Rib fractures in infancy: establishing the mechanisms of cause from the injuries – a literature review

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ABSTRACT

In the absence of a history of a significant accidental event, the most likely diagnosis in an infant with rib fractures is non-accidental injury. Medical opinion is essential when deciding if child abuse has taken place or not and this requires a consideration of whether a proposed causal explanation fits with the observed injuries. To assist in the interpretation of injuries and inform medical practitioners, it is essential to develop a clear understanding of their biomechanical mechanism of causation. The types and 'likely' mechanisms of rib fracture are well-documented, however, what forces, deflections and loading rates are required to produce particular fractures are relatively unknown. This paper presents a review of the literature, from a biomechanical engineering perspective, to assess information regarding the various types of rib fracture and their likely mechanisms, paying particular attention to the likely forces, deflections and loading rates involved.

The biomechanical parameters, applied during 'two finger' infant cardiopulmonary resuscitation (CPR), are identified and discussed, and are currently believed to be below the limit at which rib fracture may occur. However, a new 'two thumb' CPR technique is identified which involves a holding/gripping mechanism of the infant thorax, similar to that which is believed to occur in inflicted injury scenarios, such as shaking. The two thumb method may provide a greater magnitude of force and deflection, a greater rate of loading and may perhaps pose a greater risk of fracture, compared with the 'two finger' supine, anterior-posterior chest compression approach. It is proposed to introduce a force/deflection boundary condition into mechanical and computer/numeric infant models. Subject to the future inclusion of loading rate/response data, a three-dimensional (force/deflection/loading rate) boundary condition will be used to provide a minimum injury threshold for potentially injurious scenarios. A number of further studies are suggested, since this paper is intended to provide a first step to developing a more sophisticated understanding of the causes of infant rib fracture. Areas of further study include specific rib fracture mechanisms, as well as the effects of age dependent characteristics, positioning and area of force application. Such additional information would allow the proposed initial boundary condition to be further refined to provide an indication of the likelihood, type and number of fractures that might be expected.

INTRODUCTION

The most likely diagnosis in an infant with rib fractures is non-accidental injury. Experts must decide on the balance of probability whether child abuse has taken place or not. In the majority of cases, there is a need to decide whether proposed causal explanations fit with the profile of injuries seen, to confirm or exclude a diagnosis of physical abuse. The consequences of missing or making a wrong diagnosis can be catastrophic for the child and family. There is still no clear understanding of what forces and mechanisms of injury are involved in the production of rib fractures. Experts have only a limited understanding of the biomechanics of infant rib injury and, as a consequence, there are gaps in the evidence base on which a decision of abuse is or is not made. This limits the expert's ability to provide clear evidence-based opinion in court, as well

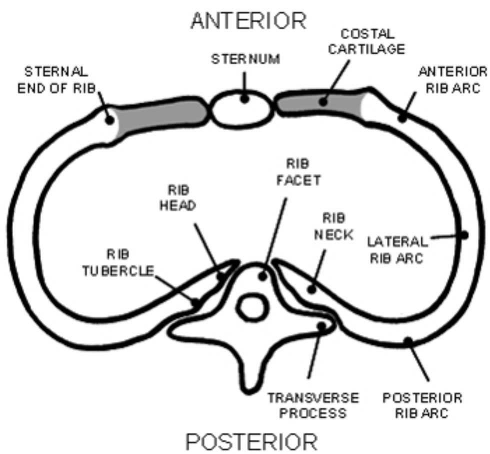

Figure 1. Anatomy of the ribs.

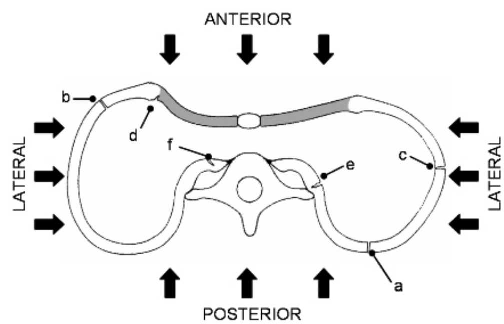

Figure 2. Ribs under anterior-posterior compression resulting in (a) posterior arc fracture, (b) anterior arc fracture, (c) lateral arc fracture and (d) costochondral junction fracture. Excessive levering of the rib over the transverse process produces (e) costotransverse process articulation fracture, (f) rib head fracture. Arrows show the common direction of forces, which cause these fractures to occur (adapted from Kleinman et al., 1996)

as their ability to form injury preventative strategies. *In vivo* experimentation in this field is impossible and, as a consequence, an alternative programme of work is required to further develop an understanding of the biomechanics of these injuries.

RIB FRACTURE MECHANISMS

Anterior-posterior compression

Anterior-posterior compression may result in a number of different mechanisms, depending on the amount of compression, the location of the applied forces and whether the body is supported.

Regardless of the scenario, anterior-posterior compressive forces will bring the anterior and posterior rib arcs towards one another (see Figure 1). This results in compression of the inner margins and tension in the outer margins of the rib. When the ultimate tensile strength of the rib is exceeded, the rib will fail and a distracted fracture along its outer margin in one of the three rib arcs can be produced (posterior, anterior or lateral, labelled ‘a’, ‘b’ and ‘c’ in Figure 2, respectively) (Kleinman et al., 1996; Reece, 2002).

Force applied frontally, to either the sternum or costal cartilage (see Figure 1), results in the downwards depression of these regions. This, in turn, leads to the production of stresses at the costochondral junctions (CJ) (labelled ‘d’ in Figure 2), resulting in mechanical failure of the rib about this point (Kleinman et al., 1996).

