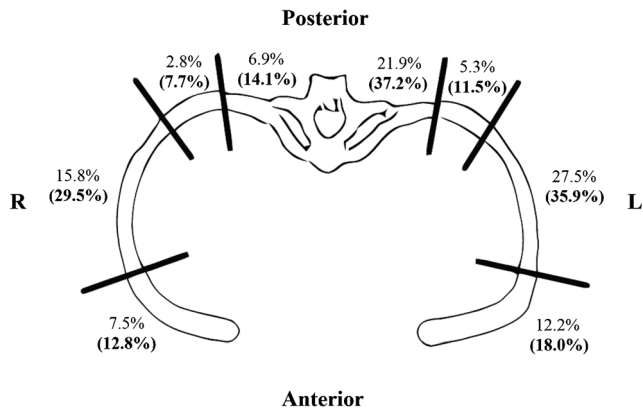
Fig. 8 Diagram shows distribution of fractures by rib region. Percentage of total rib fractures (*n*=360 rib fractures) within region (top number). Percentage of subjects (*n*=78 children) with a fracture within a region (bottom number in parentheses in boldface). *L* left, *R* right

found to have healing fractures as evidenced by periosteal reaction; this represented 86% of all fractures. Conversely, only 10 children (13%) presented with acute rib fractures, with 3 of these children having both acute and healing rib fractures.

Determining whether other skeletal fractures are present is also crucial when conducting a forensic assessment of a child where abuse is suspected. The majority of children in our study (*n*=42; 54%) sustained additional skeletal fractures; these children were found to have a mean of 2.4 additional fractures. Many of these fractures occurred in long bones, in particular the femur (28%) and the tibia (30%) (Fig. 10). It is important to note that the most common type of additional fracture was a classic metaphyseal lesion (45%), occurring most frequently in the femur and tibia. There was also a difference in the side of the body where other skeletal fractures were found, with most occurring on the left side. When considering the non-rib fractures except skull fractures (*n*=10), there were significantly more left-side skeletal fractures (*n*=58, 65%) than right-side skeletal fractures (*n*=31, 35%) (*P*=0.006).

Fig. 10 Distribution of other skeletal fractures (*n*=99). The greatest proportion of non-rib fractures occurred in the lower extremities, affecting the femur and tibia. *L* left, *R* right

Discussion

In our study, we found an unequal distribution of rib fractures in abused infants, with a significantly greater proportion of left-side rib fractures. Additionally, the mean number of left-side rib fractures was significantly greater than the mean number of right-side fractures. Given that violent thoracic compression is the presumed mechanism of rib fracture in abused infants, it is possible that this asymmetrical distribution of rib

