RIB FRACTURE ANALYSIS OF INFANT CARDIOPULMONARY RESUSCITATION METHODS USING PORCINE SURROGATES

By

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LIST OF ABBREVIATIONS

Abbreviation	Description
AHA	American Heart Association
CCJ	Costochondral junction
COD	Cause of death
CPR	Cardiopulmonary resuscitation
CT	Computed tomography
GEFARL	Grady Early Forensic Anthropology Research Lab
HCIFS	Harris County Institute of Forensic Science
HCITDB	Harris County Infant Trauma Database
MOD	Manner of death
MVA	Motor vehicle accident
NAT	Non-accidental trauma
ORPL	Osteological research processing lab
PSE	Pediatric skeletal examination
SBS	Shaken baby syndrome

I. INTRODUCTION

This research is an investigation of two different infant cardiopulmonary resuscitation (CPR) techniques and the incidence of rib fractures sustained from the intervention. The purpose of this research is to identify fracture frequency and location of rib injury sustained during therapeutic intervention using a porcine surrogate model. Furthermore, the experimentally induced rib fractures are compared to rib fractures documented by the Harris County Infant Trauma Database (HCITDB). Similarities and differences are noted between rib fractures sustained from CPR and those sustained in conjunction with abusive trauma. This research benefits those in the fields of forensic anthropology, pathology, and pediatric medicine who attempt to differentiate the causation of infant rib fractures as therapeutic or abusive. The expectation of this research is to create a more comprehensive understanding of how CPR induced rib fractures are presented in infants.

Prior to 2005, the American Heart Association (AHA) suggested all infant and newborn CPR scenarios be performed using the second and third digits of one-hand to compress the sternum of a supine infant at least one-third the diameter of the chest at a rate of 100-120 compressions per minute. Every five years, the AHA convenes to review CPR and life-support measures. In 2005, the AHA modified their infant CPR guidelines for two rescuer scenarios (American Heart Association 2005). AHA now recommends when two healthcare providers are present, CPR should be performed by encircling the infant's chest with both hands and use both thumbs as means of compression (American Heart Association 2011). This modification has been shown to potentially increase cardiovascular circulation as well as minimizing interruptions during compressions

(Houri, Frank, Menegazzi, & Taylor 1997; Meaney et al. 2013; American Heart Association 2015). However, since making this change, the rate of infant rib fractures seen in autopsy has dramatically increased (Reyes et al. 2011; Franke et al. 2014).

The variation of CPR technique is dependent on the number of providers, creating scenarios in which one infant may receive CPR initially by a single provider using one-handed technique and additionally by healthcare providers using two-handed technique. Additionally, AHA stipulates that rescuer fatigue will decrease the effectiveness of cardiovascular perfusion which has been more frequently noted when performing infant CPR using one-hand (American Heart Association 2005). Recognizing infant and rescuer size variation, it is advised that a single rescuer may use either one or two-hands to compress the infant's chest. This flexibility promotes emphasis on achieving high-quality CPR consisting of adequate compression depth and full chest recoil between compressions regardless of using one-hand or two-hands (American Heart Association 2005). However, these technique discrepancies create an array of variation in which an infant will ultimately be handled during resuscitation. Cardiac compressions require aggressive physical effort on the rescuers behalf and by proxy can cause unintentional rib fractures to the infant. These injuries can complicate the forensic investigation regarding mechanism of injury (Olds et al. 2015). Since CPR is performed only as a last effort to save a life, the consequence of rib fracture is less significant than survival and therefore an accepted effect.

Research has been conducted which support the notion that infant CPR may result in rib fractures (Feldman and Brewer 1984; Reyes et al. 2010; Love et al. 2011; Franke et al. 2014). However, conflicting sources insist that the forces associated with CPR will not result in rib fractures unless there are pre-existing medical conditions which would impair bone integrity (Gunther 2000; Heldrich 2011; Abel 2011). Multiple studies citing the possibility of CPR related fractures have been conducted by interpreting the medical record radiographs of infants who received resuscitation (Spevak et al. 1994; Franke et al. 2014; Kessel et al. 2014). While x-rays can show evidence of rib fractures, radiographic imaging routinely fails to detect the full extent of rib injury (Cattaneo et al. 2006). Current research suggests infant CPR associated fractures occur rarely and are generally located in the anterior and anterolateral region of the rib, typically among ribs three through six presenting as buckle-fractures (Love, Derrick, and Wiersema 2011; Wedel and Galloway 2014). Despite continuing research of CPR related rib fractures, it remains difficult to accurately describe the full extent of the injury without a skeletal evaluation (Cattaneo et al. 2006; Weber et al. 2009; Love et al. 2014). A pediatric skeletal examination can only be conducted on deceased individuals and requires invasive and labor-intensive evaluation by a forensic anthropologist (Love and Sanchez 2009). Therefore, this technique is not always performed unless child abuse is highly suspected.

In cases where violence is questioned as a cause of injury, interpreting rib fracture causation becomes difficult. Any rib fracture in a newborn or infant is concerning and demands investigation to establish whether the fractures are secondary to abuse or CPR (Bulloch 2000; Kleinman et al. 1997; Love et al. 2011; Franke et al. 2014; Feldman and Brewer 1984). Rib fractures are considered highly suspicious of non-accidental trauma (NAT) as they are the most common skeletal injury in cases determined as child abuse (Love et al. 2011; Reyes et al. 2011; Ross and Abel 2011; Spevak et al. 1994). The most commonly proposed mechanism rib fractures caused by child abuse is generated during an antero-posterior compression of the chest which occurs when grasping a child by the chest and shaking. This occurs when the perpetrator grasps the child's thorax with both hands placing their thumbs near the sternum and the fingers wrapping around the posterior chest while applying compression while possibly shaking (Caffey 1972; Kleinman and Schlesinger 1995). The hand positioning when administrating two-hand CPR are similar to that of the perpetrator of shaken baby syndrome (SBS). For this reason, administers of CPR may become more cautious about performing resuscitation (Feldman and Brewer 1984). Furthermore, abusers aware of this resemblance may use a legal defense attributing rib fractures inflicted by SBS were instead attributed secondarily to CPR (Gunther et al. 1999). The location of the fracture is significant to ascertain the mechanism of injury as well as meticulous examination of the injured rib by a forensic anthropologist to determine bending direction and application of force (Gunther et al. 1999). Biomechanical response studies have been performed on infant ribs primarily to further the understanding of fractures secondary to abuse (Kleinman and Schlesinger 1997; Tsai et al. 2012; Blackburne et al. 2016).

Harris County Institute of Forensic Science (HCIFS) in Houston, Texas created an infant trauma database beginning in 2010 which contains documentation on any child whose death was investigated by the office and is under the age of approximately one year. The database categorizes child deaths as traumatic or non-traumatic and currently has approximately 500 cases as of 2018. The skeletal injuries cataloged are comprehensive, but for the purpose of this research, only infants documented as having received CPR and those with rib fractures were evaluated. Additionally, documentation is listed if the infant received CPR from bystanders, medical personnel or both. This resource provides a large sample of infants with identified rib fractures and the contributing mechanism of injury as determined by a forensic anthropologist and pathologist. While the majority of infants received CPR regardless of their mode of injury, a comparison will be made between the piglet sample having only received CPR to groups of infants documented as sustaining blunt-force injury and infants who sustained non-traumatic skeletal injuries.

The research proposed in this thesis extends beyond the current studies by creating a controlled model to investigate the results of two CPR techniques and the rib fractures they may or may not cause. Piglets are used to represent a human sample, and the same principals of one and two-hand CPR are applied to the animal model. Following compression, the ribs are macerated, and a detailed inspection of each rib is conducted. The classification of rib fracture types follows the method used for the Harris County Infant Trauma Database (HCITDB), which is based on that developed by Love and Pinto (Love et al. 2013; Pinto et al. 2014). Using a congruent schema allows for the fractures seen in the piglet sample to be compared accurately to that in the database while additionally allowing for repeatability in future research.

When a highly skilled forensic anthropologist uses meticulous inspection techniques and the proper rib fracture classification system, identifying infant rib fractures post-mortem can be done with precision. However, the point of contention is properly categorizing the fractures' mechanism of injury. The failure to accurately differentiate between rib injury caused by CPR and those caused by abuse will result in a massive injustice if not properly identified. It requires a team of highly skilled clinicians to ultimately make this decision. Therefore, it is crucial to establish common and thorough guidelines for evaluating rib fractures. The aim of this study is to help forensic anthropologists and other clinicians further their understanding of infant rib fractures when having to differentiate between traumatic and non-traumatic deaths. In order to meet these objectives, the proposed research aims to answer the following research questions:

1.) Does two-handed infant CPR cause more rib fractures than one-handed infant CPR?
2.) Do rib fracture types and locations occur as a result of infant CPR methods?
3.) Are rib fracture patterns distinguishable between porcine surrogate samples and those documented within the Harris County Infant Trauma Database including non-abusive and abusive deaths?

The following chapter will be a literature review of infant CPR methods and the current understanding of how infant ribs respond to biomechanical forces including both CPR and non-accidental trauma. Additionally, the reasoning for using porcine surrogates for human ribs will be addressed.

II. LITERATURE REVIEW

Introduction

Infant cardiopulmonary resuscitation (CPR) uses the same principals of adult CPR, but the hand placement for applying compression is modified to account for the surface area of an infant chest (American Heart Association 2015). Infant bone differs from adult bone in multiple ways including anatomy, morphology, physiology, and biomechanical properties (Humphries 2011). These factors are integral to interpreting the fractures that occur during both infant CPR and abusive scenarios. This literature review will consist of an overview of these topics as well as the consideration for using an animal model for comparative analysis.

Cardiopulmonary Resuscitation

Successful CPR is focused on performing high-quality chest compression to increase cardiac output and profusion (American Heart Association 2015). While CPR is performed to save lives, if resuscitation is successful, the individual may experience secondary injuries related to therapeutic intervention. Fractures of the ribs and sternum are commonly seen in autopsies of adults who received CPR (Feldman and Brewer 1984; Hashimoto 2007). However, it remains in conjecture throughout literature whether infant CPR produces rib fractures (Heldrich 2011; Abel 2011).

One-Hand Method

Prior to 2005, infant CPR was administered only using one-handed digital compressions (Figure 1) regardless of being a medical professional or a by-standard (American Heart Association 2005). In 1983, Feldman and Brewer (1984) conducted a retrospective study of 113 abused and non-abused children. It was concluded that all documented fractures were not attributed to CPR. However, this study only analyzed radiograph films and not autopsy findings. In 1994, Spevak and colleagues conducted a study and found that of 91 infants, without evidence of abuse but who had received CPR, did not show any signs of rib fracture. This research was conducted using autopsy reports and radiological film. Kleinman and Schlesinger (1997) further explored rib fractures associated with one-hand CPR and abusive chest squeezing using a rabbit model. The study used only three animal subjects, none of which sustained fractures from CPR. These findings were based on exclusively reviewing computed tomography (CT) imagining of the rabbits without autopsy.

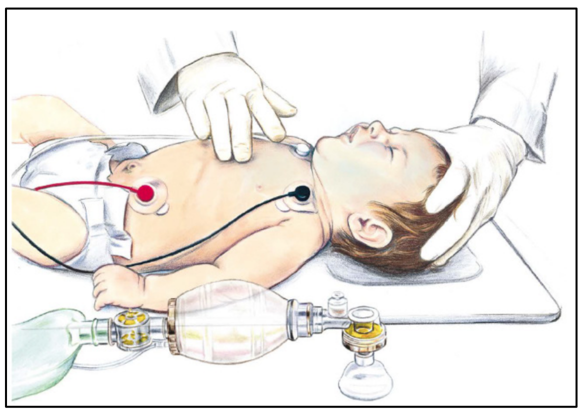


Figure 1. One-Hand Infant CPR Method (Image from American Heart Association 2015).

Two-Hand Method

Two-hand infant CPR was introduced in 2005 to encourage high-quality CPR from rigorous chest compressions between two health-care providers (Figure 2). Along with this change in methodology, encouragement to “push hard; push fast” was emphasized to maintain adequate organ perfusion (American Heart Association 2015). There is no data to confirm that one-hand or two-hand methods produces better compressions or better profusion. However, studies have shown that providers show less rescuer-fatigue when using a two-hand method (American Heart Assoiciation 2015).

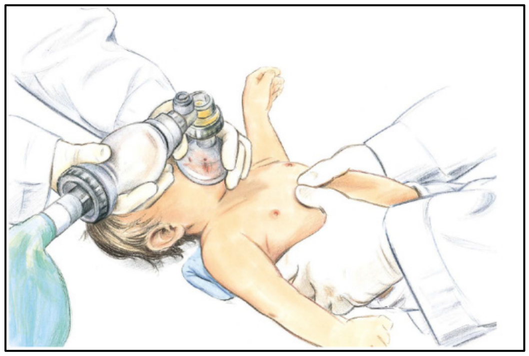


Figure 2. Two-Hand Infant CPR Method (Image from American Heart Association 2015).

Several years after the CPR change, Reyes et al. (2011) recognized an increase in infant rib fractures identified during autopsies, which were seemingly related to CPR. To confirm this observation, a retrospective study was conducted using autopsy reports from 1997 to 2008 on 571 infants who received CPR. Their findings indicated that nearly 74% of the CPR-associated fractures occurred between 2006-2008 demonstrating a significant increase in incidence of resuscitation-associated rib fractures since CPR revisions. Franke et al. (2014) conducted a retrospective study reviewing only the anterior-posterior chest x-rays of 80 infants between 2001-2010. Radiologists were unable to positively confirm any posterior rib fractures. The researchers recognize their own limitations of reviewing only radiological imagining and suggested two-handed CPR fractures receive further research. Love et al. (2013) found the presence of buckle fractures on the anterior and anterolateral regions. The concentration of these fractures in the upper and mid-range ribs does support previous studies specifically linking buckle fractures with anterior to posterior compression of the chest as commonly seen in CPR.

Currently, infant CPR standards encourage compressions to be of high-quality and ultimately either method can be used by the provider (American Heart Association 2015). While inconsistent for charting purposes, this flexibility prioritizes the outcome of the patient. This disparity has not been recognized in any retrospective studies and it should not be assumed that all CPR provided after 2005 is provided using a two-hand technique. The research conducted in this study controls for the method of compression delivery and the results are clearly differentiated between the two.

Infant Rib

At the time of birth, an infant will typically have 12 pairs of ribs. The ribs are part of the thoracic cage comprised of 12 thoracic vertebrae posteriorly and a lateral series of 12 pairs of ribs attached anteriorly by cartilage to the sternum creating an osteo-cartilaginous framework. All ribs attach posteriorly to the thoracic vertebrae, but only 10 pairs are connected anteriorly to the sternum via costal cartilage (Figure 3). Ribs 1-7 are considered true ribs as they connect directly to the sternum, while ribs 8-10 are considered false ribs, which attach indirectly by costal cartilage to the sternum. The eleventh and twelfth rib are referred to as free or floating ribs which are unattached anteriorly (White 1991; Scheuer and Black 2000; Schwartz 2007). The anterior and posterior surfaces of the rib are referred to as the pleural (toward the thoracic cavity) and the cutaneous (toward the anterior) surface.