In some cases, where the posterior body is not supported by a flat surface, the compressive forces may result in excessive levering of the rib over the transverse process (demonstrated by Figure 2) (Kleinman 1990; Kleinman et al., 1992; Betz and Liebhardt, 1994; Kleinman et al., 1996; Kleinman and Schlesinger 1997; Reece, 2002). Excessive levering has been described as the rib passing through the horizontal plane of the transverse process, after which, presuming the costovertebral ligaments are stronger than the rib, the rib will fail and produce a fracture about the costotransverse process articulation (CPA) (labelled ‘e’ in Figure 2) (Kleinman and Schlesinger, 1997; Reece, 2002). Excessive levering of the rib over the transverse process is also known to cause abnormal tensions at the costovertebral attachment, where the rib head (RH) articulates with the rib facet of the vertebra (see Figure 1). As the ligaments between the RH and the vertebra restrict displacement of the RH, the abnormal tensions often result in mechanical failure of the RH through the primary spongiosa, which is the area where the RH fracture (labelled 'f' in Figure 2) is shown (Kleinman et al., 1992).

Effectively, any scenario during which the required mechanism occurs, could lead to rib fracture. Some scenarios that have been suggested as leading to the required anterior-posterior compression, include direct blows (e.g. automotive accidents, resulting in a rapid forward deceleration, due to the chest impacting with a solid object, a child falling onto a rigid surface, or heavy objects falling or pressing on the chest anteriorly or posteriorly) and manual assaults (e.g. violent shaking, slamming the infant face down onto a solid surface, and violent squeezing). However, it should be noted that both heavy objects falling or pressing on the chest anteriorly, or a child falling onto a rigid surface, is unlikely to cause the excessive levering required to cause either CPA or RH fracture, as this scenario implies that the posterior body is supported by a flat surface, such as the ground (Kleinman 1990; Betz and Liebhardt, 1994; Kleinman et al., 1996; Kleinman and Schlesinger, 1997; Reece, 2002).

Lateral compression

The lateral compression mechanism is described by Cameron and Rae (1975) as simply the compression of the chest from side to side (indicated by arrows in Figure 2) until the ribs are forced to fracture at their fixed points. Thus, any scenario during which the required mechanism is incurred, could lead to rib fracture. Lateral compression appears to be much less well-documented as a potential mechanism of injury when compared with anterior-posterior compression. Indeed, the literature observed in this review only suggested violent shaking as a potential circumstance, which could lead to the required lateral compression (Cameron and Rae 1975). Though unreported, it is reasonable to postulate that other scenarios such as direct blows (e.g. automotive accidents, resulting in a rapid lateral impact to the thorax, heavy objects falling or pressing on the lateral aspect of the chest, or a child falling onto a rigid surface) and manual assaults (e.g. slamming the infant sideways onto a solid surface, and violent squeezing) could also result in the required lateral compression.

TYPES OF RIB FRACTURE

Costotransverse process articulation

A costotransverse process articulation (CPA) fracture is indicated in Figure 2 by the letter 'e', and is generally considered to be one of the most common rib fractures found in infants, with Kleinman et al. (1996) showing 27 of 84 (32% approximately) abusive infant rib fractures to be CPA (Kleinman 1990; Kleinman et al., 1996) In some studies these fractures are grouped with both RH (labelled 'f' in Figure 2) and posterior arc (PA) rib fractures (labelled 'a' in Figure 2), being termed posterior fractures, due to their location (Merton et al., 1983; Feldman and Brewer, 1984; Cadzow and Armstrong, 2000; Barsness et al., 2003). Such studies have been performed by Feldman and Brewer (1984) and Barsness et al. (2003), who showed 24 of 61 (39% approximately), and 132 of 336 (39% approximately) infant and paediatric rib fractures respectively, from a variety of injury scenarios, to be posterior rib fractures. Another study, by Cadzow and Armstrong (2000), showed 44 of 101 (44% approximately) infant rib fractures, again from a variety of injury scenarios, to be posterior rib fractures.

The likely fracture mechanism is thought to be anterior-posterior compression (see Figure 2). Many authors favour manual thoracic compression over direct blows as the likely mechanism of rib fracture. This is especially the case when fractures are found to be multiple, there is little evidence of bruising and there is lack of plausible patient history (Thomas, 1977; Kleinman, 1990; Kleinman et al., 1996; Reece, 2002). Reece (2002) suggested that cardiopulmonary resuscitation (CPR) may not cause CPA fractures, as the position of the infant laid down upon a flat surface would make excessive levering of the ribs over the transverse processes impossible. However, this claim may now require reconsideration, since the introduction of a new method of CPR that does not place the infant lying down on a flat surface. This method is known as the two thumb (TT) technique and will be discussed in detail later in this paper (The Australian Resuscitation Guidelines, 1996; Houri et al., 1997; Niermeyer et al., 2000; Martin and Butler, 2004).

Posterior arc

A posterior arc (PA) fracture is indicated in Figure 2 by the letter 'a', and is reported to be one of the less common rib fractures found in infants, with Kleinman et al. (1996) showing eight of 84 (10% approximately) abusive infant rib fractures to be PA (Kleinman et al., 1988). In some studies these fractures are grouped with both RH and CPA rib fractures (labelled 'f' and 'e' in Figure 2, respectively), being termed posterior fractures, due to their location (Feldman and Brewer, 1984; Cadzow and Armstrong, 2000; Barsness et al., 2003). The findings of these studies are discussed in greater detail during the section on CPA rib fractures.

Research provides two views as to the likely mechanism of PA fracture. Cameron and Rae (1975), Thomas (1977) and Merton et al.(1983), postulate that a lateral compression mechanism is the likely cause. This is contrasted by the views of Betz and Liebhardt (1994), Kleinman et al. (1996) and Ng and Hall (1998), who all report anterior-posterior compression as the likely mechanism of rib fracture. It has been stated that greater forces are required for PA rib fracture to occur compared with other rib fractures. This is believed to be due to the greater thicknesses of the posterior rib arcs (Garcia et al., 1990).

Rib head

A rib head (RH) fracture is indicated in Figure 2 by the letter 'f' and is considered to be one of the most common rib fractures found in infants, with Kleinman et al. (1996) showing 28 of 84 (33% approximately) abusive infant rib fractures to be RH. In some studies these fractures are grouped with both CPA and PA rib fractures (labelled 'e' and 'a' in Figure 2, respectively), being termed posterior fractures, due to their location (Feldman and Brewer, 1984; Cadzow and Armstrong, 2000; Barsness et al., 2003). These findings are discussed in greater detail during the section on CPA rib fractures. The likely mechanism is noted to be anterior-posterior compression (Ng and Hall, 1998; Niermeyer et al., 2000).