Fig. 9 Graph shows distribution of fractures by rib number (*n*=360 rib fractures). Fractures occurred predominantly at the mid level (Ribs 5, 6, 7 and 8) and on the left side of the thoracic cage
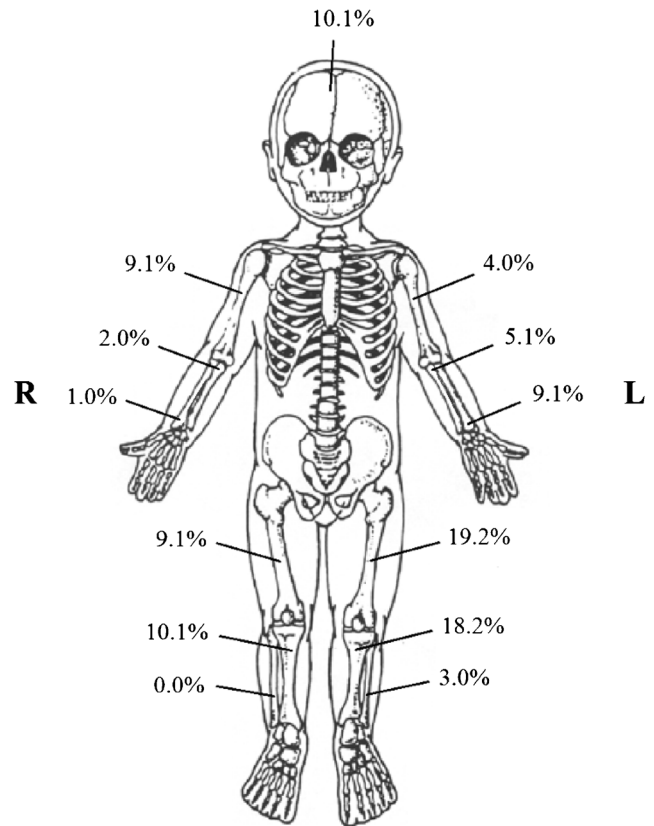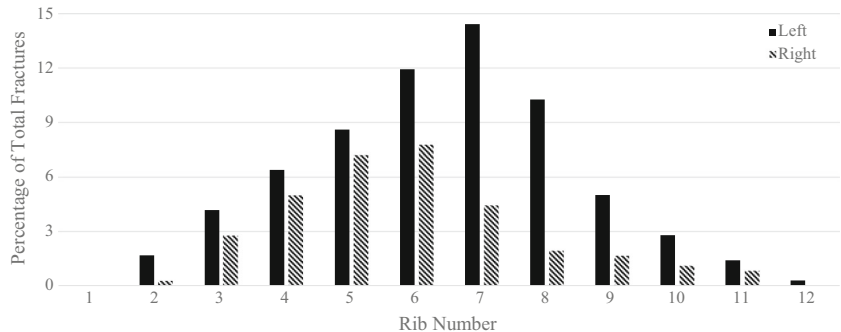
fractures is caused by perpetrator handedness. Preferential usage of the dominant hand with potential asymmetrically stronger dominant hand could be factors influencing the unequal distribution of rib fractures in abused children. It is possible that a right-hand-dominant perpetrator has a higher likelihood of fracturing left-side ribs (presuming the victim is facing the perpetrator) and vice versa. The greater population incidence of right-hand dominance could be a factor in our finding of a left-side-skewed distribution of rib fractures in abused children.

A skewed-left-side rib fracture distribution was also reported by Barber et al. [17]. In their study, 490 rib fractures were identified on the skeletal surveys of 77 infants evaluated for suspected abuse [17]. The distribution of the rib fractures was 288 left-side fractures and 202 right-side fractures, a left-to-right ratio of 1.4. The ratio of left-to-right rib fractures in our study was greater (2.0), but we included only cases determined to be definite abuse after a comprehensive review by the child abuse medicine team, whereas Barber et al. included all cases in which a skeletal survey was performed for suspected abuse. Thus, our sample differs from Barber et al.'s. In another study evaluating rib fractures, Love et al. [18] reported a more even distribution of rib fractures (79 left, 75 right; 1.05 left-to-right ratio) in infant autopsies. However, their study included fatalities that were caused by all manners of death; of the 24 infant decedents, only 3 fatalities were determined to be caused by homicide, and the remainder were ruled as accidents, natural deaths or undetermined (J. Wiersema, personal communication, June 13, 2019). It can be postulated that their nearly equal left-to-right distribution was a result of differing rib fracture mechanisms associated with non-homicidal fatalities versus that associated with abuse. It is important to note the difference in samples between our study and Love et al.'s given that we included only abusive cases, and all of our subjects were living.

Radiographs could potentially offer assistance in the identification of abusive perpetrators. In infants and young children determined to be abused, radiographic identification of rib fractures is presumed to result from a perpetrator's hands compressing or applying a load to the victim's torso [13, 14]. However, radiographs cannot offer insight into whose hands caused the injury. It is important to note that the results of this study should not be applied as evidence for perpetrator identification or exclusion in an individual case. Further prospective investigation might validate an association between radiographic asymmetrical rib fractures and perpetrator handedness. Until such studies are performed, the association of sidedness of rib fractures with handedness of perpetrators remains unproven.