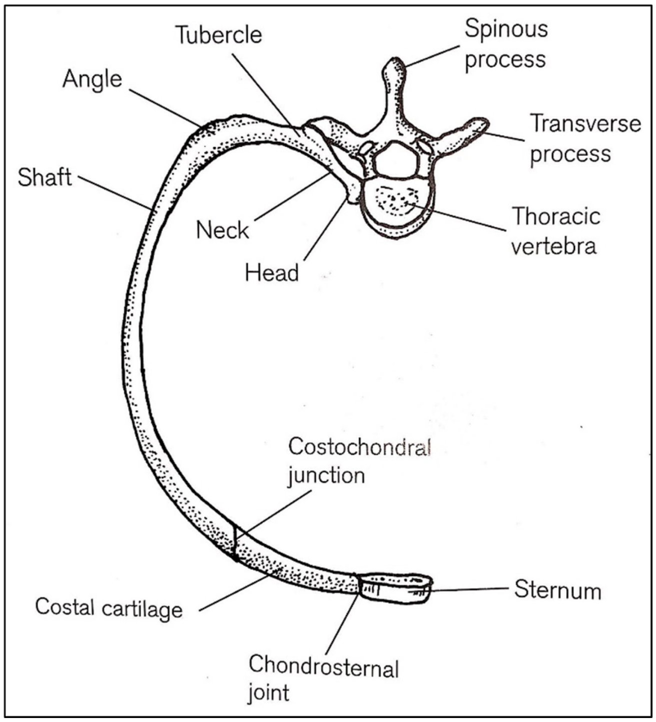


Figure 3. Articulation of a Typical Right Rib (Image from Scheuer and Black 2000).

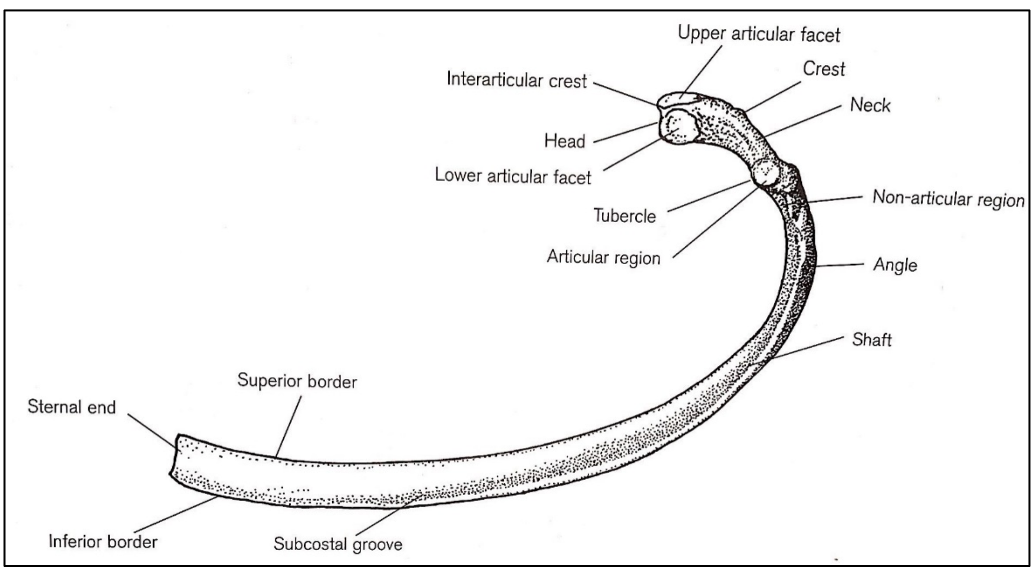


Figure 4. Anatomical Landmarks of a Typical Right Rib (Image from Scheuer and Black 2000).

Rib morphology is commonly categorized as either "typical" or "atypical." Typical ribs occupy the middle of the series and have an overall similar morphology (Figure 4). They include ribs 3-9. The most superior and most inferior ribs are termed atypical because of their individual characteristics (Figure 5). They include ribs 1, 2, 10, 11, and 12 (White 1991; Scheuer and Black 2000).

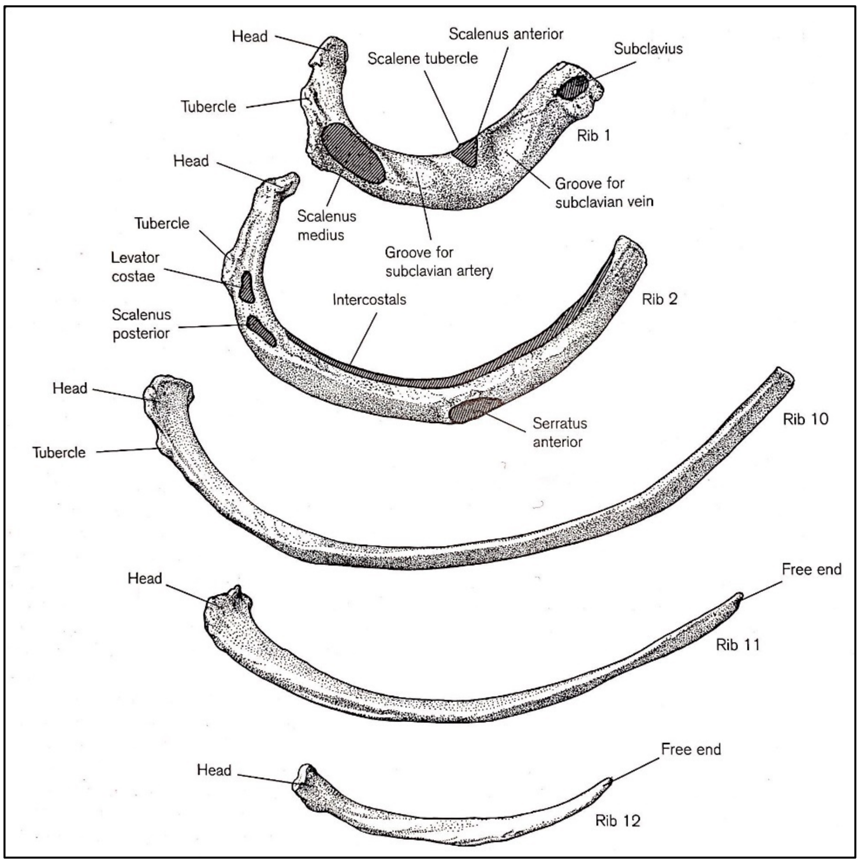


Figure 5. Atypical Right Ribs (Image from Scheuer and Black 2000).

The ossification of the ribs occurs in utero beginning at the center angle and continues out toward the ends. It is not until the age of 16-20 years old that the head and tubercle ossify and fully fuse with the remaining rib (Schwartz 2007).

Human bone is composed of organic and inorganic (hydroxyapatite) material. In children, the organic portion is proportionally larger with a lower mineral content than in adults. The organic material is composed primarily of protein collagen, which provides a higher degree of elasticity, flexibility and tensile strength (Black and Scheuer 2000; Baker et al. 2005a; Humphries 2011). Furthermore, the increased flexibility in the bones of children is a result from increased haversian canals (which allow blood flow) within the cortex (hard exterior of bone), making young bone more porous than that of adult bone (Rang and Wenger 2005). This excessive blood supply to bone is one of the reasons young bone heals faster than adult bone (Rang and Wenger 2005; Malone et al. 2011). Adding to the stability of immature bone is the presence of a thick periosteum surrounding the cortical surface. Even after fractures, an intact periosteum has been observed in children (Jacobsen 1997).

Biomechanical Properties

To properly interpret bone fractures, it is imperative to understand the biomechanical properties of the bone being analyzed (Ubelaker and Montaperto 2011). Kieser et al. (2013a, 4) defines forensic biomechanics as, "…the study of forensic biological phenomena by means of the methods of mechanics, in terms of the structure and function of relevant biological systems." However, due to their unique overall morphology, rib fractures can be more difficult to interpret than fractures to other bones as they tend to respond unexpectedly to stress (Love and Symes 2004). This can be explained by the cross-sectional design of a rib, which is a thin-walled tube of variable thickness. The ability of a whole bone to bear applied loads relies on its total mass, geometric distribution of the mass, and the material properties. The ribs' variation in distribution of bone mass in a cortical cross-section is proportional to the bending failure strength of the whole bone (Cole and van der Meulen 2011).

Although this research is studying the effects of whole bone mechanical behavior, analogous tests can be performed to measure the tissue level mechanical properties. These test results are independent of bone size, shape and measure homogenous samples (Cole and van der Meulen 2011). Regardless of which whole bone is evaluated, the fracture response can be understood using a biomechanical model between stress and strain. Stress refers to the magnitude of the load applied to the affected material's, such as bone, surface area. Strain describes the material's response to the applied stress (Ubelaker and Montaperto 2011). The slope of the stress-strain curve is the material's stiffness and is known as the modulus of elasticity. At this point, when stress is removed, the structure will return to its normal shape. After passing this point of elasticity, the material exhibits plastic deformation, which is characterized by permanent bending even after the stress is removed. The final relationship between stress and strain results in the point of failure (in the case of bone, a fracture) which determines the structure strength given the loading conditions. (Love and Symes 2004; Cowin 2009; Zephro and Galloway 2014). This concept between stress and strain is referred to as Young's modulus which measures the intrinsic stiffness of the material (Love and Symes 2004; Turner and Burr 2009; Ubelaker and Montaperto 2011; Zephro and Galloway 2014). Figure 6 illustrates this relationship.

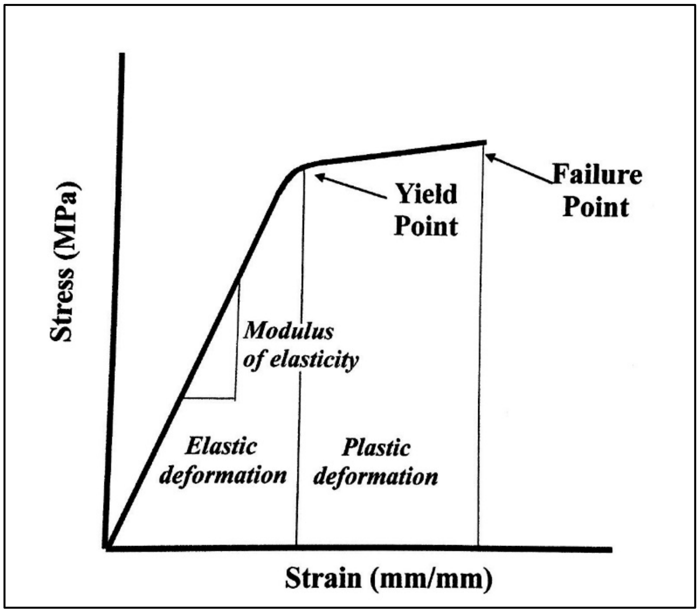


Figure 6. Stress-Strain Curve (Images from Zephro and Galloway 2014).

Based on the composition of pediatric bone and the biomechanical properties of fractures, healthy infant bone has a longer plastic phase than seen in adults. Additionally, it can absorb more energy without fracturing than adult bone. However, infant bone fractures with less force than adult bone (Zephro and Galloway 2014).

Bones are designed so that their architecture can properly respond to and absorb the typical forces they experience (Zephro and Galloway 2014). Generally understood, bone is more resistant to compression than tension (Galloway et al. 2014; Love and Symes 2004). However, as previously described, the thin-walled tube structure of rib creates a scenario in which compressive instability results in collapse or buckling. Under these circumstances, when forces are great enough to produce fracture, unlike other bones, ribs often first fail under compression rather than tension (Love and Symes, 2004). The geometry of a bone dictates its mechanical properties. Predicting bone fracture is theoretically possible if knowledge of loading conditions and a complete accounting of material and structural composition are known. However, the type of fracture produced is dependent on the structural and material properties of the bone at and near the location of the force (Wescott 2013). This is relatable to forensic context because trauma is not applied identically in every case. Therefore, it is not surprising that rib fracture patterns are inconsistent and understanding them is grounded in laboratory experimentation (Daegling et al. 2008).

Classification System

Distinguishing accidental from non-accidental rib fractures is heavily dependent on the location of the injury, which is imperative to determining mechanism of injury (Bullock et al. 2000; Love et al. 2011; Tsai 2012; Pinto et al. 2015). Therefore, having a consistent classification system is imperative for a proper descriptive record as it is an effective assessment for both fracture characteristics and context. This classification system does not denounce descriptive observation, but rather adds a standardization to the record. Love and Symes (2004) initially published a studying describing the lack of biomechanical literature that would properly describe the type of fractures seen in ribs, regardless of age. The aim of this study was to distinguish a buckle fracture from an incomplete fracture and the biomechanical properties required to produce the uniqueness of the injury. While an incomplete fracture was defined as any partial fracture, regardless of the location and morphology, a buckle fracture is when the bone fails at the point of compressive stress prior to fracture at the point of tensile stress (Love and Symes 2004).

It was not until 2013 that a rib classification system was developed by Love and colleagues (2013) whom recognized the inconsistency and lack of detail available to describe the location and type of all fractures observed in infant ribs (2013). The schema's initial development resulted in being able to categorize 153 of 157 (97%) infant rib fractures (Love et al. 2013). The system defines four fracture types and four regions of the rib which have been given definitions as seen in Table 1. Visualization of the rib locations can be seen in Figure 7.

Table 1. Definitions of Fracture Locations and Types (Love et al. 2013).

Location of Fracture	Definition
Posterior	Area from the lateral margin of the rib tubercle to the medial tip of the rib head
Posterolateral	Area from the lateral most point of the rib body to the lateral margin of the rib tubercle
Anterolateral and anterior	The anterior and anterolateral regions of the rib span from the most lateral point of the rib body to the sternal end. The interface of the anterior and anterolateral regions is the midpoint of this section of the rib
Type of Fracture	**Definition**
Buckle	Incomplete fracture on the pleural surface of the rib
Transverse	Complete fracture with a vertical (superior-inferior) orientation
Oblique	Incomplete or complete fracture with a superolateral to inferomedial orientation or vice versa
Sternal end plate	Fracture of the sternal end plate or rim

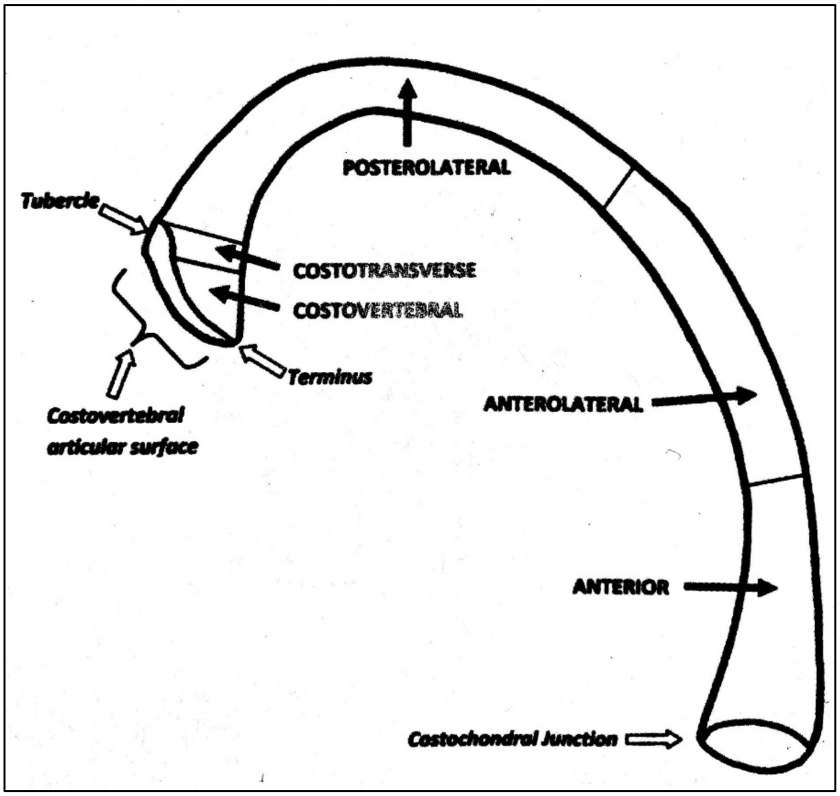


Figure 7. Diagram of the Regions of the Rib (Image from Love and Sanchez 2009).