Costochondral junction

A costochondral junction (CJ) fracture is indicated in Figure 2 by the letter 'd', and is considered to be rare in abused infants, with Kleinman et al. (1996) showing ten of 84 (12% approximately) abusive infant rib fractures to be CJ. In some studies these fractures are grouped with anterior arc (AA) rib fractures (labelled 'b' in Figure 2) and termed anterior fractures, due to their location (Feldman and Brewer, 1984; Cadzow and Armstrong, 2000; Barsness et al., 2003). Feldman and Brewer (1984) showed 18 of 61 (30% approximately) infant rib fractures, and Barsness et al., (2003) showed 67 of 336 (20% approximately) paediatric rib fractures, from a variety of injury scenarios, to be anterior rib fractures, whereas Cadzow and Armstrong (2000), showed 41 of 101 (40% approximately) infant rib fractures, again from a variety of injury scenarios, to be anterior rib fractures. The greater occurrence of anterior rib fractures shown in Cadzow and Armstrong's study could indicate that anterior rib fractures are more likely to occur in infants than older children. This may suggest that the changes in rib anatomy and material properties seen in infancy have a direct link with the likelihood of certain fractures occurring. Another hypothesis would be that the circumstances during which the required mechanism of injury was acquired, are related to the age of the child, due to the activities in which the child is likely to participate or to which he or she is subjected. Further research would be required to establish whether either of these theories have any merit.

Two scenarios have been suggested as the likely mechanism of CJ fracture. Cameron and Rae (1975) and Thomas (1977) claimed that the mechanism is due to lateral compression of the rib cage. However, Kleinman (1990), Kleinman et al. (1996) and Ng and Hall (1998), considered anterior-posterior compression to be the likely mechanism.

Anterior arc

An anterior arc (AA) fracture is indicated in Figure 2 by the letter 'b', and is considered to be rare in abused infants with Kleinman et al. (1996) showing six of 84 (7% approximately) abusive infant rib fractures to be AA. In some studies these fractures are grouped with CJ rib fractures (labelled 'd' in Figure 2) and termed anterior fractures, due to their location (Feldman and Brewer, 1984; Cadzow and Armstrong, 2000; Barsness et al., 2003). The findings of these studies are discussed in greater detail during the section on CJ rib fractures.

The likely mechanism involved in AA rib fractures is anterior-posterior compression (Betz and Liebhardt, 1994; Kleinman, 1996; Ng and Hall, 1998). It should be noted that direct blows are considered to be a more likely mechanism for producing AA fractures, though the likelihood of incurring accidental direct blows in infancy is considered rare (Ng and Hall, 1998; Reece, 2002).

Lateral arc

A lateral arc (LA) rib fracture is indicated in Figure 2 by the letter 'c', and is considered to be one of the most uncommon rib fractures in abused infants, with Kleinman et al. (1996) showing five of 84 (6% approximately) abusive infant rib fractures to be LA. Studies by Feldman and Brewer (1984), and Barsness et al. (2003), showed 19 of 61 (31% approximately), and 137 of 336 (41% approximately) infant and paediatric rib fractures respectively, from a variety of injury scenarios, to be LA rib fractures. Cadzow and Armstrong (2000), showed 16 of 101 (16% approximately) infant rib fractures, again from a variety of injury scenarios, to be LA rib fractures. The large differences between the proportion of LA rib fractures in studies where older children were included and those where only infants were sampled, suggests that LA rib fractures are much less common in infants than they are in older children. This may suggest links between the likelihood of LA rib fracture with the structural and material properties of the ribs, or the likely mechanism of injury. Again, further research would be required to establish the validity of these hypotheses.

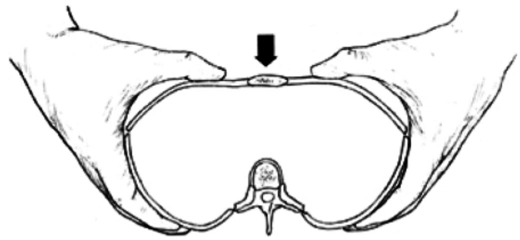

Figure 3. Technique used to apply anterior-posterior compression in squeezing or shaking infant abuse (adapted from Reece, 2002).

The likely mechanism of injury is considered to be anterior-posterior compression (Thomas, 1977; Merton et al., 1983; Kleinman, 1990; Betz and Liebhardt, 1994; Kleinman et al., 1996; Ng and Hall, 1998; Reece, 2002). Feldman and Brewer (1984) suggested that LA rib fractures are the most likely rib fractures that may be caused by CPR.

POTENTIAL CAUSES OF RIB FRACTURE

Abuse

Following the emphasis on evidence-based medicine around 1998/99 a number of studies have been performed that attempt to establish a link between certain rib fractures and abuse (Donohoe, 2003). Many authors appear to agree that rib fractures in infancy are a strong indicator of abuse. Worlock et al. (1986), showed 28 of 47 (60% approximately) cases of rib fractures in children under the age of 18 months to be due to child abuse and Strouse and Owings (1995) showed 12 of 35 (34% approximately) cases of rib fractures in children under the age of four to be due to child abuse. An even stronger link was established by Barsness et al. (2003), who showed 51 of 61 (82% approximately) children under the age of three found with rib fractures to be due to abuse and after the exclusion of children with a legitimate history of bone disease or severe accidental trauma, they suggested that rib fractures in infancy had a 100% positive predictive value for abuse. These findings are backed up by a general consensus that rib fractures, due to less than severe accidental trauma, are unlikely in infants, since they are not subjected to the significant forces believed to be required to deform an infant's naturally elastic thorax to an injurious level (Merton et al., 1983; Garcia et al., 1990; Kleinman et al., 1992; Strouse and Owings, 1995; Cadzow and Armstrong, 2000; Reece, 2002).