A similar unequal distribution was also present within the additional skeletal injuries, with a significantly greater number of left-side skeletal fractures than right-side skeletal fractures. The same theorized etiology of perpetrator handedness might be a factor in this discrepancy. If abuse occurs with the victim facing the perpetrator, especially in non-ambulatory infants, this suggests a possibility that right-handed perpetrators are more likely to injure left-side skeletal components. However, many potential abusive scenarios could result in these non-rib skeletal fractures. Further research is necessary to understand the possible mechanisms of injury and reasons for the greater proportion of left-side skeletal injuries.

The frequent occurrence of posterior and lateral rib fractures, and the significant proportion of fractured mid-level ribs, suggest a common mechanism of injury in these children. Other studies of rib fractures in abused infants have reported similar distributions (Table 1), with the highest proportions of rib fractures generally in the posterior or lateral regions [2, 3, 9, 16, 17]. Differences in rib fracture location across studies could be caused by (1) differences in delineation of regions (e.g., Barsness et al. [9] and Cadzow and Armstrong [16] classified fractures as anterior, posterior or lateral without definition of region boundaries); (2) differences in subject age (e.g., Barsness et al. [9] included children up to 3 years of age); or (3) differences in method of abuse determination. Additionally, Kleinman et al. [3] identified fractures at autopsy rather than from radiographs alone. This is likely the reason for the increased incidence of posterior (rib head and rib neck) fractures in that study compared to others; e.g., fractures at the rib head and costotransverse process articulation are particularly difficult to differentiate on radiographs, but these two distinct fracture locations made up the majority of fractures reported by Kleinman et al. [3].

The larger proportion of lateral fractures found in our study compared to other studies (Table 1) might stem from the relatively large lateral regions used to classify fracture locations (Fig. 2). The regions were defined to (1) provide consistent classification of fractures on radiographs and (2) reflect the changing morphology of the rib, in particular isolating regions with greatest curvature, which sometimes undergo increased stress and increased likelihood of fracture during loading of the rib. This classification scheme differs from that used by Love et al. [18], who did not have a single lateral region but rather divided it into anterolateral and posterolateral regions. Additionally, the Love et al. scheme was used to classify rib fractures at autopsy; it is not clear how effective the same scheme would be if applied to radiographic identification only.

The distribution of rib fractures by rib number fit a relatively normal distribution with the highest frequency at the mid-level (67% of fractures compared to 20% and 13% at the upper and lower levels, respectively), and specifically, at the 6th and 7th ribs (Fig. 9). This finding is consistent with prior studies. Barber et al. [17] also reported an approximately normal distribution of rib fractures by rib number in infants suspected of being abused, with the highest incidence of fractures at the 7th rib; 65% of rib fractures in that study were at the mid level (Ribs 5–8) compared to 67% in our study. The predominance

Table 1 Distribution of rib fractures by region compared to other studies of abused children

	Posterior	Posterolateral	Lateral	Anterolateral
This study	29%	8%	43%	20%
Bulloch et al. [2]	35%	25%	34%	6%
Kleinman et al. [3]	65%	10%	13%	12%
Barsness et al. [9]	43%	N/A	35%	22%
Cadzow & Armstrong [16]	42%	N/A	13%	45%
Barber et al. [17]	24%	24%	28%	24%

N/A not available

of rib fractures in the mid-region of the thoracic cage suggests that loading is often being imparted to the abused infant such that it is concentrated near the 7th rib. These findings support the presumed mechanism of abusive grasping of the thoracic cage; rib fractures found at the mid-level of the thoracic cage are consistent with the positioning of a perpetrator's hands under the victim's axilla. The fracture distribution reported by Love et al. [18], which included decedents who died from causes other than abuse, was also a bell-curve shape but was skewed slightly higher with the peak number of fractures occurring at the 5th rib; only 47% of fractures in that study were at the mid level (46% of fractures were at the upper rib level and 6% were at the lower level).