The morphology of the posterior rib further required examination as the newly developed classification system lacked specificity to account for the terminus (tip of the rib head), tubercle, and costovertebral articular surface (Figure 8). When a rib is compressed in an anterior-posterior manner, it can create excessive leveraging of the rib head over the vertebral process (Kleinman and Schlesinger 1996). When force exceeds the tensile strength of the bone, fractures occur within the rib head. Pinto et al. (2015) created a subdivision classification system specifically for classifying pediatric rib head fractures which is described in Table 2.

The fractures observed in this research use the same schema for classification of porcine rib fractures. Additionally, the HCITDB has been recently reclassified using a version of this system for consistency throughout all cases.

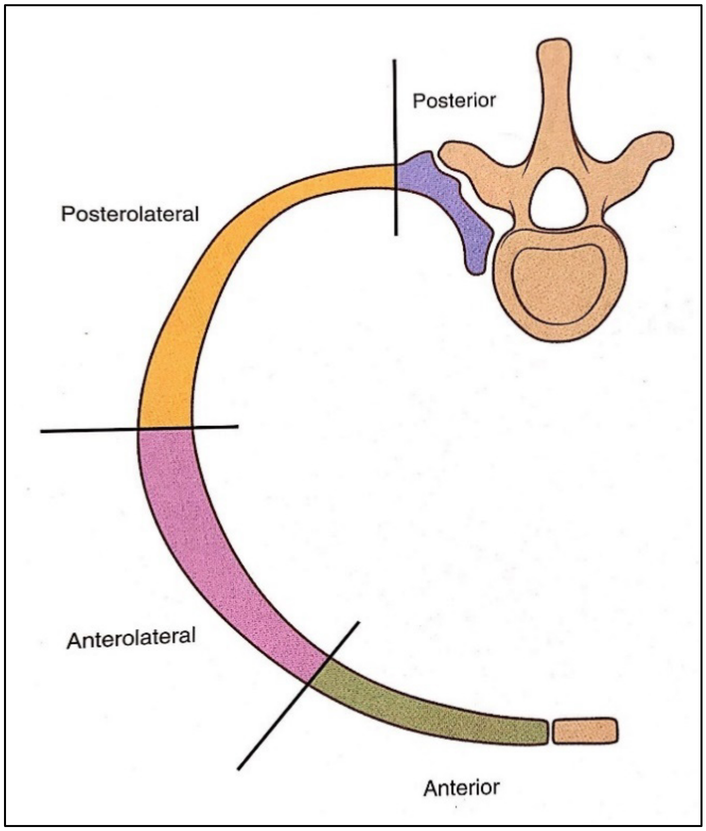


Figure 8. Posterior Landmarks for Describing Infant Rib Head Fractures (Image from Pinto et al. 2015).

Table 2. Definitions of Infant Rib Head Fractures (Pinto et al. 2015).

Category	Anatomic Identifier	Fracture Description
Landmark	Terminus	Transverse fracture through tip of the rib head
Landmark	Tubercle	Transverse fracture through articulation site for the vertebral transverse process
Landmark	Costovertebral articular facet	Fracture causing avulsion of the cortical bone at bone-cartilage interface
Subregion	Costovertebral subregion	Transverse fracture located between the terminus and medial margin of the tubercle

Pediatric Skeletal Examination

When a pediatric case is suspicious of abuse, a thorough and complete autopsy is recommended including investigation of both soft tissue and bone. Love and Sanchez (2009) have described this method for recognition and documentation of skeletal injuries, which has since been referred to as the "pediatric skeletal examination" (PSE). The PSE requires the investigator to reflect the soft tissue covering the bone for visualization. After the ribs are exposed, the rib body is inspected for trauma. If irregularities are noted, the rib is removed from the rib cage and macerated for gross and histological inspection (Love et al. 2014). Within the state of Texas, forensic anthropologists are permitted to participate in helping to determine the cause, manner, and time of death in conjunction with the medical pathologist. Therefore, this technique can aid in recognition of non-accidental trauma that may otherwise go unnoticed (Love et al. 2009). This technique, while effective and detailed, is labor intensive and invasive (Love and Sanchez 2009). For the purpose of this research, a survey of only the PSE related to rib inspection will be discussed.

Infant rib fractures can often go undetected in radiographic imaging not at fault of the radiologist, but because of the lack of visibility of small fractures (Kleinman et al. 1988). In a study conducted by Cattaneo et al. (2006), only 47% of the total rib fractures were identified via radiological survey in a piglet model for proxy of abused infants. It is recommended from this study that in all cases of fatal child abuse, the direct areas of concern be visually analyzed during autopsy or even macerated. Love et al. (2014) found in a retrospective review of 94 autopsies conducted at the HCIFS that documented rib fractures were significantly higher in cases where a PSE was conducted over those that were not.

Porcine Surrogates for Research

Domestic pigs are widely used in scientific and medical research as they have anatomical and physiological similarities to humans. Because of their small size, miniature pigs are also easier to handle compared with larger domestic animals (Tanaka and Kobayashi 2006). While human cadavers are ideal to conduct biomechanical bone research, there is not sufficient pediatric human cadaver material available, and therefore, animal models pay an important role in helping to understand the mechanisms of injury (Wei et al. 2017; Bertocci and Pierce 2006).

There are obviously physical differences between human and porcine osteology. However, overall the generalized shape of the porcine thorax is similarly barrel shaped to that of a human. While humans usually have 12 pairs of ribs, pig ribs number typically between 14 and 15 pairs, of which seven are connected directly to the sternum, and seven or eight pairs are false. When the 15^{th} rib is present, it is a floating rib and substantially shorter than the remaining pairs (Sisson 1975). Unlike human ribs, the most caudal ribs have only a slight angle but with a wide and flat body. The 7th and 8th rib are the longest and the rib angle becomes more distinct. Similarly, to human ribs, the angle becomes less distinct toward the end of the series.

Animal injury biomechanical models are commonly used in a variety of ways in support of child abuse diagnosis (Bertocci and Pierce 2006; Baumer et al. 2009). Similarly, to the purpose of this research, the intent of these studies is to better understand skeletal fractures related to accidental versus non-accidental injuries (Bertocci and Pierce 2006). Examples of animal injury models have been published by Blackburne et (2016) who investigated the structural, biomechanical and fractures under stress mimicking a high-velocity fist impact using a piglet model. Pediatric abusive head trauma studies have also been carried out using porcine models. Wei et al. (2017) utilized a porcine head model as proxy for distinguishing the difference in pediatric cranial fracture patterns under varying energy forces using a computer interface. Powell et al. (2011) used piglets aged 2-28 days to document patterns of skull fractures under rigid and compliant forces.

An animal model study in bone research are as reliable as the similarities between the response from the animal bone to that in human bone. Different animals may provide a better comparison depending on which bone is being studied. Animal models used for biomechanical testing regimens must be tailored according to the goals of the study and the constraints associated with the specific animal (Turner and Burr 2001). In a comparison study using the most commonly used vertebrates for bone research, pig bone was shown to be most similar in fracture stress compared to human bone (Aerssens et al. 1998). Infant bone structure differs from that of adult bone and therefore the animal model must reflect these age dependent properties. Baumer et al. (2009) conducted a study addressing the age effects on the mechanical properties of parietal bone in piglets aged 3-21 days old in comparison to that of infant parietal bones. The results showed a correlation suggesting that the days of pig age may correlate with months of human age.

Multiple compressive rib studies using porcine samples have been conducted which use individually resected, fleshed, pig ribs (Kieser et al. 2013a; Bradley et al. 2014). While valuable in understanding forensic biomechanics, using these animal model studies as a comparison to the reactive response seen during an abusive situation should be cautionary as they fail to compensate for the structural integrity of the entire chest including soft tissue. Attention is rather focused to the axial strength of the rib. The presence of skin, cartilage, muscles, and internal thoracic pressure will potentially resist the onset of fracture (Blackburne et al. 2016). The research conducted in this thesis chose to use an intact porcine to conduct CPR for this very reason. Resuscitation studies using an animal model have most frequently been found to use a pig surrogate model because of the similarity in physiology to humans (Xanoths et al. 2007; Walters 2011; Cherry et al. 2015). However, these studies focus on organ injury and overall clinical response rather than rib fractures.

III. MATERIALS AND METHODS

This chapter is an explanation of the materials and methods used to conduct this research. Descriptions are given of the piglet samples and the Harris County Infant Trauma Database (HCITDB). Further explained are the techniques used for administering CPR, maceration and autopsy technique. The methods used for rib fracture analysis and categorization are additionally explained.

Materials

Porcine Samples

Piglets were obtained from Duelm's Prevailing Genetics in New Braunfels, Texas. Pig breeds were reported as predominately Hampshire (*Sus scrofa domesticus*). Request was for naturally deceased piglets that did not sustain any traumatic injury prior to death. Piglet ages were not determined individually but reported from the farmer as between stillborn and 11 days old at the time of death. Sex was not determined. A total of 34 whole piglets were collected fresh by the facility and frozen shortly after the time of death at the farm. The samples were transported in a cooler to the Texas State University Osteology Research and Processing Lab (ORPL) where they were further stored in a deep freezer at 30°F. Prior to administering CPR, the piglets were removed from the freezer and completely defrosted over three days in a refrigerator at 45°F (Hale 2017). Once completely thawed and dried, each piglet was weighed. Weights ranged between 643-1984g (individual sample weights are listed in Appendix A). One piglet was reserved as a control sample, and neither method of CPR was performed.

Harris County Infant Trauma Database Samples

Harris County Institute of Forensic Science (HCIFS) located in Houston, Texas began categorizing skeletal injuries seen in children beginning in 2010. The Harris County Infant Trauma Database (HCITDB) is currently composed of 629 deceased individuals who have been examined for skeletal injury. While the name of the database implies infants only, the database contains young children as old as 4.8 years. Only children under 12-months of age were used in this study (n=571). There is no reported cases of bone disease or bone integrity compromise within the database. Apart from age, all additional demographic information, bench notes and photographs were withheld from analysis to preserve anonymity of all individuals.

Manner of death (MOD) is determined by the medical pathologist and is categorized into five categories: accident, accident by motor vehicle accident (MVA), homicide, natural and undetermined. The purpose of this research is to analyze rib fractures resulting from CPR or abusive scenarios. Therefore, individuals with a MOD as 'accident by MVA' were removed (n=6). When analysis was conducted on those who received CPR, samples with a MOD as 'homicide' were removed. Cause of death (COD) is also ultimately determined by the medical pathologist but is a list of any identifiable injury or diseases that were responsible for death, and therefore specific to the individual. The variability of COD increases the chance of inaccurate reporting and was therefore not used primarily to remove any samples from the study (Lloyd et al. 2017). A cause category was created by HCIFS as a subdivision of COD and classifies the COD into seven categories including: asphyxia/drowning, co-sleeping; infectious, other, sudden infant death syndrome, trauma and undetermined. When MOD was listed as 'accident' or ‘undetermined,’ the cause category was utilized to assess if the sample should be removed if categorized as a traumatic death.

Cardiopulmonary resuscitation is reported as ‘performed,’ not ‘performed,’ or ‘unknown.’ If CPR is performed, the individual administering is listed as either ‘by-stander,’ ‘medical personnel,’ ‘both’ or ‘unknown.’ All cases coded as ‘performed’ for CPR were included in the analysis (N= 531). The database information is a compilation from numerous sources including law enforcement, forensic investigators, forensic anthropologist and medical pathologist.

The rib fractures have been identified by either the medical pathologist or forensic anthropologist. It is not distinguished if the fractures were observed *in situ* or after maceration. Furthermore, the HCITDB is not inclusive of all data collected from individual autopsies. It is rather an attempt to classify and organize generalized information of skeletal injuries. Love et al. (2013) novel classification scheme was used as the basis for the HCITDB model. The costochondral junction (CCJ) is differentiated from the anterior region and the terminus is differentiated from the posterior region of the rib creating six total landmarks. Ribs 1-10 are identified as having all six landmarks: CCJ, anterior, anterolateral, posterolateral, posterior, and terminus. As ribs 11 and 12 do not attach to the sternum, they are not considered to have anterior portions. Therefore, ribs 11 and 12 document three landmarks: posterolateral, posterior and terminus. The type of fractures remains similar apart from the “sternal end plate” specific fracture. This was replaced with an avulsion fracture indicating a fracture resulting from a shearing or tearing of the region (Kleinman and Zito 1984). All rib landmarks can be documented as having any combination of five categories of fractures including avulsion, buckle, transverse, oblique and indeterminate.

Methods

Cardiopulmonary Resuscitation

Prior to administering CPR, verification of the integrity of the skeletal anatomy of each piglet was performed. This ensured that underlying trauma was not falsely attributed to CPR efforts. First, each piglet was palpated and visually inspected for any gross abnormalities of the ribcage. Furthermore, the pigs were radiographed 360° in a vertical position using X5000 North Star Imaging. No fractures were identified and therefore all piglets were used in this research. Figure 9 shows how the piglets were positioned during radiographing.

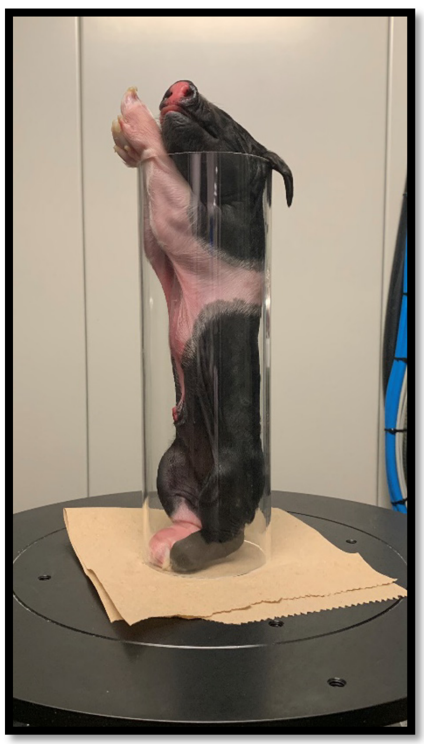


Figure 9. Piglet Positioned for Thorax Radiograph Prior to Receiving CPR.

A semi-randomized method was used to determine which method of CPR would be performed on each sample to ensure CPR methods were evenly distributed throughout the weight classes. All 33 piglets were weighed and ordered from least to most heavy. The 33 samples were split into two groups which were 16 of the least heavy and 17 of the heaviest piglets. Each piglet was given a randomized number between 1-16 or 1-17 in each group. Odd numbers received one-handed CPR and even numbers received two-handed CPR. This method ensures each group receiving CPR had an even weight distribution.

Figure 10. Hand Placement while Conducting One-Handed CPR on Piglets.

To administer CPR on the porcine samples, hand placement and compressions were delivered similarly to administering compressions on a child (American Heart Association 2015). The piglet was placed on a hard, flat surface regardless of administering method. One-handed CPR was administered while kneeling perpendicularly beside the piglet, and the right, dominant hand's second and third digits were placed over the sternum at the same level as the axilla. Two-hand CPR was administered while kneeling at the caudal end of the piglet. Both thumbs were placed in the same location as one-hand compressions, and the remaining digits were wrapped around the thorax. Figure 10 and 11 show the hand positions while performing CPR on the piglets.

Figure 11. Hand Placement while Conducting Two-Handed CPR on Piglets.

Compressions were administered at 100 compressions per minute and timed for five minutes. Compression depth was approximately one third the diameter of the chest and complete chest recoil was allowed in between compressions. Provider fatigue occurs when chest compression depth or rate is compromised by provider exhaustion (Reyes 2010). This was avoided by implementing rest breaks between each specimen.