The likely mechanism of rib fracture in abuse is generally perceived to be anterior-posterior compression, which may be applied by the assailant gripping the infant in the manner shown in Figure 3 and either shaking the infant in a violent fashion, or applying a sudden violent compression (Merton et al., 1983; Betz and Liebhardt, 1994; Kleinman and Schlesinger, 1997; Cadzow and Armstrong, 2000; Carty and Pierce, 2002).

The mechanism produced during shaking requires further consideration, since it is a complex combination of both anterior-posterior and lateral compressive forces producing both compression and tension in the rib structures. The authors are of the opinion that the mechanism involves an initial potentially injurious quasi-static loading of the ribs, due to the existence of a gripping phase, followed by a subsequent dynamic shaking phase. The shaking phase further compounds the pre-loaded condition, since the grip fixes the ribs such that during shaking the unsecured masses of the body reciprocate about the ribs. Thus, the shaking mechanism has a pre-loaded grip phase followed by a sinusoidal periodic shaking phase, which produces concomitant periodic peak inertial forces at the maximum and minimum excursion of the arms. Thus, the shake mechanism produces an initial level of strain in the ribs during the grip phase followed by a periodic high rise in strain during the dynamic shake phase (Jones, 2000; Cory and Jones, 2003).

Many of the previously mentioned authors have commented on the types of rib fracture that are found in abuse cases, and indeed, all of the previously mentioned rib fracture types are discussed.

Costotransverse process articulation fractures (labelled 'e' in Figure 2) are considered to be highly specific to abuse with Kleinman et al. (1992) noting 21 (42%) abusive rib fractures in their study of 50 cases, and Kleinman et al. (1995) noting 27 of 84 (32% approximately) abusive rib fractures in their study of 31 cases to be CPA.

Posterior arc rib fractures (labelled 'a' in Figure 2) are also noted to be common in abuse cases, though Kleinman et al. (1995) found only eight of 84 (10% approximately) abusive rib fractures in their study of 31 cases to be PA fractures.

Rib head fractures (labelled 'f' in Figure 2) have also been described as strong indicators of abuse, with 29 of 50 (58%) abusive rib fractures in Kleinman et al's (1992) study, found to be RH fractures. A number of authors have grouped CPA, PA and RH fractures together to form the posterior rib fracture group (Kogutt et al., 1974; Merton et al., 1983; Kleinman et al., 1988; Spevak et al., 1994; Houri et al., 1997; Lancon et al., 1998; Cadzow and Armstrong, 2000; Reece, 2002; Barsness et al., 2003). These posterior rib fractures are thought to be highly specific for abuse (Merton et al., 1983; Kleinman et al., 1988; Kleinman et al., 1992; Spevak et al, 1994; Cadzow and Armstrong, 2000). Indeed, Ng and Hall (1998) stated that in a study of over 75 children, with suspected abusive rib fractures, over 95% were found to be located either posteriorly or laterally. Reece (2002) stated that over 80% of abusive rib fractures were to be found posteriorly, and lateral arc rib fractures (labelled 'c' in Figure 2) are also considered common in abuse cases. Barsness et al. (2003) showed 130 of 303 (43% approximately) of abusive rib fractures to be posterior, and showing 107 of 303 (35% approximately) abusive rib fractures to be located in the lateral arcs.

Costochondral junction fractures (labelled 'd' in Figure 2) have been noted to occur in abuse cases but are considered to be much more unusual, with Kleinman et al. (1995) noting only ten of 84 (12% approximately) abusive rib fractures in 31 cases as CJ. Costochondral junction fractures are often grouped with anterior arc fractures (labelled 'b' in Figure 2) to form the anterior rib fracture group (Ng and Hall, 1998; Cadzow and Armstrong, 2000; Barsness et al., 2003). These fractures are considered to be less common than others in cases of abuse, with Ng and Hall

Figure 4. Two finger (TF) infant cardiopulmonary resuscitation technique (from Gilbert, The Centre for Pediatric Emergency Medicine.)

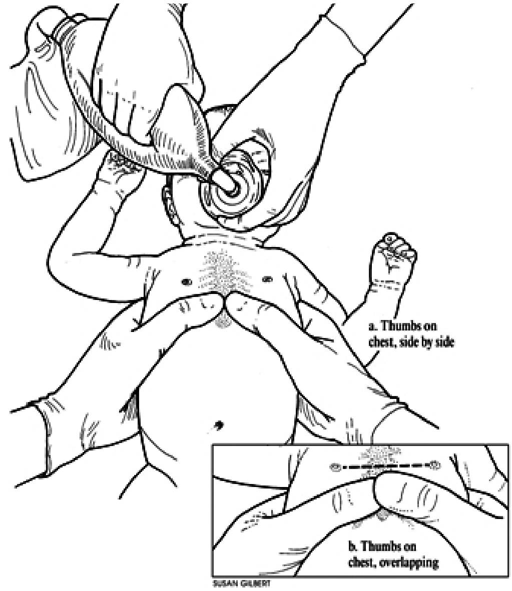

Figure 5. Two thumb (TT) infant cardiopulmonary resuscitation technique (from Gilbert, The Centre for Pediatric Emergency Medicine.)

(1998) stating that 4% of over 75 abusive rib fractures were anterior, and Barsness et al. (2003) showing 66 of 303 (22% approximately) abusive rib fractures to be located anteriorly.

It should also be noted that abusive rib fractures are frequently multiple, with Carty and Pierce (2002) showing only 31 of 154 (20% approximately) of abusive rib fractures to be singular, and Barsness et al. (2003) indicating an average of 5.9 rib fractures in each case of abuse in their study of 336 rib fractures. This point is emphasized by the fact that accidentally incurred rib fractures are most commonly singular in nature, with Worlock et al. (1986) noting no accidental cases with more than two rib fractures in 47 infants and Barsness et al. (2003) showing an average of 1.2 rib fractures in each case of accidental injury in their study of 336 rib fractures.