Given differences in rib fracture regions reported by studies with different population ages, we sought to determine whether fracture locations differed by age. It is possible that varying child age, rib developmental stage (e.g., size, structure and material properties) and injury mechanisms (e.g., how the child is held or how force is applied to the ribs) could lead to differences in fracture locations. However, for the age range included in this study (0–18 months), there were no significant differences in fracture regions or fracture levels when subdividing the children into younger and older groups (0–9 months and 10–18 months). The small number of children older than 6 months might have limited our power to detect differences.

Like prior studies, most of the abused infants in this study presented with multiple rib fractures. Eighty-one percent of children presented with multiple fractures, and the mean number of fractures per child was 4.6. Other studies of rib fractures in abused infants have reported mean ranges of 3.7–7.0 fractures [2, 9, 17]. Interestingly, almost 50% of our subjects had fractures in multiple rib regions or at multiple rib levels (36% had fractures in multiple regions *and* at multiple levels). This suggests that forces might be applied at various locations throughout the circumferential path of the rib to cause multiple fractures. This scenario would be consistent with the presumed mechanism of a perpetrator's hands encircling and squeezing the ribcage. Tsai et al. [14] evaluated the distribution of stress in the ribs with anterior–posterior compression from violent squeezing using a finite element model. This

biomechanical model predicted peak stresses at the lateral and posterior aspects of the ribs, which coincide with the locations of highest fracture incidence in our study. This suggests that abusive squeezing, causing anterior–posterior compression of the chest, might result in rib fractures found in the posterior or lateral regions of the rib. However, the Tsai et al. [14] model was used to evaluate stresses in a single rib. Further research is necessary to understand how forces are distributed along the entire ribcage under this mechanism.

A high proportion (86%) of rib fractures identified in our study were determined to be healing, which is consistent with findings from other studies [17, 19]. The low percentage of acute rib fractures in our study likely points to the difficulty in recognizing their presence on a radiograph. The periosteal reaction associated with healing is easier to identify on radiographs than a subtle acute cortical rib disruption. Repeat skeletal surveys are often performed to increase the yield of discovery of occult abusive injuries, particularly of the ribs [20]. Recent research also suggests the use of low-dose thoracic CT as an adjunct to radiography to improve rib fracture detection [21, 22].

Our study was limited by its retrospective method and thus its lack of definitive information regarding fracture mechanism. Moreover, data concerning the perpetrators, including handedness, were not available. A prospective study that includes perpetrator confessions with detailed mechanisms of injury is necessary to definitively correlate perpetrator handedness with the sidedness of abusive rib fractures. Additionally, this study only included cases referred to the child abuse medicine team and determined to be definite abuse; no control group was included. The determinations of abuse were made based on the multidisciplinary evaluation of the constellation of injury findings and provided histories. As a result, the true mechanism of the rib fractures is unknown and there remains a possibility that rib fractures had other causes. Last, while unlikely, it is possible that a case included in this study was incorrectly determined to be abuse and was erroneously included in the analysis. However, our use of subjects diagnosed by a multidisciplinary team led by board-certified child abuse pediatricians ensures that multiple steps were taken to minimize chances of misdiagnosis.

Conclusion

In this study, we found an unequal distribution of rib fractures in abused infants, with a significantly greater number of left-side or predominantly left-side rib fractures. The proportion of other skeletal fractures in these infants was also significantly greater on the left side of the body. Further research is needed to understand whether factors such as perpetrator handedness and dominant hand strength are associated with this asymmetrical distribution of rib and other skeletal fractures in abused children.

Although rib fractures have been shown to have high specificity for abuse, further characterization of these fractures might aid in diagnosing abuse. In our population of abused infants and young children, there was a predominance of rib fractures in the posterior and lateral regions and at the mid level of the thoracic cage (Ribs 5–8), along with fractures in multiple regions of the rib and at multiple levels of the thoracic cage. Children presenting with these rib fracture characteristics should raise concern for abuse.

Compliance with ethical standards

Conflicts of interest None

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