Skeletal Examination

After compressions were administered, the piglets were either refrozen or prepared for dissection. Dissection was performed at ORPL following a similar protocol as described by Love and Sanchez (2009). Each piglet, regardless of CPR received, was dissected similarly. The piglets were positioned supine. A disposable scalpel #10 was used to create a Y-incision to reflect the skin and muscles from the thorax. The cartilage between the sternum and ribs was cut to remove the chest plate, followed by removal of all the abdominal organs. Figure 12 shows a piglet up to the point of evisceration.

Figure 12. Dissection and Evisceration of a Piglet Post-CPR.

All ribs were removed individually from the spinal column. First a horizontal cut was made between each rib through the intercostal muscles. Then the scalpel was inserted through the cartilaginous portion of the rib head, cutting toward the posterior apex of the transverse process of the vertebra. Extreme caution was implemented throughout the process to prevent scalpel artifact, especially on the rib head. Scalpel blades were changed often throughout each dissection.

When all the ribs were removed, they were prepared for maceration. They were placed in a container filled with a solution of 1/3 Foremost 1553-ES Super Kleen® (Delta Foremost Chemical Corporation, Memphis, TN) and 2/3 water. Super Kleen is an industrial strength liquid soap specifically used to break down oil and grease. The containers were then placed in a Thermo Scientific 2051 incubator at approximately 130° Fahrenheit. After 24 hours, the specimens were checked for easy removal of soft tissue. While the majority of samples were free of soft tissue after one day, some larger samples were soaked for an additional 24 hours. The ribs were then cleaned with water to remove any remaining soft tissue, dried, and transported to the Grady Early Forensic Anthropology Research Laboratory (GEFARL) for analysis. The control piglet was first processed and received a pediatric skeletal examination (PSE) and rib resection. The ribs from the control piglet were atraumatic and used as a reference to identify trauma in the remaining samples.

Each rib was individually inspected for fractures using a Dinolite Edge digital microscope with Dino Capture 2.0 software. All trauma, including artifact, was photographed and documented. The location of the trauma (CCJ, anterior, anterolateral, posterolateral, posterior, or terminus), type of fracture (avulsion, buckle, transverse, oblique, indeterminate, or artifact) in listed in Appendix B. Each type of fracture is documented in Appendix C-G.

Statistical Analysis

Due to the data type and small sample size, multivariate statistics were not possible. To interpret the extent of fractures for each CPR method, t-test or Wilcoxon tests were performed to find statistical significance within either group. While both tests interpret the data similarly, a Wilcoxon test makes fewer assumptions about the data and decreases the chances of giving a false significance when the data is not equally distributed (Madrigal 2012). To analyze the fracture characteristics and locations, Fischer's exact tests were conducted, examining the significance of the associations between fracture type and fracture location through contingency tables. Graphs were created using Excel or JMP Pro 14. The statistical analyses were performed with JMP Pro 14 for Windows 2010.

IV. RESULTS

The following chapter outlines the results observed from the piglet samples and the data extracted from the HCITDB. All statistical analysis performed used coefficients with an associated p-value less than 0.05 as considered statistically significant.

Piglet Sample

Abnormalities, Artifact & Indeterminate Observations

All piglets rib cage anatomy showed no incidence of abnormality apart from right rib 1 of sample 8.21.18 #3 which had a bifurcation of the anterior and costochondral region. This abnormality was localized to a single rib, and therefore concluded to be normal variation and the sample remained in the study.

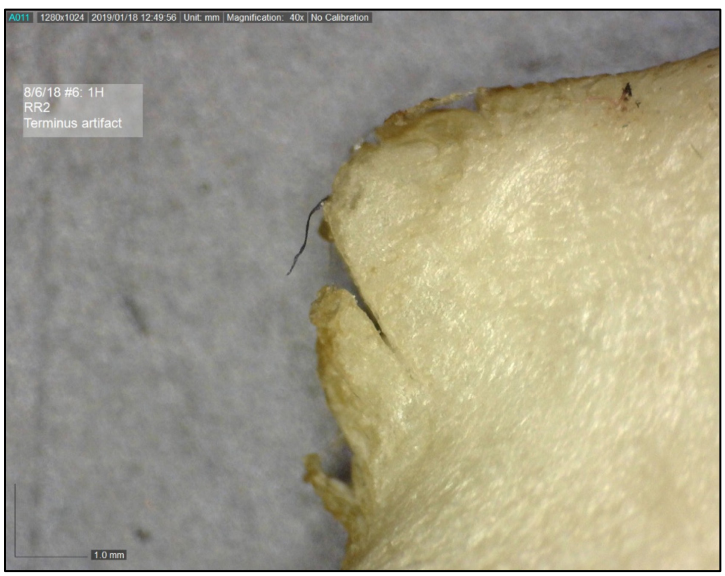


Figure 13. Terminus artifact caused by scalpel dissection.

Artifact was observed in 17 ribs. Of the 17 ribs with artifact, all observations were seen on the head of the rib caused by scalpel cuts while dissecting the ribs prior to maceration. The artifact was identified by a clear linear demarcation indicating a sharp force trauma. Examples of the artifact are shown in Figure 13 and 14.

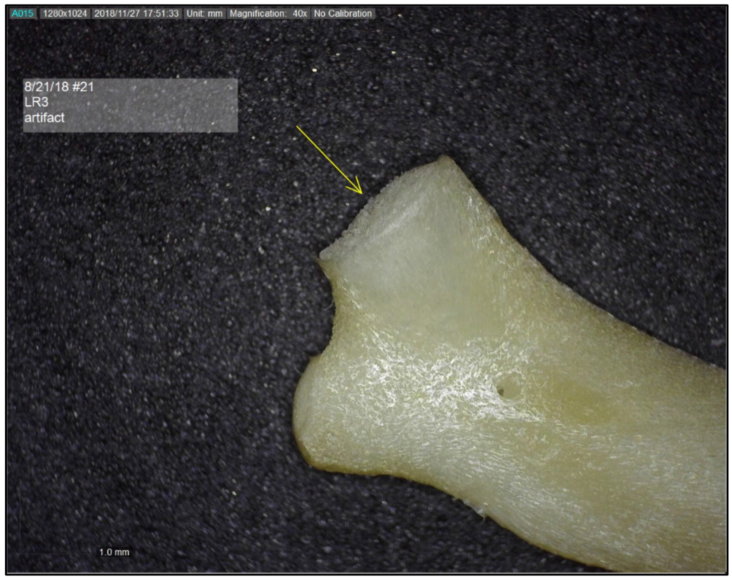


Figure 14. Complete Terminus Artifact Caused by Scalpel Dissection.

Indeterminate observations were recorded because they did not clearly fit into any of the defined fracture types. All seven observations (7%) were recorded within the anterior portion of the rib amongst five different samples showing similar characteristics including fractures visible on both the pleural and cutaneous surface. Since these fractures did not result in a complete separation, they would best be categorized as incomplete transverse fractures.

One-Handed CPR Fracture Distribution

Analysis was conducted on 16 piglets all of which received one-handed CPR only. Six of the 16 individuals (37.5%) were documented with observed rib fractures. A total of 24 fractures were documented within the sample. The average number of fractures per individual is 1.5. Figure 15 demonstrates the distribution of the number of fractures caused by one-handed CPR across the rib number and side of injury. Ten fractures occurred on the left side (42%) and 14 fractures occurred on right side (58%). There were no fractures observed on rib pairs 1, and 8-15.

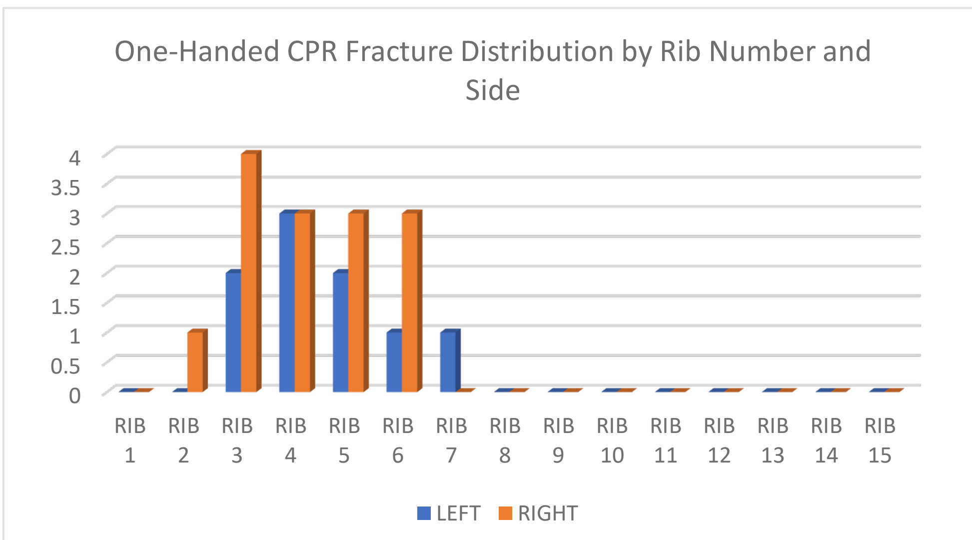


Figure 15. Distribution of Fractures Observed for Piglets: One-Handed CPR.

Two-Handed CPR Fracture Distribution

Analysis was conducted on 17 piglets all of which received two-handed CPR only. Ten of the 17 individuals (59%) were documented with observed rib fractures. A total of 73 fractures were documented within the sample. The average number of fractures per individual is 4.29. Figure 16 demonstrates the distribution of the number of fractures caused by two-handed CPR across the rib number and side of injury. Thirty-six fractures occurred on the left side (49%) and 37 fractures occurred on right side (51%). There were no fractures observed on rib pairs 1 and 11-15.

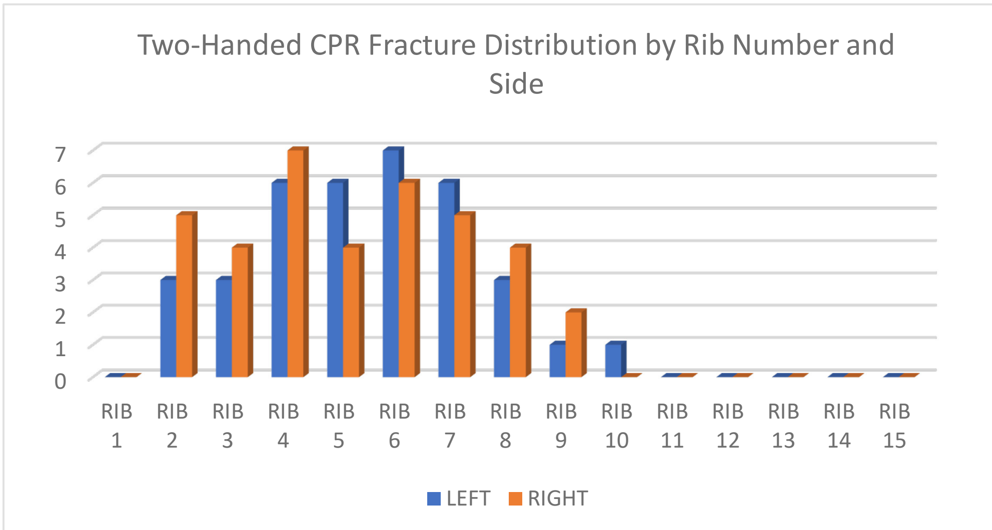


Figure 16. Distribution of Fractures Observed for Piglets: Two-Handed CPR.

<u>Both CPR Methods Fracture Distribution</u>

A total of 96 fractures were observed between both CPR piglet samples. The fractures are tabulated as present or absent. Sixteen (48.5%) of the 33 piglet samples had observable fractures. Figure 17 demonstrates the distribution of the number of fractures caused by both one and two-handed CPR across the rib number and side of injury. A table of each piglet and their observed rib fractures is displayed in Appendix B.

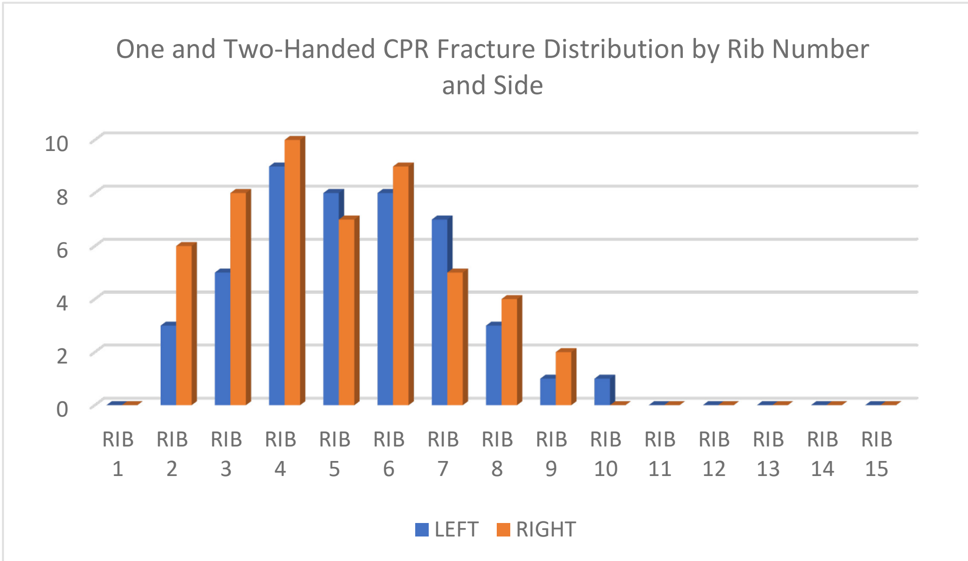


Figure 17. Distribution of Fractures Observed for Piglets: One and Two-Handed CPR.

Each pig sample has between 14 and 15 rib pairs. Between each CPR method, fractures were only observed between rib pairs 2-10. Table 3 and Figure 18 illustrates the relation between the rib pairs and the observed fractures from both CPR methods. One-handed CPR fractures exhibits a narrower distribution of fractures than two-handed fractures. While the one-handed method is unimodal distribution of fractures between ribs 2-7, two-handed CPR fractures are bimodally distributed between ribs 2-10. One-handed CPR fractures were most commonly observed on rib numbers 3 and 4 (six fractures) and two-handed CPR fractures were most commonly observed on rib numbers 4 and 6 (13 fractures).

Table 3. CPR Fractures Observed by Rib Pair: Piglets.

Rib Pair	Total Fractures Observed	One-Hand Fractures Observed		Two-Hand Fractures Observed	
1	0	0	-	0	-
2	9	1	11.1%	***8***	***88.9%***
3	13	6	46.1%	***7***	***53.9%***
4	19	6	31.6%	***13***	***68.4%***
5	15	5	33.3%	***10***	***66.7%***
6	17	4	23.5%	***13***	***76.5%***
7	12	1	8.3%	***11***	***91.7%***
8	7	0	0%	***7***	***100%***
9	3	0	0%	***3***	***100%***
10	1	0	0%	***1***	***100%***
11	0	0	-	0	-
12	0	0	-	0	-
13	0	0	-	0	-
14	0	0	-	0	-
15	0	0	-	0	-

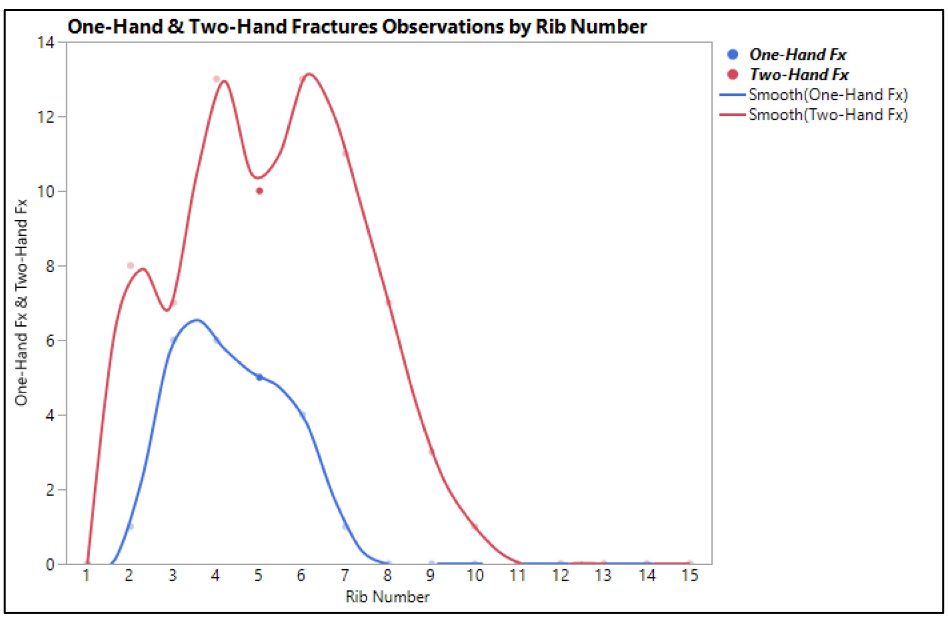


Figure 18. Distribution of Fractures per Rib Pair: Piglets.