Cardiopulmonary resuscitation

The issue of whether rib fractures can be inflicted during the administration of CPR in infants, is one which has been investigated by a number of authors (Kleinman et al., 1992; Betz and Liebhardt, 1994; Spevak et al., 1994; Strouse and Owings, 1995; Kleinman and Schlesinger, 1997; Cadzow and Armstrong, 2000; Reece, 2002). Feldman and Brewer (1984) and Ng and Hall (1998) note an incidence of rib fracture of 16-80% and 10-80% respectively after CPR in adults. However, this potentially high rate of rib fracture is not apparent in infants, with a number of authors stating that rib fractures in infants as a result of CPR are either rare or do not occur at all (Feldman and Brewer, 1984; Kleinman et al., 1992, Betz and Liebhardt, 1994; Spevak et al., 1994; Strouse and Owings, 1995; Kleinman and Schlesinger, 1997; Ng and Hall, 1998; Cadzow and Armstrong, 2000; Reece, 2002). Both Thomas (1977) and Feldman and Brewer (1984) stated that rib fractures are more likely to occur in the LAs than anywhere else. However, Thomas's study showed only one infant, out of a total of 25, to have rib fractures that could be attributed to CPR, noting that the infant in question was of a low birth weight and had been suffering from a chest infection, which would have increased the likelihood of incurring rib fractures. Feldman and Brewer's (1984) study of 29 infants with rib fractures showed none to be attributed to CPR.

Table I. Sternal compression forces involved in the two finger (TF) and two thumb (TT) infant cardiopulmonary resuscitation technique (adapted from Houri et al., 1997).

	Two thumb (TT) with feedback	Two thumb (TT) without feedback	Two finger (TF) with feedback	Two finger (TF) without feedback
Sternal compression force (psi)	22.9 *	20.3 *	17.0 *	14.6 *
Sternal compression force $(N/cm^2)_{(3d.p.)}$	15.7	13.9	11.7	10.0
Sternal compression force $(N)_{(3d.p.)}$	251.6 **	223.0 **	105.1 ***	90.2 ***

* Values taken from Houri et al. (1997)
** Assumes the area of applied force for two thumbs is $16cm^2$
*** Assumes the area of applied force for two fingers is $9cm^2$

Kleinman and Schlesinger (1997) reported that CPR is frequently used to explain posterior rib fractures (RH, PA and CPA) in cases of suspected infant abuse, but warned that there was no evidence to support this view. This position was supported by Spevak et al. (1994) who had argued that excessive levering of the rib over the transverse process, which is required for posterior rib fractures, is not possible in the case of CPR because the child's position, lying on a flat surface, would restrict this motion. Spevak et al. (1994) were referring to the two finger (TF) method of CPR chest compression, shown in Figure 4, which is described as two fingers of one hand being placed upon the sternum, and a force applied at right angles to the chest, with the infant lying flat on a surface and the other hand being placed on the infant's head to provide support (Niermeyer et al., 2000). At the time of Spevak et al's (1994) publication the TF method was the only method recommended by governing bodies, such as the Pediatric Working Group of the International Liaison Committee on Resuscitation (Martin and Butler, 2004). However, since 2000, a new method has been introduced to succeed the TF approach (Martin and Butler, 2004). The two thumb (TT) CPR chest compression method is shown in Figure 5 and is described as two thumbs being placed upon the sternum and depressing anteriorly, with the hands encircling the chest, and fingers placed along the spine to provide stability posteriorly (anterior-posterior compression), combined with lateral compression of the thorax (Australian Resuscitation Council Guidelines, 1996, Houri et al., 1997; Niermeyer et al., 2000; Martin and Butler, 2004). This method is preferred because it has been proven to produce improved haemodynamic states in experimental models (Martin and Butler, 2004). The TT method bears a striking resemblance to the method commonly believed by authors to be attributable to abusive compression or shaking of an infant (shown in Figure 3) (Caffey, 1972, 1974; Duhaime et al., 1987; Kleinman, 1990; Kleinman et al., 1996; Cadzow and Armstrong, 2000; Reece, 2002), and now invalidates Spevak et al's (1994) comments that the excessive levering of the rib over the transverse process cannot be achieved during CPR, due to the restrictions of the infant's back being placed upon a solid surface. Indeed, the adoption of the TT technique raises the question whether this new technique may lead to rib fractures? With regard to CPR, all of the literature reviewed in this study was already published, or referred to studies that were performed before the introduction of the International Consensus on Science's revised guidelines in 2000 (Martin and Butler, 2004). Hence, it would seem likely that all of the instances of CPR examined were those of the TF method and were prior to the introduction of the TT method.

A study performed by Houri et al. (1997), using an infant porcine model, measured the sternal compression forces involved in the two methods of chest compression, with and without pressure feedback to the individual applying the compressions, the results of which are shown in Table 1. Sturtz (1980) noted in his study on the biomechanical data of children, that the breaking load for dynamic bending of the sixth and seventh ribs of children under the age of 14 was 234N. When Houri et al's (1997) force measurements are compared to the breaking load noted in Sturtz's (1980) study, it is clear that the breaking load is not reached in the TF compression technique, but is reached during the TT compression technique. This would suggest that rib fractures may be possible when the new TT technique is applied. However, it is accepted that this comparison is flawed in a number of ways. Firstly, the load rates applied in the two studies are unknown, and would need to be similar to make a valid comparison, due to the load rate dependent characteristics of bone (McElhaney, 1966). Secondly, the data in Sturtz's (1980) study was that of children under the age of 14. It has been stated that an infant's bones are more flexible than the bones of older children (Garcia et al., 1990). Also, Sturtz's (1980) values may be biased, since they are protection values for automotive accident prevention. Hence, one might expect infant rib material to have a greater tolerance to load (Garcia et al., 1990). Finally, assumptions had to be made as to the average size of the thumb and fingertips of the individuals who applied the compressions in Houri et al's (1997) study to convert their reported pressures into comparable forces. The large number of assumptions means that further research is required to investigate whether there is an increased risk of rib fracture associated with the TT CPR chest compression technique.

In general, research to date appears to indicate that rib fractures are highly unlikely to occur as a direct consequence of CPR (Feldman and Brewer, 1984; Kleinman et al., 1992; Betz and Liebhardt, 1994; Spevak et al., 1994; Strouse and Owings, 1995; Kleinman and Schlesinger, 1997; Ng and Hall, 1998; Cadzow and Armstrong, 2000; Reece, 2002). This is believed to be due to the relative compliance of the ribs during infancy, which provide a tendency to bend rather than break when subjected to relative deformations that would result in fracture in adults (Betz and Liebhardt, 1994; Ng and Hall, 1998). The likelihood of occurrence would, of course, be significantly increased if the infant was suffering from bone diseases, such as osteopenia, osteomakazia, bone dystrophy, rickets or osteogenesis imperfecta, as these will increase the fragility of the ribs (Feldman and Brewer, 1984; Paterson, 1990; Betz and Liebhardt, 1994; Spevak et al., 1994).

Birth trauma

Many authors appear to be in agreement that though a few isolated cases of rib fracture attributed to birth trauma have been reported, the likelihood of such an occurrence is extremely rare. This claim is backed up by Rubin (1964), in a study of 15,435 births and Levine et al. (1984) in a study of 13,870 births, who noted that no rib fractures could be attributed to birth trauma. Thomas (1977), in a study of 10,000 births, showed only two (0.02%) of infants to have rib fractures that could be attributed to birth trauma, and Bhat et al. (1994) in a study of 34,946 births found no rib fractures that could be accounted for by birth trauma. It should be noted, however, that these figures are potentially misleading, since rib fractures in infants are known to be rare, regardless of the scenario from which they are caused. Thus, it would appear to be more appropriate to demonstrate the proportion of children found to have rib fractures, which are then attributed to birth trauma. For example, in Thomas's study, only 25 of the 10,000 infants examined were found to have rib fractures, and as two of those 25 were put down to possible birth trauma, it would suggest that 8% of rib fractures found in infants could be attributed to birth trauma. Thomas's study appears, therefore, to suggest a much greater proportion of rib fractures to be due to birth trauma than is generally believed to be the case.

Bhat et al., (1994), found no infants with rib fracture that could be explained by birth trauma out of a study of 35 infants, Cumming

(1979), also found that out of 23 infants with rib fracture, none could be attributed to birth trauma, and Bulloch et al. (2000), found that out of 39 infants with rib fracture only one (2.5%) could be explained reasonably by birth trauma. These figures show that though rib fractures caused by birth trauma are indeed rare, when considered as a proportion of all rib fractures sustained by infants, they appear to be considerably less rare. The variation in birth related rib fractures (0-8%) is thought likely to be due to the low number of infants with rib fractures who were examined. A larger study, using greater numbers of infants with rib fracture, would aid in clarifying the proportions that may be attributed to birth trauma. It should be noted that in most cases where rib fracture may be attributed to birth trauma, the infants suffered from bone diseases, which increase the fragility of the ribs, or there were complications during birth, such as shoulder dystochia, breech delivery, premature delivery or very large babies (Feldman and Brewer, 1984; Rizollo and Coleman, 1989; Paterson, 1990; Betz and Liebhardt, 1994; Spevak et al., 1994; Reece, 2002). It may therefore, be concluded that if neither history of abnormal delivery nor metabolic or bone disease is present, it is extremely unlikely that rib fracture would have occurred from birth trauma. Further research is required to confirm this claim.

The likely forces and deflections required to cause rib fracture

The likely mechanisms of rib fracture are relatively well-documented in the literature but none of the studies examined in this review provided any indication as to the likely forces and deflections required to produce fracture in an infant's ribs. Moral and ethical considerations make post-mortem human subject testing undesirable. There is, therefore, a need for other methods of analysis such as the development of physical and computational models, which may provide a more likely way to move forward in this area of research.

Since CPR is very rarely considered the cause of infant rib fractures, the forces, load-rates and deflections experienced in CPR chest compressions could be applied to provide a three-dimensional boundary condition. Thus, any force/load-rate/deflection characteristic that can be considered less than that produced in CPR, would not be considered likely to result in a rib fracture, assuming no bone abnormalities. Conversely, any force/load-rate/deflection characteristic that can be considered greater than that produced in CPR, would result in an increasing likelihood of a rib fracture. This boundary condition would provide a valid threshold level, which could then be improved upon by further research.

The likely deflections in infant CPR chest compressions are well-documented, with most guidance organisations recommending a maximum compression to a relative depth of one third of the infant's total chest depth, rather than an absolute depth (Nadkarni et al., 1997; Niermeyer et al., 2000). The likely forces involved in infant CPR chest compressions are documented in Table I. The forces found in the TF method should be used as the boundary until further research has been carried out to identify whether the new TT technique, which applies higher compressive forces, is capable of producing rib fractures. If the TT technique is not found to be a cause of rib fractures in infants, this will raise the level of the boundary condition. Conversely, if the TT technique is found to be a cause of rib fractures in infants, this will provide further backing to the force/load-rate/deflection characteristics of the TF technique as a boundary condition. The load-rates applied during infant CPR chest compressions are not documented in any literature reviewed in this study and would need to be identified to complete the proposed boundary condition.

Furthermore, since birth related rib fractures are considered extremely rare, the forces and deflections experienced during birth, via a vacuum extraction delivery method, which has been noted as a cause of rib fracture in a few cases, could provide a boundary condition, in a similar manner to that which was discussed with reference to CPR (Rizollo and Coleman, 1989). Unfortunately, though studies have been performed that assess the forces exerted on an infant's head by the vacuum extractor during delivery, no literature could be found that indicated the likely forces exerted on the thorax during delivery (Svenningsen, 1987). It should also be noted that the force or deflection values, derived from birth scenarios, would be limited in its application to gripping type mechanisms rather the shaking or impact, since the loading rate can be considered to be over a longer time period and is therefore quasi-static in nature.