T-Test Comparisons of CPR Fractures

In order to determine if the number of fractures differ from each method of CPR, regardless of fracture type and location, a two-tailed, paired t-test was run on the total number of fractures observed in each method. A statistical significance was found with a p-value= 0.0368 indicating the number of fractures occurring between each method differs from one another.

The weight of the piglets (n=33) ranged from 643-1984g. The mean weight of the piglet samples is 1262.03g. Bivariate regression analysis was performed to determine if there was a relationship between the piglet weight and the number of fractures observed. A weak trend is noticed over between increasing weight and increased fractures, however statistically, there is no significance (intercept= 0.098).

CPR Rib Fracture Location and Type

Analysis of the fracture site and fracture type have been analyzed within and between each CPR method. Based on the resulting observations and some small cell sizes, a Fisher's Exact test was used to determine if there was significance between the type of fracture and the site of the fracture.

First, a Fisher's Exact test was run on the fracture types and corresponding rib sites resulting from one-handed CPR only (n=23). Table 4 shows the statistical description of the fracture types occurring on each rib section. The results from the Fisher's Exact test show there is a significant difference between the type of fracture and the rib site where it occurred (p value= < 0.0001). The only resulting fractures from one-handed CPR were CCJ avulsion (78%), anterior buckle (17%), and anterior indeterminate (4%) fractures exclusively. Therefore, a highly significant difference was found between the two identified fracture types when compared to one another in each region. Table 5 lists the Fisher Exact pairs and their corresponding p-values.

Table 4. Contingency Table: Piglets One-Handed CPR Fractures.

Count Total % **Column %** Row %	Avulsion	Buckle	Oblique	Transverse	Indeterminate	Total
Anterior	**0** 0.00 **0.00** 0.00	**4** 17.39 **100.00** 80.00	**0** 0.00 **-** 0.00	**0** 0.00 **-** 0.00	**1** 4.35 **100.00** 20.00	**5** 21.74
Anterolateral	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **-** -	**0** 0.00 **-** -	**0** 0.00 **0.00** **-**	**0** 0.00
CCJ	**18** 78.26 **100.00** 100.00	**0** 0.00 **0.00** 0.00	**0** 0.00 **-** 0.00	0 0.00 **-** 0.00	**0** 0.00 **0.00** 0.00	**18** 78.26
Posterior	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **-** -	**0** 0.00 **-** -	**0** 0.00 **0.00** **-**	**0** 0.00
Posterolateral	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **-** -	**0** 0.00 **-** -	**0** 0.00 **0.00** **-**	**0** 0.00
Terminus	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **-** -	**0** 0.00 **-** -	**0** 0.00 **0.00** **-**	**0** 0.00
Total	**18** 78.26	**4** 17.39	**0** 0.00	**0** 0.00	**1** 4.35	**23**

Table 5. Fisher Exact Pairs: Piglets One-Handed CPR Fractures. Fisher Exact pairs of fracture type and landmark from one-handed CPR methods and the corresponding p-value; bolded values are statistically significance; landmarks without fractures are not included

Fisher Exact Pairs	Anterior/CCJ
Avulsion	***0.0000***
Buckle	***0.0006***
Oblique	1.0000
Transverse	1.0000
Indeterminate	0.2174

Secondly, a Fisher's Exact test was run on the fracture types and corresponding rib site resulting from two-handed CPR only (n=73). Table 6 shows the statistical description of the fracture types occurring on each rib section. The results from the Fisher's Exact test show there is a significant difference between the type of fracture and the location on the rib where it occurred (p value= 0.0129). All fracture types were identified in the samples receiving two-handed CPR. However, avulsion fracture was only identified once, while the remaining types were identified more frequently. Buckle fractures were the most commonly occurring fracture type within the two-handed sample accounting for 37% of the fractures. The anterior region was the most common location for two-handed CPR fractures to occur accounting for nearly 95% of the fractures. Table 7 lists the Fisher Exact pairs and their corresponding p-values.

Finally, all the rib fractures observed from both CPR methods were analyzed (n=96). A contingency table is shown in Table 8 which lists the statistical description of the fracture types occurring on each rib section. The results from the Fisher's Exact test show there is a highly significant difference between the type of fracture and the site of where it occurred (p value= < 0.0001).

Table 6. Contingency Table: Piglets Two-Handed CPR Fractures. Categorized by fracture type and rib landmark.

Count Total % **Column %** Row %	Avulsion	Buckle	Oblique	Transverse	Indeterminate	Total
Anterior	**0** 0.00 **0.00** 0.00	**24** 32.88 **88.89** 34.78	**27** 36.99 **100.00** 39.13	**12** 16.44 **100.00** 17.39	**6** 8.22 **100.00** 8.70	**69** 94.52
Anterolateral	**0** 0.00 **0.00** 0.00	**3** 4.11 **11.11** 100.00	**0** 0.00 **0.00** 0.00	**0** 0.00 **0.00** 0.00	**0** 0.00 **0.00** 0.00	**3** 4.11
CCJ	**1** 1.37 **100.00** 100.00	**0** 0.00 **0.00** 0.00	**0** 0.00 **0.00** 0.00	**0** 0.00 **0.00** 0.00	**0** 0.00 **0.00** 0.00	**1** 1.37
Posterior	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00
Posterolateral	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00
Terminus	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00
Total	**1** 1.37	**27** 36.99	**27** 36.99	**12** 16.44	**6** 8.22	**73**

Table 7. Fisher Exact Pairs: Piglets Two-Handed CPR Factures. Fisher Exact pairs of fracture type and landmark from two-handed CPR methods and the corresponding p-value; bolded values are statistically significance; landmarks without fractures are not included

Fisher Exact Pairs	Anterior/Anterolateral	Anterior/CCJ	Anterolateral/CCJ
Avulsion	1.0000	***0.0143***	0.2500
Buckle	**0.0490**	1.0000	1.0000
Oblique	0.2870	1.0000	1.0000
Transverse	1.0000	1.0000	1.0000
Indeterminate	1.0000	1.0000	1.0000

Table 8. Contingency Table: Piglets One and Two-Handed CPR Fractures. Categorized by fracture type and rib landmark.

Count Total % **Column %** Row %	Avulsion	Buckle	Oblique	Transverse	Indeterminate	Total
Anterior	**0** 0.00 **0.00** 0.00	**28** 29.17 **90.32** 37.84	**27** 28.13 **100.00** 36.49	**12** 12.50 **100.00** 16.22	**7** 7.29 **100.00** 9.46	**74** 77.08
Anterolateral	**0** 0.00 **0.00** 0.00	**3** 3.13 **7.89** 100.00	**0** 0.00 **0.00** 0.00	**0** 0.00 **0.00** 0.00	**0** 0.00 **0.00** 0.00	**3** 3.13
CCJ	**19** 19.79 **100.00** 100.00	**0** 0.00 **0.00** 0.00	**0** 0.00 **0.00** 0.00	**0** 0.00 **0.00** 0.00	**0** 0.00 **0.00** 0.00	**19** 19.79
Posterior	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00
Posterolateral	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00
Terminus	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00
Total	**19** 19.79	**31** 32.29	**27** 28.13	**12** 12.5	**7** **7.29**	**96**

Of the six rib landmarks, only three sites were observed to have fractures including the CCJ, anterior, and anterolateral regions. The posterolateral, posterior, and terminus regions of the ribs were intact with the exception of artifact. All four of the fracture types were documented. Buckle fractures were most numerous accounting for 32% of all the fractures followed by oblique (28%), avulsion (20%), transverse (13%) and indeterminate (7%).

Avulsion fractures were exclusively observed only on the CCJ, and therefore have a highly significant difference from the anterior (p= 0.0000) and anterolateral (p=0.0006) regions. Buckle fractures cannot occur on the CCJ, so a highly significant correlation was observed when compared to the anterior (p= 0.0005) and anterolateral (p=0.0006) regions. Oblique fracture location is shown only to have a significant difference between the anterior and CCJ regions (p= 0.0011). There was no significance observed in the location of transverse or indeterminate fractures. Table 9 lists all Fisher Exact pairs and their corresponding p-values.

Table 9. Fisher Exact Pairs: Piglets One and Two-Handed CPR Fractures. Fisher Exact pairs of fracture type and landmark from both CPR methods and the corresponding p-value; bolded values are statistically significance; landmarks without fractures are not included.

Fisher Exact Pairs	Anterior/Anterolateral	Anterior/CCJ	Anterolateral/CCJ
Avulsion	1.0000	***0.0000***	***0.0006***
Buckle	0.0614	***0.0005***	***0.0006***
Oblique	0.5478	***0.0011***	1.0000
Transverse	1.0000	0.1171	1.0000
Indeterminate	1.0000	0.3377	1.0000

Harris County Infant Trauma Database

From the total sample of 574 individuals, 531 infants were documented as having received CPR. CPR technique is documented as either: one-hand only; two-hand only; both methods; method unknown. The purpose of this analysis is to interpret rib fractures as a result of CPR methods and abusive cases. Therefore, manner of death (MOD) and cause of death (COD) were used to remove cases that would skew this data. Fifty-two individuals were documented as having received one-handed CPR, 108 individuals received two-handed CPR, 246 individuals received both types of CPR, 125 individuals received an unknown method of CPR, and 46 individuals were documented as having a MOD as homicide. It is amongst these groups that analysis is conducted.

<u>One-Handed CPR Fracture Distribution</u>

Fifty-two individuals were documented as having received one-handed CPR. Three individuals were removed as the MOD was homicide. An additional individual was removed as the COD was 'multiple blunt force injuries' with an unknown MOD. Therefore, analysis was conducted on 48 individuals who are documented to have only received one-handed CPR. Eight of the 48 individuals (17%) were documented with observed rib fractures. A total of 33 fractures were documented within the sample. The average number of fractures per individual is 0.7. Figure 19 demonstrates the distribution of the number of fractures caused by one-handed CPR across the rib number and side of injury. Eighteen fractures occurred on the left side (55%) and 15 fractures occurred on right side (45%). There were no fractures observed on rib pairs 1, 9, 10, 11, or 12.

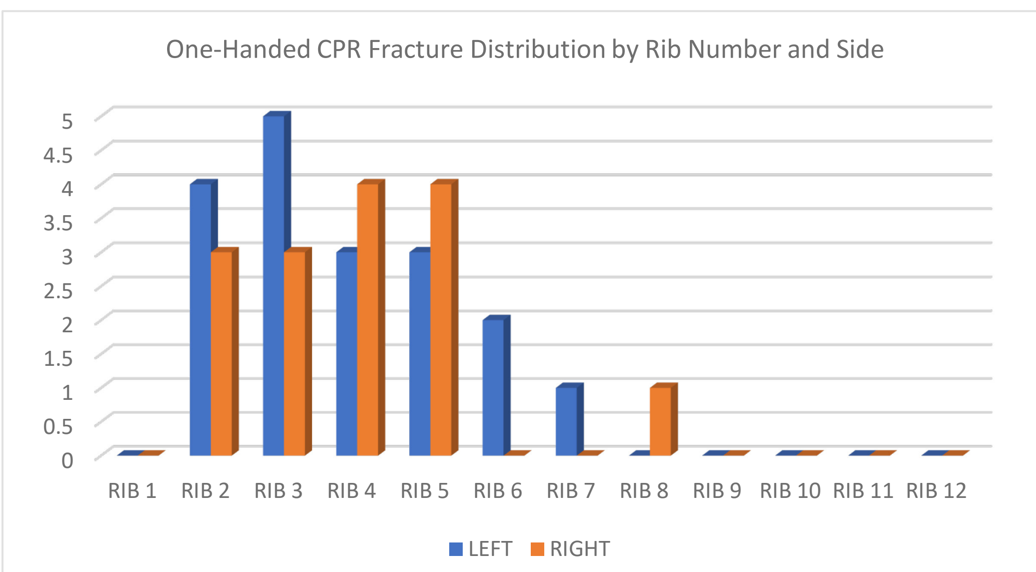


Figure 19. Distribution of Fractures: HCITDB One-Handed CPR.

Two-Handed CPR Fracture Distribution

One-hundred eight individuals were documented as having received only two-handed CPR. Fourteen samples were removed as the MOD was homicide. An additional 25 individuals were removed as the "cause of death category" was 'trauma' with an unknown COD. Therefore, analysis was conducted on 69 individuals who are documented to have only received two-handed CPR. A total of 200 fractures were documented. Twenty-eight of the 69 individuals (41%) were documented with observed rib fractures. The average number of fractures per individual is 2.9. Figure 20 demonstrates the distribution of the number of fractures caused by two-handed CPR across the rib number and side of injury. One-hundred seven fractures occurred on the left side (54%) and 93 fractures occurred on right side (46%). There were no fractures observed on rib pairs 11 or 12.

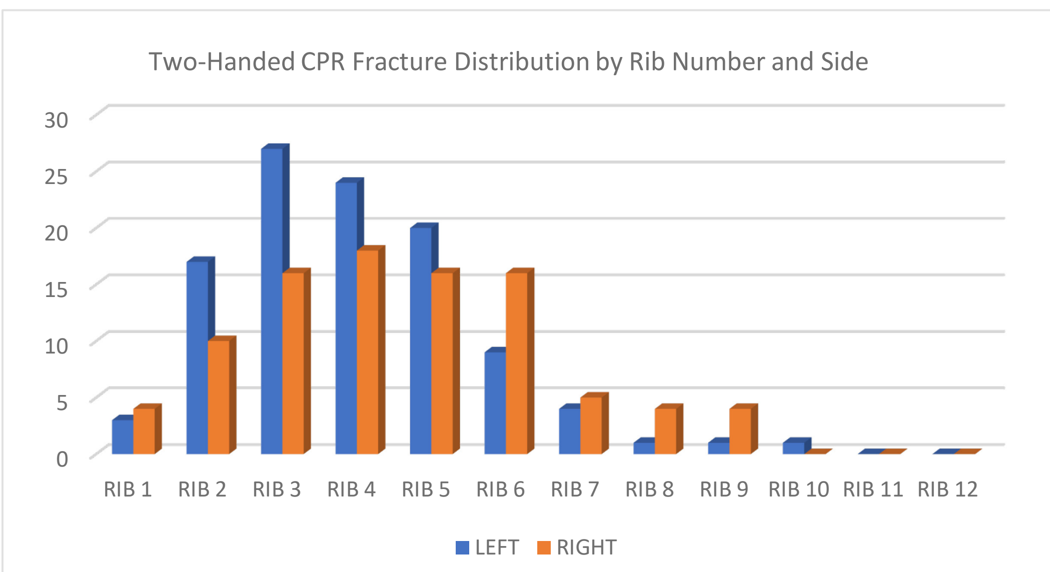


Figure 20. Distribution of Fractures: HCITDB Two-Handed CPR.