CONCLUSIONS

This review has identified six types of rib fracture (CPA, PA, RH, CJ, AA and LA) but notes that there are inconsistencies between authors, with many reducing these six types into three groups (posterior, anterior and lateral). Though the likely fracture mechanisms are thought to be either anterior-posterior or lateral compression, literature notes that each fracture may be caused by a variation of one of the two main mechanisms. No studies appear to have been carried out to confirm how each of the specific types of rib fractures occur and whether there are variations to the proposed mechanisms of anterior-posterior and lateral compression which would make certain fractures more likely than others. Indeed, the positioning, magnitude, load-rate, deflection of compression and the area to which the force is applied may all have an effect on the type of rib fracture that is likely to occur, but further research is required to clarify this.

This review has also identified that although CPR has previously been shown to be an unlikely cause of infant rib fracture, a new method of CPR chest compression, known as the TT technique, has recently been adopted as the recommended method. This new technique has been proven to apply greater forces to the infant's chest, and does so by a different mechanism than was applied via the previous TF technique. It remains to be seen whether this new technique is a more likely cause of rib fractures and, if so, whether it presents a characteristic pattern of injury.

Rib fractures due to birth trauma are believed to be highly unlikely. However, the proportion of all infant rib fractures found to be due to birth trauma, though small, when expressed as a percentage of total fractures may be as high as 8%. This variation is believed to be due to the small number of rib fracture cases investigated and a larger study would aid in clarifying the exact proportion of rib fractures that can be attributed to birth trauma. It was, however, noted that in the cases where rib fracture was attributed to birth trauma, there was either a history of bone disease or complications during birth. Thus, if further research confirms this, then this should make it difficult to misinterpret a rib fracture due to birth trauma for one caused by abuse.

The biomechanical mechanisms, the magnitude of the forces and deflections, required to inflict any of the six types of rib fractures do not appear to have been addressed to date. However, with rib fractures commonly being used as indicators of abuse, a greater understanding of the forces and deflections required to cause such rib fractures is an important factor in improving diagnostic confidences in these cases.

The age dependent characteristics of infant ribs were not considered in any of the reviewed literature, though variations in the number of certain rib fracture types occurring in different aged children suggest that changes in both the material properties and the anatomy may have an effect on the types of fracture that are likely to occur. Alternatively, different stages of child development may present different biomechanical injury scenarios. Again, further research is required to evaluate these theories.

The load-rate characteristics of an infant's ribs were also unapparent in the literature reviewed. Though studies have been performed that identify load-rate as a critical factor in the breaking load of infantile ribs, further research should be performed to identify how load-rate affects the likelihood of rib fracture.

To move forward with classifying the likely conditions required to inflict infant rib fractures, a simple 3D boundary condition has been proposed. The boundary condition indicates the force/load-rate/deflection characteristics that are believed to be unlikely to cause rib fracture, with points increasingly higher than the boundary condition indicating an increasing likelihood that rib fracture may occur.

The proposed boundary condition provides a valid threshold/starting point that can be improved by further research. A multi disciplinary collaboration with clinical partners is required to refine and improve the sensitivity of the biomechanical parameters and include age dependent characteristics, the position of force application and the area of force application. It is envisaged that with sufficient clinical input, additional information could allow the proposed initial boundary condition to be further refined to provide an indication of the likelihood, type and number of fractures that might be expected. The boundary conditions can be further developed to produce a nomogram to assist clinical practitioners with a valid methodology to provide consistency in clinical diagnoses.

REFERENCES

Australian Resuscitation Council Advanced Life Support Committee (1996) Paediatric advanced life support: the Australian resuscitation council guidelines. *MJA* **165**, 199–206.

Barsness K.A., Cha E., Bensard D.D. Calkins C., Patrick D.A., Karrer F.M. and Strain J.D. (2003) The positive predictive value of rib fractures as an indicator of non-accidental trauma in children. *J. Trauma* **54**, 1107–10.

Betz P. and Liebhardt E. (1994) Rib fractures in children – resuscitation or child abuse? *Int. J. Legal Med.* **106**, 215–8.

Bhat B.V., Kumar A. and Oumachigui A. (1994) Bone injuries during delivery. *Ind. J. Paediatrics* **61**, 401–5.

Bulloch B., Schubert C.J., Brophy P.D., Johnson N. Reed M.H. and Shapiro R.A. (2000) Cause and clinical characteristics of rib fractures in infants. *Pediatrics* **105**, e48.

Cadzow S.P. and Armstrong K.L. (2000) Rib fractures in infants: red alert! *J. Pediatr. Child Health* **36**, 322–6.

Caffey J. (1972) On the theory and practice of shaking infants. *Am. J. Dis. Child* **124**, 161–9.

Caffey J. (1974) The whiplash shaken infant syndrome: manual shaking by the extremities with whiplash-induced intracranial and intraocular bleedings, linked with residual permanent brain damage and mental retardation. *Pediatrics* **54**, 396–403.

Cameron J.M. and Rae L.J. (1975) *Atlas of the Battered Child Syndrome*. Edinburgh, London and New York: Churchill Livingstone.

Carty H. and Pierce A. (2002) Non-accidental injury: a retrospective analysis of a large cohort. *Eur. Radiol.* **12**, 2919–25.

Cory C.Z. and Jones M.D. (2003) Can shaking cause fatal head injury? *Med. Sci. Law* **43** (4), 317–33.

Cumming W.A. (1979) Neonatal skeletal fractures: birth trauma or child abuse? *J. Can. Assoc. Radiol.* **30**, 30–3.

Donohoe M. (2003) Evidence-based medicine and shaken baby syndrome part 1: literature review, 1966-1998. *Am. J. Forensic Med. Pathol.* **24**, 239–42.

Duhaime A.C., Gennarelli T.A., Thibault L.E., Bruce D.A., Margulies, S.S. and Wiser R. (1987) The shaken baby syndrome: a clinical, pathological, and biomechanical study. *J. Neurosurg.* **66**, 409–15.

Feldman K.W. and Brewer D.K. (1984) Child abuse, cardiopulmonary resuscitation, and rib fractures. *Pediatrics* **84; 73**, 339–42.

Garcia V.F., Gotschall C.S., Eichelberger M.R.. and Bowman L.M. (1990) Rib fractures in children: a marker of severe trauma. *J. Trauma* **30**, 695–700.

Gilbert S. (2006) List of tripp images [The Centre for Pediatric Emergency Medicine Website]. Available at: http://www.cpem.org/html/giflist.html. Accessed February 9th, 2006.

Houri P.K., Frank L.R., Menegazzi J.J. and Taylor R. (1997) A randomized, controlled trial of two-thumb vs two-finger chest compression in a swine infant model of cardiac arrest. *Prehosp. Emerg. Care* **1**, 65–7.

Jones M.D. (2000) Modelling Shaking. *XIVth Congress of Neuropathology Conference Proceedings* Sept.

Kleinman P.K. (1990) Diagnostic imaging in infant abuse. *Am. J. Roentgenol.* **155**, 703–12.

Kleinman P.K., Marks S.C., Adams V.I. and Blackbourne B.D.(1988) Factors affecting visualisation of posterior rib fractures in abused infants. *Am. J. Roentgenol.* **150**, 635–8.

Kleinman P.K, Marks Jr S.C., Nimkin K., Rayder S.M. and Kessler S.C. (1996) Rib fractures in 31 abused infants: post-mortem radiologic-histopathologic study. *Radiology* **200**, 647–50.

Kleinman P.K., Marks Jr S.C., Richmond J.M. and Blackbourne B.D.(1995) Inflicted skeletal injury: a postmortem radiologic-histopathologic study in 31 infants. *Am. J. Roentgenol.* **165**, 647–50.

Kleinman P.K., Marks S.C., Spevak M.R. and Richmond J.M. (1992) Fractures of the rib head in abused infants. *Radiology* **185**, 119–23.

Kleinman P.K. and Schlesinger A.E. (1997) Mechanical factors associated with posterior rib fractures: laboratory and case studies. *Pediatr. Radiol.* **27**, 87–91.

Kogutt M.S., Swischuk L.E. and Fagan C.J. (1974) Patterns of injury and significance of uncommon fractures in the battered child syndrome. *Am. J. Roentgenol. Radium Ther. Nucl. Med.* **121**, 143–9.

Lancon J.A., Haines D.E. and Parent A.D. (1998) Anatomy of the shaken baby syndrome. *New Anat.* **253**, 13–8.

Levine M.G., Holroyde J. and Woods J.R. 1984) Birth trauma: incidence and predisposing factors. *J. Obstet. Gynecol.* **63**, 729–95.

Martin B. and Butler J. (2004) Two thumb compared with two finger cardiopulmonary resuscitation in infants. *Emerg. Med. J.* **21**, 711–3.

McElhaney J.H. (1966) Dynamic response of bone and muscle tissue. *J. Appl. Physiol.* **21**, 1231–6.

Merten D.F., Radkowski M.A. and Leonidas J.C. (1983) The abused child: a radiological reappraisal. *Radiology* **146**, 377–83.

Nadkarni V., Hazinski M.F., Zideman D., Kattwinkel J., Quan L., Bingham R., Zaritsky A., Bland J., Kramer E. and Tiballs J. (1997) An advisory statement from the pediatric working group of the international liaison committee on resuscitation. *Circulation* **95**, 2185–95.

Ng C.S. and Hall C.M. (1998) Costochondral junction fractures and intra-abdominal trauma in non accidental injury (child abuse). *Pediatr. Radiol.* **28**, 671–6.

Niermeyer S., Kattwinkel J. and Van Reempts P. (2000) International guidelines for neonatal resuscitation: an excerpt from the guidelines 2000 for cardiopulmonary resuscitation and emergency cardiovascular care. *Pediatrics* **106**, e29.

Paterson C.R. (1990) Osteogenesis imperfecta and other bone disorders in the differential diagnosis of unexplained fractures. *J. R. Soc. Med.* **83**, 72–4.

Reece R.M. (2002) What the literature tells us about rib fractures in infancy. In: *SBS Quarterly,Fall, National Centre on Shaken Baby Syndrome.*

Rizollo P.J. and Coleman P.R. (1989) Neonatal rib fracture: birth trauma or child abuse? *J. Fam. Pract.* **29**, 561–3.

Rubin A.(1964) Birth injuries: incidence, mechanisms, and end results. *J. Obstet. Gynecol.* **23**, 218–21.

Spevak M.R., Kleinman P.K., Belanger P.L., Primack C. and Richmond M. (1994) Cardiopulmonary resuscitation and rib fractures in infants. A postmortem radiologic-pathologic study. *JAMA* **272**, 617–8.

Strouse P.J. and Owings C.L. (1995) Fractures of the first rib in child abuse. *Radiology* **197**, 763–5.

Thomas P.S. (1977) Rib fractures in infancy. *Ann. Radiol.* **20**, 115–22.

Sturtz G. (1980) Biomechanical data of children. *SAE Transactions 801313.* 513-59.

Svenningsen L. (1987) Birth progression and traction forces developed under vacuum extraction after slow or rapid application of suction. *Eur. J. Obstet. Gynecol. Reprod. Biol.* **26**, 105–12.

Thomas P.S. (1977) Rib fractures in infancy. *Ann. Radiol.* **20**, 115–22.

Worlock P. Stower M. and Barbor P. (1986) Patterns of fractures in accidental and non-accidental injury in children: a comparative study. *Br. Med. J. (Clin Res Ed).* **293**, 100–2.

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The prize for the best thesis presented as part of the MSc Course in Forensic Science at King's College, London, has been awarded to Ms Kerry-Ann Harris.

The Legal Prize for obtaining the highest mark in the Criminal Law Option of the Bar Vocational Course of the Inns of Court School of Law has been awarded to Ms Rachel Kapila.

The Legal Prize for obtaining the highest overall marks in Litigation at the Legal Practice Course of the College of Law has been awarded to Ms Gail Cockroft.

The David Paul Memorial Prize for the best casebook presented as part of the Diploma in Medical Jurisprudence of the Society of Apothecaries has not been awarded this year.