Both CPR Methods Fracture Distribution

Three-hundred and seventy-one individuals were documented as having received a variation of CPR methods. Of these infants, 246 received both one and two-handed CPR, and 125 received an undocumented method of CPR. Thirty-six individuals were removed from the sample for the following reasons: MOD of homicide (23); MOD of accident by motor-vehicle-accident; COD category as trauma with an unknown COD (2). Therefore, analysis was conducted on 335 individuals who are documented to have received a combination of infant CPR methods. The average number of fractures per individual is 3.6. One-hundred and fifty of the 335 individuals (45%) were documented to have a total of 1220 fractures. Figure 21 demonstrates the distribution of the number of fractures observed in individuals who received both one and two-handed CPR across the rib number and side of injury. Six-hundred and eighty-nine fractures occurred on the left side (56%) and 531 fractures occurred on right side (44%). Fractures were observed on all rib pairs.

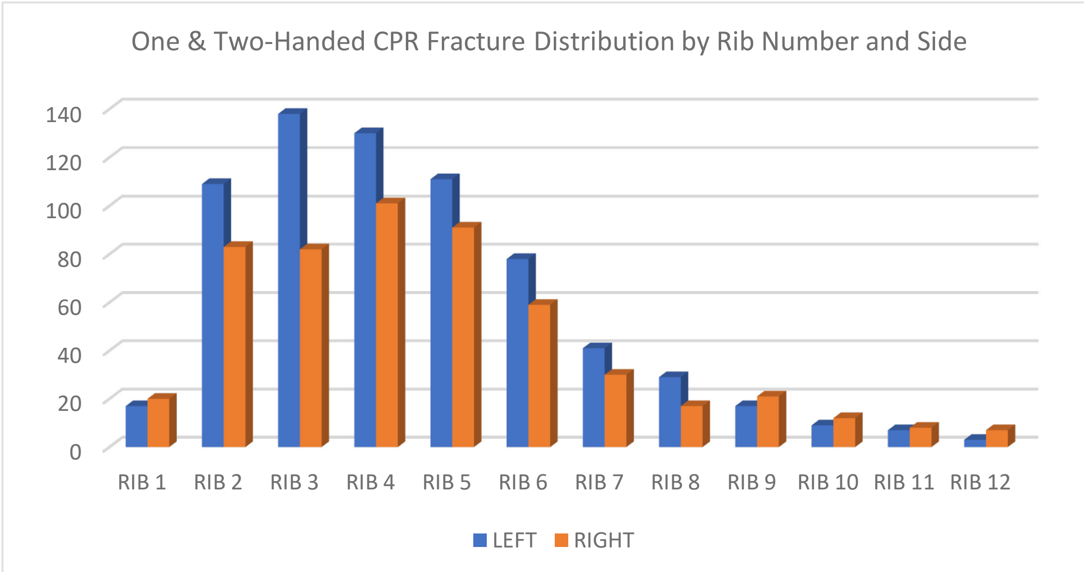


Figure 21. Distribution of Fractures: HCITDB One and Two-Handed CPR.

Comparisons of CPR Fractures

In order to determine if the number of resulting fractures differ from each method CPR, regardless of fracture type and location, a two-tailed, paired t-test was run on the total number of fractures observed for each known method. Individuals who received a combination of CPR methods or an unknown CPR method were not included. A statistical significance was found with a p-value= 0.0102 indicating the number of fractures occurring between each method differs from one another. A Wilcoxon test was also run to account for the outlying fractures skewing the normal distribution of the data. Statistical significance was also found with a p-value= <.0001.

Of the 531 individuals who were documented as having received CPR, 201 were documented as having received resuscitation from either only bystanders (n=56) or only medical personnel (N=145). The mean total fractures documented on individuals receiving CPR from bystanders is 1.02, while the mean total fractures documented on individuals receiving CPR from medical personnel is 3.11. A two-tailed, paired t-test was run on the total number of fractures observed for individuals who received CPR from a bystander versus from medical personnel. A statistical significance was found with a p-value= 0.0014.

The individuals with a documented age having receiving CPR (N=452) ranged from 0.03-11.93 months. The mean age of the infants is 3.87 months. Bivariate regression analysis was performed to determine if there was a relationship between the infant age and the number of fractures observed. A weak trend is noticed between increasing age and declining fractures with a statistically significant correlation (intercept= 5.26; correlation= -0.139). The impact of age on fractures is noted within the parameter estimates (age parameter estimate= -0.324), suggesting that for each month of age, fractures decline by approximately 0.3.

Homicide Rib Fracture Distribution

Forty-six individuals were documented as having a MOD as homicide. Forty of the individuals received CPR while six did not. Analysis was conducted on all 46 homicide victims. Twenty-two of the 46 individuals (48%) were documented with observed rib fractures. A total of 413 fractures were documented. The mean total number of fractures per individual is 8.98. Figure 22 demonstrates the distribution of the number of fractures in homicide victims by the rib number and side of injury. Two-hundred and two fractures occurred on the left side (49%) and 211 fractures occurred on right side (51%). Fractures were observed on all rib pairs.

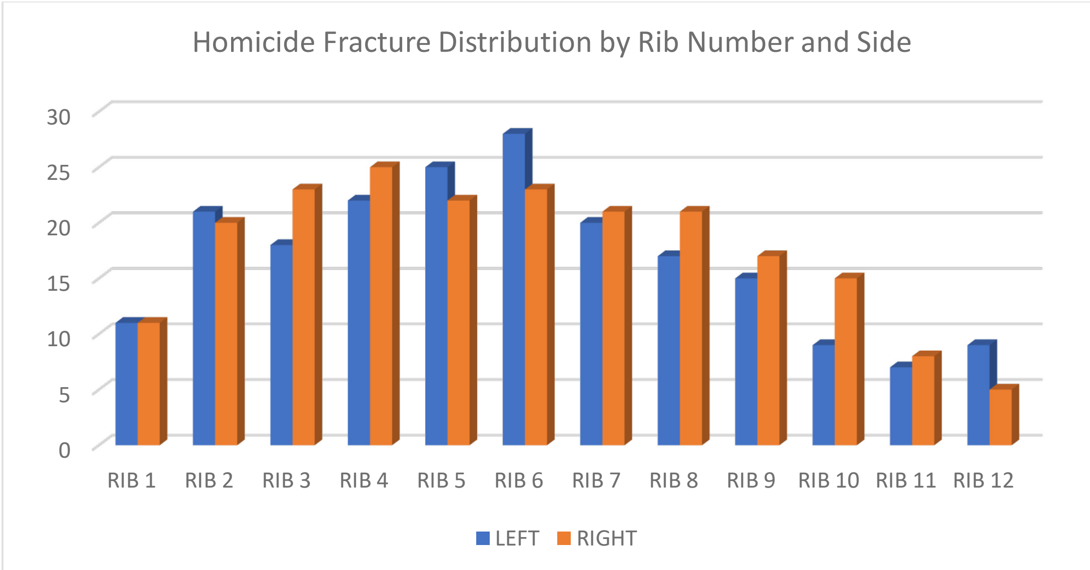


Figure 22. Distribution of Fractures: HCITDB MOD Homicide.

In order to determine if the number of resulting fractures differ between either method of CPR and those with a MOD as homicide, regardless of fracture type and location, a two-tailed, paired t-test was run on the total number of fractures observed in each group. A statistical significance was found with a resulting p-value= 0.0140.

CPR Rib Fracture Location & Type

Analysis of the fracture site and fracture type have been analyzed within and between each HCITDB group. Based on the resulting observations and some small cell sizes, a Fisher's Exact test was used to determine if there was significance between the type of fracture and the site of the fracture.

First, all the rib fractures observed from one-handed CPR methods were analyzed (n=48). A contingency table is shown in Table 10 which lists the statistical description of the fracture types occurring on each rib section. The results from the Fisher's Exact test shows no significant difference between the type of fracture and the site of where it occurred (p value= 0.3529).

Of the six rib landmarks, only two sites were observed to have fractures including the anterior and posterior regions. Only one fracture (3%) was observed on the posterior region, while nearly all the fractures were observed on the anterior region. Avulsion fractures were not documented. Buckle fractures were most numerous accounting for nearly 65% of all the fractures followed by transverse (32%), and oblique (3%).

Table 10. Contingency Table: HCITDB One-Handed CPR. Categorized by fracture type and rib landmark.

Count Total % **Column %** Row %	Avulsion	Buckle	Oblique	Transverse	Indeterminate	Total
Anterior	**0** 0.00 **-** 0.00	**22** 64.71 **100.00** 66.67	**1** 2.94 **100.00** 3.03	**10** 29.41 **90.91** 30.30	**0** **0.00** **-** **0.00**	**33** 97.06
Anterolateral	**0** 0.00 **-** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** **0.00** **-** -	**0** 0.00
CCJ	**0** 0.00 **-** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** **0.00** **-** -	**0** 0.00
Posterior	**0** 0.00 **-** 0.00	**0** 0.00 **0.00** 0.00	**0** 0.00 **0.00** 0.00	**1** 2.94 **9.09** 100.00	**0** 0.00 **-** 0.00	**1** 2.94
Posterolateral	**0** 0.00 **-** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **-** -	**0** 0.00
Terminus	**0** 0.00 **-** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **0.00** -	**0** 0.00 **-** -	**0** 0.00
Total	**0** 0.00	**22** 64.71	**1** 2.94	**11** 32.35	**0** 0.00	**34**

Secondly, all the rib fractures observed from two-handed CPR method was analyzed (n=69). A contingency table is shown in Table 11 which lists the statistical description of the fracture types occurring on each rib section. The results from the Fisher's Exact test show there is a highly significant difference between the type of fracture and the site of where it occurred (p value= 0.0001).

All six rib landmarks had observed fractures. All four of the fracture types were documented, including six indeterminate fractures. Transverse fractures were most numerous accounting for 51% of all the fractures followed by buckle (31%), avulsion (8.5%), oblique (6.5%), and indeterminate (3%). Two-handed CPR fractures are observed across the entirety of the rib and therefore the number of cells for calculations were extensive. The rib sections were compressed into three areas to find where the significant difference is between fracture type and landmark. The three sections are: anterior area (CCJ, anterior), lateral area (anterolateral and posterolateral) and posterior area (posterior and terminus). The majority of the fractures were observed on the anterior area (49.5%) followed by the posterior area (26%) and lateral area (24.5%). Table 12 lists the Fisher Exact pairs and their corresponding p-values.

Table 11. Contingency Table: HCITDB Two-Handed CPR. Categorized by fracture type and rib landmark.

Count Total % **Column %** Row %	Avulsion	Buckle	Oblique	Transverse	Indeterminate	Total
Anterior	**1** 0.50 **5.88** 1.14	**47** 23.50 **75.81** 53.41	**10** 5.00 **76.92** 11.36	**29** 14.50 **28.43** 32.95	**1** 0.50 **16.67** 1.14	**88** 44.00
Anterolateral	**1** 0.50 **5.88** 2.56	**13** 6.50 **20.97** 33.33	**0** 0.00 **0.00** 0.00	**21** 10.50 **20.59** 53.85	**4** 2.00 **66.67** 10.26	**39** 19.50
CCJ	**11** 5.50 **64.71** 100.00	**0** 0.00 **0.00** 0.00	**0** 0.00 **0.00** 0.00	**0** 0.00 **0.00** 0.00	**0** 0.00 **0.00** 0.00	**11** 5.50
Posterior	**4** 2.00 **23.53** 10.81	**0** 0.00 **0.00** 0.00	**1** 0.50 **7.69** 2.70	**32** 16.00 **31.37** 86.49	**0** 0.00 **0.00** 0.00	**37** 18.50
Posterolateral	**0** 0.00 **0.00** 0.00	**2** 1.00 **3.23** 20.00	**1** 0.50 **7.69** 10.00	**6** 3.00 **5.88** 60.00	**1** 0.50 **16.67** 10.00	**10** 5.00
Terminus	**0** 0.00 **0.00** 0.00	**0** 0.00 **0.00** 0.00	**1** 0.50 **7.69** 6.67	**14** 7.00 **13.73** 93.33	**0** 0.00 **0.00** 0.00	**15** 7.50
Total	**17** 8.50	**62** 31.00	**13** 6.50	**102** 51.00	**6** 3.00	**200**

Table 12. Fisher Exact Pairs: HCITDB Two-Handed CPR. Fisher Exact pairs of fracture type and landmark and the corresponding p-value; bolded values are statistically significance.

Fisher Exact Pairs	Anterior Area/ Lateral Area	Anterior Area/ Posterior Area	Lateral Area/ Posterior Area
Avulsion	0.0609	0.5793	0.3635
Buckle	0.0541	***0.0000***	***0.0000***
Oblique	0.1013	0.2200	1.0000
Transverse	***0.0037***	***0.0000***	***0.0003***
Indeterminate	***0.0154***	1.0000	***0.0241***

The final CPR method analyzed within the HCITDB is the individuals who received an unknown method or a combination of CPR methods (n=335). A contingency table is shown in Table 13 which lists the statistical description of the fracture types occurring on each rib section. The results from the Fisher's Exact test show there is a highly significant difference between the type of fracture and the site of where it occurred (p value= 0.0001).

All six rib landmarks had observed fractures. All four of the fracture types were documented. Transverse fractures were most numerous accounting for 49% of all the fractures followed by buckle (27%), avulsion (18%), indeterminate (4%) and oblique (2%). Combination CPR fractures are observed across the entirety of the rib and therefore the number of cells for calculations were extensive. Again, the rib sections were compressed into three areas to find where the significant difference are between fracture type and landmark. The three sections are: anterior area (CCJ, anterior), lateral area (anterolateral and posterolateral), and posterior area (posterior and terminus). The majority of the fractures were observed on the anterior area (55.6%) followed by the posterior area (22.7%) and lateral area (21.7%) almost equally. Table 14 lists the Fisher Exact pairs and their corresponding p-values.

Table 13. Contingency Table: HCITDB One and Two-Handed CPR Fractures. Categorized by fracture type and rib landmark.

Count Total % **Column %** Row %	Avulsion	Buckle	Oblique	Transverse	Indeterminate	Total
Anterior	**2** 0.16 **0.93** 0.35	**251** 20.57 **75.60** 44.35	**16** 1.31 **53.33** 2.83	**295** 24.18 **49.33** 52.12	**2** 0.16 **4.44** 0.35	**566** 46.39
Anterolateral	**2** 0.16 **0.93** 1.65	**64** 5.25 **19.28** 52.89	**7** 0.57 **23.33** 5.79	**34** 2.79 **5.69** 28.10	**14** 1.15 **31.11** 11.57	**121** 9.92
CCJ	**70** 5.74 **32.56** 62.50	**0** 0.00 **0.00** 0.00	**0** 0.00 **0.00** 0.00	**30** 2.46 **5.02** 26.79	**12** 0.98 **26.67** 10.71	**112** 9.18
Posterior	**68** 5.57 **31.63** 28.81	**2** 0.16 **0.60** 0.85	**4** 0.33 **13.33** 1.69	**161** 13.20 **26.92** 68.22	**1** 0.08 **2.22** 0.42	**236** 19.34
Posterolateral	**69** 5.66 **32.09** 47.92	**15** 1.23 **4.52** 10.42	**3** 0.25 **10.00** 2.08	**55** 4.51 **9.20** 38.19	**2** 0.16 **4.44** 1.39	**144** 11.80
Terminus	**4** 0.33 **1.86** 9.76	**0** 0.00 **0.00** 0.00	**23** 1.89 **3.85** 56.10	**14** 1.15 **31.11** 34.15	**0** 0.00 **0.00** 0.00	**41** 3.36
Total	**215** 17.62	**332** 27.21	**53** 4.34	**589** 48.28	**31** 2.55	**1220**

Table 14. Fisher Exact Pairs: HCITDB One and Two-Handed CPR Fractures. Fisher Exact pairs of fracture type and landmark and the corresponding p-value; bolded values are statistically significance.

Fisher Exact Pairs	Anterior Area/ Lateral Area	Anterior Area/ Posterior	Lateral Area/ Posterior
Avulsion	***0.0000***	***0.0000***	0.6277
Buckle	***0.0403***	0.0000	***0.0000***
Oblique	0.2683	***0.0000***	***0.0102***
Transverse	***0.0001***	***0.0004***	***0.0000***
Indeterminate	***0.0032***	***0.0337***	0.5761

Homicide Rib Fracture Location & Type

The final group of individuals analyzed from the HCITDB are those with a MOD documented as homicide (n=46). A contingency table is shown in Table 15 which lists the statistical description of the fracture types occurring on each rib section. The results from the Fisher's Exact test show there is a highly significant difference between the type of fracture and the site of where it occurred (p value= < 0.0001).

All six rib landmarks had observed fractures. All four of the fracture types were documented including indeterminate. Transverse fractures were the most numerous accounting for 57% of all the fractures followed by avulsion (18%), indeterminate (12%), buckle (11%) and oblique (2%). Homicide fractures are observed across the entirety of the rib, and therefore the number of cells for calculations were extensive. The rib sections were compressed into three areas to find where the significant difference is between fracture type and landmark. The three sections are: anterior area (CCJ, anterior), lateral area (anterolateral and posterolateral), and posterior area (posterior and terminus). The majority of the fractures were observed on the posterior area (42.2%) followed by the anterior area (40.7%) and lateral area (17.1%) Table 16 lists the Fisher Exact pairs and their corresponding p-values.

Table 15. Contingency Table: HCITDB Homicide. Categorized by fracture type and rib landmark.

Count Total % **Column %** Row %	Avulsion	Buckle	Oblique	Transverse	Indeterminate	Total
Anterior	**0** 0.00 **0.00** 0.00	**28** 6.75 **60.87** 34.15	**5** 1.20 **83.33** 6.10	**46** 11.08 **19.33** 56.10	**3** 0.72 **5.88** 3.66	**82** 19.76
Anterolateral	**0** 0.00 **0.00** 0.00	**10** 2.41 **21.74** 26.32	**0** 0.00 **0.00** 0.00	**23** 5.54 **9.66** 60.53	**5** 1.20 **9.80** 13.16	**38** 9.16
CCJ	**27** 6.51 **36.49** 31.03	**0** 0.00 **0.00** 0.00	**0** 0.00 **0.00** 0.00	**38** 9.16 **15.97** 43.68	**22** 5.30 **43.14** 25.29	**87** 20.96
Posterior	**42** 10.12 **56.76** 32.31	**7** 1.69 **15.22** 5.38	**0** 0.00 **0.00** 0.00	**80** 19.28 **33.61** 61.54	**1** 0.24 **1.96** 0.77	**130** 31.33
Posterolateral	**1** 0.24 **1.35** 3.03	**1** 0.24 **2.17** 3.03	**1** 0.24 **16.67** 3.03	**23** 5.54 **9.66** 69.70	**7** 1.69 **13.73** 21.21	**33** 7.95
Terminus	**4** 0.96 **5.41** 8,89	**0** 0.00 **0.00** 0.00	**0** 0.00 **0.00** 0.00	**28** 6.75 **11.76** 62.22	**13** 3.13 **25.49** 28.89	**45** 10.84
Total	**74** 17.83	**46** 11.08	**6** 1.45	**238** 57.35	**51** 12.29	**415**

Table 16. Fisher Exact Pairs: HCITDB Homicide. Fisher Exact pairs of fracture type and landmark and the corresponding p-value; bolded values are statistically significance.

Fisher Exact Pairs	Anterior Area/ Lateral Area	Anterior Area/ Posterior Area	Lateral Area/ Posterior
Avulsion	***0.0007***	***0.0246***	***0.0000***
Buckle	1.0000	***0.0001***	***0.0048***
Oblique	0.6730	***0.0278***	0.2886
Transverse	***0.0343***	***0.0298***	0.6661
Indeterminate	0.6976	0.0606	0.0606

CPR & Homicide Rib Fracture & Rib Number

Individuals are assumed to have 12 pairs of ribs. Between each CPR method, fractures were only observed between rib pairs 1-10. Homicide victims had rib fractures observed on all rib pairs. Table 17 and Figure 23 illustrates the relation between the rib pairs and the observed fractures from both CPR methods and homicide. One-handed CPR fractures exhibits a plateau distribution of fractures between ribs 2-5, while two-handed CPR fractures exhibits a positive skewed distribution of fractures peaking between ribs 2 and 3. The distribution of rib fractures observed on homicide victims creates an increasing stepped distribution and peaks on rib 6 before gradually decreasing.

Table 17. Rib Fractures Observed by Rib Number: HCITDB. Bolded values represent categorical majority.

Rib Pair	Total Fractures Observed	One-Hand Fractures Observed		Two-Hand Fractures Observed		Homicide Fractures Observed	
1	29	0	0%	7	24.1%	***22***	***75.9%***
2	75	7	9.3%	27	36.0%	***41***	***54.7%***
3	92	8	8.7%	***43***	***46.7%***	41	44.6%
4	96	7	7.3%	42	43.8%	***47***	***48.9%***
5	90	7	7.8%	36	40.0%	***47***	***52.2%***
6	78	2	2.5%	25	32.1%	***51***	***65.4%***
7	51	1	2.0%	9	17.6%	***41***	***80.4%***
8	44	1	2.3%	5	11.3%	***38***	***86.4%***
9	37	0	0%	5	13.5%	***32***	***86.5%***
10	25	0	0%	1	4.0%	***24***	***96.0%***
11	15	0	0%	0	0%	***15***	***100%***
12	14	0	0%	0	0%	***14***	***100%***

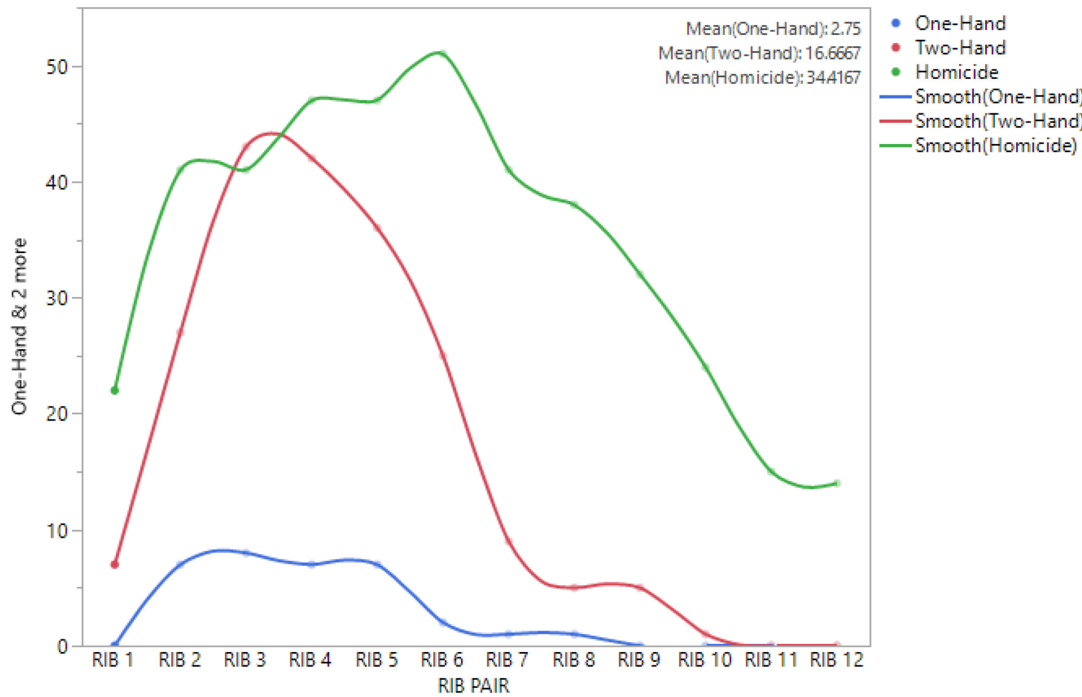


Figure 23. Distribution of Fractures: HCITDB CPR and Homicide.

V. DISCUSSION

The purpose of this research is to identify disparities between infant rib fractures secondary to CPR and abusive scenarios. In order to meet this objection, the following research questions are answered:

1.) Does two-handed infant CPR cause more rib fractures than one-handed infant CPR?
2.) Do rib fracture types and locations occur as a result of infant CPR methods?
3.) Are rib fracture patterns distinguishable between porcine surrogate samples and those documented within the Harris County Infant Trauma Database including non-abusive and abusive deaths?

Regarding question one, results from the porcine groups indicate that two-handed CPR causes statistically more rib fractures than one-handed CPR. Additionally, HCITDB groups show similar results. These results coincide with Reyes et al. (2011) and Love et al. (2013) findings who both report an increase of rib fractures. However, the overall rib fractures observed on the porcine samples are substantially higher when compared to those observed from the HCITDB. Within the HCITDB samples, 17% of infants had documented rib fractures resulting from one-handed CPR and 41% of infants had documented rib fractures resulting from two-handed CPR. The piglet samples showed 37% and 59% respectively to one-handed and two-handed CPR. Both piglet groups showed a similar increase (20% higher amongst one-handed and 18% higher amongst two-handed) in resulting rib fractures. When both groups of piglets were compared, 48.5% had observed fractures and within the combined CPR method group from HCITDB, 45% of all infants had documented rib fractures.

Possibilities for the high occurrence of rib fractures amongst the piglet sample could be related to inefficient sample size or bone integrity of the porcine. It was requested that the piglets die from natural, non-traumatic causes rather than euthanization. While each piglet was vetted for gross thoracic trauma prior to administering CPR, it cannot be ruled out that the bone integrity of the specimens was impaired. Opposingly, the HCITDB could be under representative. Removing ribs for maceration is invasive and time consuming and only performed when the fracture is observed or highly suspicious. Therefore, most ribs are left *in situ* and therefore fractures may go unidentified (Love and Sanchez 2009).

CPR fractures observed on rib pairs have similar distribution results in both the piglet and infant samples. Regardless of the CPR method, the provider uses the same anatomical landmark to position hands on the infant. However, one-handed CPR fractures showed a narrower distribution of fractures compared to those who received two-handed CPR. It is not supported by literature, but it is theorized that when using two-hands to perform compressions, the thumb pads create a larger surface area, thus creating a wider range of trauma.

While rib fractures did not show correlation with weight in the piglet sample, a trend, although weak, was noted amongst the HCITDB infants indicating that the number of documented fractures decrease slightly as the age increases. There are a few interpretations for this correlation. First, there is a wide amount of variance amongst the sample resulting in a weak slope. Additionally, the sample is not evenly distributed with a larger sample of infants under four months.

Question two explores both the location and the type of fracture occurrence. The piglet samples had observable fractures only to the anterior portion of the rib (CCJ, anterior and anterolateral) while the posterior regions remained intact in both methods of CPR. The HCITDB one-handed CPR fractures were observed 97% of the time on the anterior region of the ribs. There is a strong similarity between the porcine and infant CPR fracture location observations which is supported by literature regrading CPR related rib fractures (Love et al. 2013; Franke 2014). The fracture types within each sample are predominately buckle fractures. However, CCJ fractures are not observed on any infants. This is most likely because these ribs were not removed for maceration and therefore were not visible.

The majority of HCITDB two-handed fractures were observed on the anterior area of the rib which includes the CCJ and anterior segments (49.5%). While this is lower than the piglet samples, this may be reflective of the larger infant sample or additional fractures possibly not produced by CPR. The infants who received a combination of CPR methods was the largest sample and had a similar occurrence in anterior portion rib fractures accounting for 55.57%. Additionally, buckle fractures were statistically shown to be most commonly occurring on the anterior portion of the ribs. Literature citing infant rib fractures secondarily to CPR is supportive of this finding including the location and fracture type observed secondarily to CPR (Maguire et al. 2006; Weber et al. 2009; Maguire 2010; Love et al. 2013). Surprisingly was the high frequency of avulsion fractures documented across the rib body. Avulsion fractures are described as the process of a bone fragment being torn away from the bone, typically at a site of cartilage, ligaments or muscle attachments (Kleinman and Zito 1984). Therefore, it is expected that avulsion fractures are most likely to occur on the CCJ or terminus regions (Love et al. 2011). To further analyze these fractures, it is suggested that casework bench notes and photo documentation be investigated.

Question three explores a highly contentious subject of differentiating between rib fractures caused by CPR or abuse. This research assumes that infants with a MOD listed as homicide to have rib fractures most representative of abusive scenarios. The findings were not unexpected as the abused sample show more than double the average number of rib fractures per infant when compared to the CPR samples. Additionally, a higher incidence of rib fractures is observed on the posterior regions (including the posterior and terminus segment) of the rib accounting for the majority of the observations (42.2%). Anterolateral fractures are least associated with abusive trauma (Love et al. 2011) which was observed within the HCITDB. Lateral rib fractures were observed least (17.1%) when compared to anterior (40.7%) and posterior regions (42.2%). Nearly all homicide victims are documented as having received CPR, which may have caused additional anterior fractures. Additionally, the healing process of the fractures was not taken into consideration. For these reasons, a skewed depiction of abusive related fractures may be represented. Bench notes and photos of the fractures would be necessary for further analysis.

The distribution of the fractures amongst the rib pairs in homicide cases were increasingly more dispersed when compared to either CPR group. It is important to note, that fractures were not identified on ribs 11 or 12 within either CPR sample but were so amongst the homicide sample. The anatomical placement of these ribs seemingly protects them from trauma produced by CPR.

Most fracture types seen in homicide cases are transverse accounting for 42.2% of the total. Unexpectantly, the number of transverse fractures seen in the HCITDB two-handed CPR samples are also high, accounting for 51% of the fractures. It is suspected there is a bias toward transverse fractures within the database as pathologist and forensic anthropologist may have documented incomplete transverse fractures simply as transverse. However, unlike CPR samples, the homicide cases had the lowest representation of buckle fractures (11%), which have an increased correlation with anterior to posterior forces, specifically with those created during CPR (Love et al. 2013).

Limitations

As is the fact in most research studies, funding, time, sample size, and retrospective design proved to be limiting factors in this study. Based on funding, 34 piglets were afforded which is a small sample size for statistical analysis. The number of piglets used is assumed to be sufficient from which to identify correlating trends, but ideally, a larger sample size should be utilized (Blackburnea et al. 2016). Morally, this research cannot be performed on living samples. Additionally, using infant cadavers is not traditionally conducted, and therefore animal proxy is necessary to make inferences. While studies have shown similarities in composition between porcine and human bone, the overall morphology of the bone itself differs allowing for variation in fracture patterns (Baumer et al. 2001).

To ensure the porcine bone was most representative of an infant sample, piglets were requested to be under two-weeks of age at death and have died of natural causes (not euthanized). The smallest piglet weighed 643g (1.42lbs). This is exceptionally smaller than a newborn human baby. The weights of the infants within the HCITDB were not provided and comparison was not made. The resulting complications from the small piglets included maintaining precision while performing compressions as well as dissection difficulty. Artifact was created by the scalpel blade when removing the rib head from the articulate surface of the vertebra. Since the ribs were removed individually, it is suggested that when dissecting samples of this size, an *en bloc* method be utilized to ensure terminus integrity.

The rib fracture data regarding infants is limited to Harris County, Texas and may not be reflective of universal infant rib fractures. This is especially critical to the data representative of homicide victims. Socio-economic and societal models operate and interact simultaneously increasing and decreasing the changes of child abuse within a family (Klevens et al. 2018). Analysis of one Texas county may be skewed in its representation of infant abuse cases as a whole.

The HCITDB was not initiated until 2010; three years after the AHA initiated the infant CPR methodology change. The sample size for infants who received one-handed CPR is substantially smaller than that of the two-handed sample. Unlike the porcine group, it is impossible to associate all rib fractures observed within the HCITDB as exclusively secondary to therapeutic efforts. While MOD and COD was used to remove infants from that study who were thought to have rib fractures secondarily to accidental trauma, all causation cannot be fully accounted.

Rib fractures were not documented *in situ* and only fully analyzed after maceration. In retrospect, documenting the factures prior to dissection would have strengthened the comparison between CPR related fractures seen between the porcine groups and HCITDB. While all the porcine samples were analyzed without any soft tissue, Harris County pathologist and anthropologist would likely not remove ribs from the thorax unless highly suspicious of an abusive scenario. Fractures such as those to the CCJ would not be visible and therefore, remain undocumented (Love and Sanchez 2009).

Documented CPR associated rib fractures are naturally acute in nature, while fractures resulting from abuse can be both acute or in a process of healing. This research did not account for documentation of healed fractures. If the fracture is in advanced stages of healing, it is more likely to be categorized as indeterminate.

Future Research

Although this study is not without limitations, the results are useful for application in current trauma analysis as well as initiating future research. Similarly, to Love et al. (2013) findings while creating a classification system for infant rib fractures, the only fractures which could not be categorized from this study were those which would most accurately be described as incomplete transverse fractures. The complexity of fracture interpretation is reflective of the heterogeneous makeup of the bone, and therefore researchers are not consistent describing rib fractures. Love and Symes (2004) addressed the complexity of this topic as they explored the differences between incomplete and buckle fractures. While they define in detail the nature of a buckle fracture, incomplete transverse rib fractures arguably remain unclassified allowing for broad categorization. Galloway et al. (2014) labels incomplete, transverse fracture as greenstick fractures and sites them as being common on both ribs and on the long bones of children. Solan et al. (2002) uses the term buckle fracture and torus fracture interchangeably when describing injury to the outer cortex of the bone. This does not indicate that documentation is incorrect, but rather suggests further research is needed to create a definitive definition to create consistency when describing a rib fracture which is horizontally oriented with visible fractures on the both the pleural and cutaneous surfaces without complete separation.

It has been proposed that more CPR associated injuries occur when performed by medical professionals than when compared to bystanders (Betz and Liebhardt 1994; Franke et al. 2014). The argument is that bystanders may be afraid to cause greater injury to the child and therefore compressions are delivered with less force. Using the HCITDB documentation, when CPR was conducted by medical personnel exclusively compared to when administered by bystanders, a statistically significant increase in rib fractures were noted when being delivered by medically trained providers. It is suggested that further research to investigate this disparity and encourage detailed documentation of CPR methods and administrators.

VI. CONCLUSION

This research has demonstrated that methods of infant CPR are capable of producing rib fractures. While some researchers continue to discuss this as a matter of debate, those that recognize infant CPR fractures routinely describe them as "highly unlikely" or "rare" (Feldman and Brewer 1984; Bullock et al. 2000; Abel 2011; Franke et al. 2014). Literature goes so far as to describe infant rib fractures as "due to abuse unless proven otherwise" (Heldrich 2011). Without argument, all infant rib fractures should be handled as suspicious. Distinguishing therapeutic from abusive thorax trauma is an important component of the forensic autopsy. However, acute rib injuries can be difficult to view on radiograph and even during a skeletal examination (Cattaneo et al. 2006; Love and Sanchez 2009). Pathologist and anthropologist are less likely to remove ribs for analysis when there is no suspected abuse, and therefore, less likely to fully document all fractures. Alternatively, in suspected homicide cases, ribs are routinely removed for further examination and rib fracture documentation is more precise.

A valid argument is anticipated which would cite that if abusers are aware CPR can cause rib injuries, they will use this evidence as a legal defense. While the fractures with highest specificity for abuse are rib fractures, fractures are only the second most common presentation of child abuse following soft tissue bruising and burns (Feldman 1984; Maguire 2010; Abel 2011; Love et al. 2011; Leaman 2016). Therefore, it is suggested that rib fractures alone are not cause for child abuse. Skeletal injuries are often the strongest indicators of child abuse, but a single skeletal injury is rarely evidence for causation of death (Love and Sanchez 2009). Furthermore, as demonstrated within this research, exclusion of CPR as a cause of posterior region rib fractures in infants increases the diagnostic accuracy of abusive trauma.

The argument of this research is concerned with the delivery of quality CPR by both bystanders and medical personnel. The belief that rib fractures are only secondary to abuse may cause caregivers to become excessively cautious while administering compressions. Cardiopulmonary resuscitation is performed in extreme circumstances and currently, those that receive CPR have only between a 2-11% survival rate (American Heart Association 2015). Jeopardizing the quality of CPR will ultimately jeopardize the outcome of the infant.

Interpreting whether an injury is a result of child abuse or therapeutic intervention is a stressful and precarious situation. Cases may not present with obvious causes of injury, and therefore diagnostic evidence is crucial. The occurrence of rib fractures noted within this study contradict currently published research regarding infant CPR related rib fractures, and therefore, reinforce the need for continued research.

APPENDIX SECTION

APPENDIX A: PIGLET SAMPLE

PIGLET IDENTIFIER	WEIGHT (G)	PAIRED NUMBER OF RIBS	CPR METHOD
8/6/18 6	917	14	One-hand
8/6/18 7	643	15	
8/21/18 2	1468	14	
8/21/18 3	1591	15	
8/21/18 4	1984	14	
8/21/18 5	1156	14	
8/21/18 6	877	15	
8/21/18 8	1507	14	
8/21/18 13	1669	15	
8/21/18 14	1093	14	
8/21/18 17	931	14	
8/21/18 18	833	14	
8/21/18 19	1136	14	
8/21/18 20	1023	15	
2/12/19 4	1367	14	
2/12/19 5	1102	15	
Pilot	1170	15	Two-hand
8/6/18 1	1538	14	
8/6/18 2	1653	15	
8/6/18 3	1463	15	
8/6/18 4	1327	14	
8/6/18 5	1524	15	
8/21/18 1	968	14	
8/21/18 7	1442	15	
8/21/18 9	1236	15	
8/21/18 10	1607	15	
8/21/18 11	1078	14	
8/21/18 12	1756	15	
8/21/18 15	866	14	
8/21/18 16	908	14	
8/21/18 21	1465	15	
2/12/19 2	959	15	
2/12/19 3	1408	15	

APPENDIX B: PIGLET RIB FRACTURE OBSERVATIONS

PIG	CPR	LEFT RIBS	RIGHT RIBS
8/6/18 #2	2	None	RR2- Anterior buckle (pleural)
2/12/19 #2	2	None	None
8/6/18 #5	2	LR2- Anterior buckle (pleural) LR3- Anterior oblique (pleural and cutaneous) LR4- Anterior buckle (pleural) LR5- Anterior buckle (pleural) LR6- Anterior buckle (pleural) LR7- Anterior oblique (cutaneous)	RR2- Anterior indeterminate (pleural and cutaneous) RR3- Anterior indeterminate (pleural and cutaneous) RR4- Anterior buckle (pleural) RR5- Anterior buckle (pleural)
8/6/18 #1	2	LR3- Anterior indeterminate (pleural and cutaneous) LR4- Anterior transverse LR5- Anterior transverse LR6- Anterior oblique (pleural and cutaneous) LR7- Anterior oblique (pleural and cutaneous) LR8- Anterior oblique (cutaneous)	RR2- Anterior buckle (pleural) RR3- Anterior indeterminate (pleural and cutaneous) RR4- Anterior oblique (pleural and cutaneous) RR5- Anterior oblique (pleural and cutaneous) RR6- Anterior transverse RR7- Anterior oblique (pleural and cutaneous)
8/21/18 #1	2	LR2- Terminus artifact* LR4- Anterior buckle (pleural) LR5- Anterior oblique (pleural and cutaneous) LR6- Anterior buckle (pleural) LR7- Anterior buckle (pleural)	RR4- Anterior buckle (pleural) RR6- Anterior buckle (pleural) RR7- Anterior complete oblique RR8- Anterior oblique (cutaneous)
8/21/18 #7	2	LR5- CCJ partial avulsion LR6- Anterior indeterminate (pleural and cutaneous) LR7- Anterior oblique (pleural and cutaneous)	RR4- Anterior buckle (pleural) RR6- Anterolateral buckle (pleural) RR7- Anterolateral buckle (pleural) RR8- Anterolateral buckle (pleural)
8/21/18 #15	2	LR4- Anterior buckle (pleural) LR5- Anterior oblique (pleural and cutaneous) LR6- Anterior oblique (pleural and cutaneous) LR7- Anterior oblique (pleural and cutaneous) LR8- Anterior oblique complete	RR4- Anterior buckle (pleural) RR5- Anterior oblique (pleural and cutaneous) RR6- Anterior oblique (pleural and cutaneous) RR7- Anterior oblique (pleural and cutaneous) RR8- Anterior indeterminate (pleural and cutaneous) RR9- Anterior oblique complete

APPENDIX B, CONTINUED

PIG	CPR	LEFT RIBS	RIGHT RIBS
8/6/18 #4	2	LR2- Anterior buckle (pleural)	RR2- Anterior buckle (pleural) RR3- Anterior buckle (pleural)
8/21/18 #21	2	LR2- Terminus artifact* LR3- Terminus artifact*	None
Pilot	2	None	None
8/21/18 #16	2	None	None
8/6/18 #3	2	LR2- Anterior transverse LR3- Anterior transverse LR4- Anterior transverse	RR2- Anterior transverse RR3- Anterior transverse RR4- Anterior transverse
8/21/18 #12	2	LR4- Anterior oblique (pleural and cutaneous) LR6- Anterior oblique complete	RR4- Anterior buckle (pleural) RR6- Anterior oblique complete
8/21/18 #9	2	LR5- Anterior buckle (pleural) LR6- Anterior transverse LR7- Anterior buckle (pleural) LR8- Anterior oblique complete LR9- Anterior oblique complete LR10- Anterior transverse	RR5- Anterior buckle (pleural) RR6- Anterior transverse RR7- Anterior oblique complete RR8- Anterior oblique complete RR9- Anterior buckle (pleural)
8/21/18 #10	2	LR1- Terminus artifact* LR13- Terminus artifact* LR14- Terminus artifact*	None
8/21/18 #11	2	None	None
2/12/19 #3	2	None	None
8/21/18 #4	1	None	None
8/21/18 #14	1	None	None
8/6/18 #6	1	LR1- CCJ indeterminate LR4- CCJ partial avulsion (pleural)	RR2- Terminus artifact* RR3- Anterior indeterminate (pleural and cutaneous) RR4- Anterior buckle (pleural)
2/12/19 #4	1	LR3- Terminus artifact*	None
8/6/18 #7	1	None	None
8/21/18 #3	1	None	RR1- Abnormally shaped rib* RR6- CCJ avulsion
8/21/18 #20	1	None	None

APPENDIX B, CONTINUED

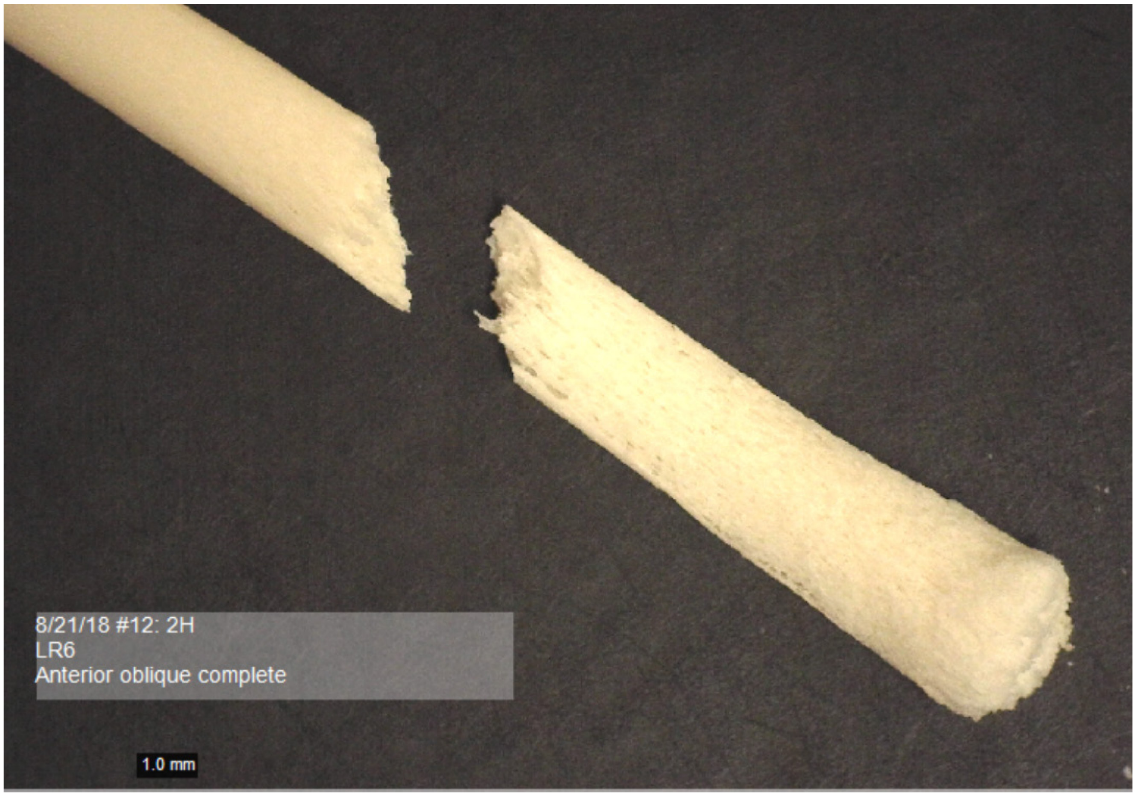
PIG	CPR	LEFT RIBS	RIGHT RIBS
8/21/18 #2	1	LR3- CCJ partial avulsion (pleural) LR4- CCJ partial avulsion (pleural) LR5- CCJ partial avulsion (pleural) LR6- CCJ partial avulsion (pleural) LR7- CCJ partial avulsion (pleural)	RR3- CCJ partial avulsion (pleural) RR4- CCJ partial avulsion (pleural) RR5- CCJ partial avulsion (pleural) RR6- CCJ partial avulsion (pleural)
8/21/18 #13	1	None	None
8/21/18 #18	1	LR1- Terminus artifact LR2- Terminus artifact LR3- Terminus artifact LR4- Terminus artifact	RR3- Terminus artifact* RR4- Terminus artifact* RR7- Terminus artifact*
8/21/18 #19	1	None	RR4- CCJ partial avulsion (pleural) RR5- CCJ partial avulsion (pleural)
8/21/18 #5	1	LR3- CCJ partial avulsion (pleural) LR4- CCJ partial avulsion (pleural) LR5- CCJ avulsion	RR2- CCJ avulsion RR3- CCJ partial avulsion
8/21/18 #6	1	LR1- Terminus artifact*	RR3- Anterior buckle (pleural) RR5- Anterior buckle (pleural) RR6- Anterior buckle (pleural)
8/21/18 #17	1	None	None
8/21/18 #8	1	None	None
2/12/19 #5	1	None	None

CPR 1	One-handed CPR method
CPR 2	Two-handed CPR method
LR	Left rib
RR	Right rib
( )	Side fracture is observation
*	Observation not included in analysis

APPENDIX C: OBSERVED AVULSION FRACTURE: PIGLET SAMPLE

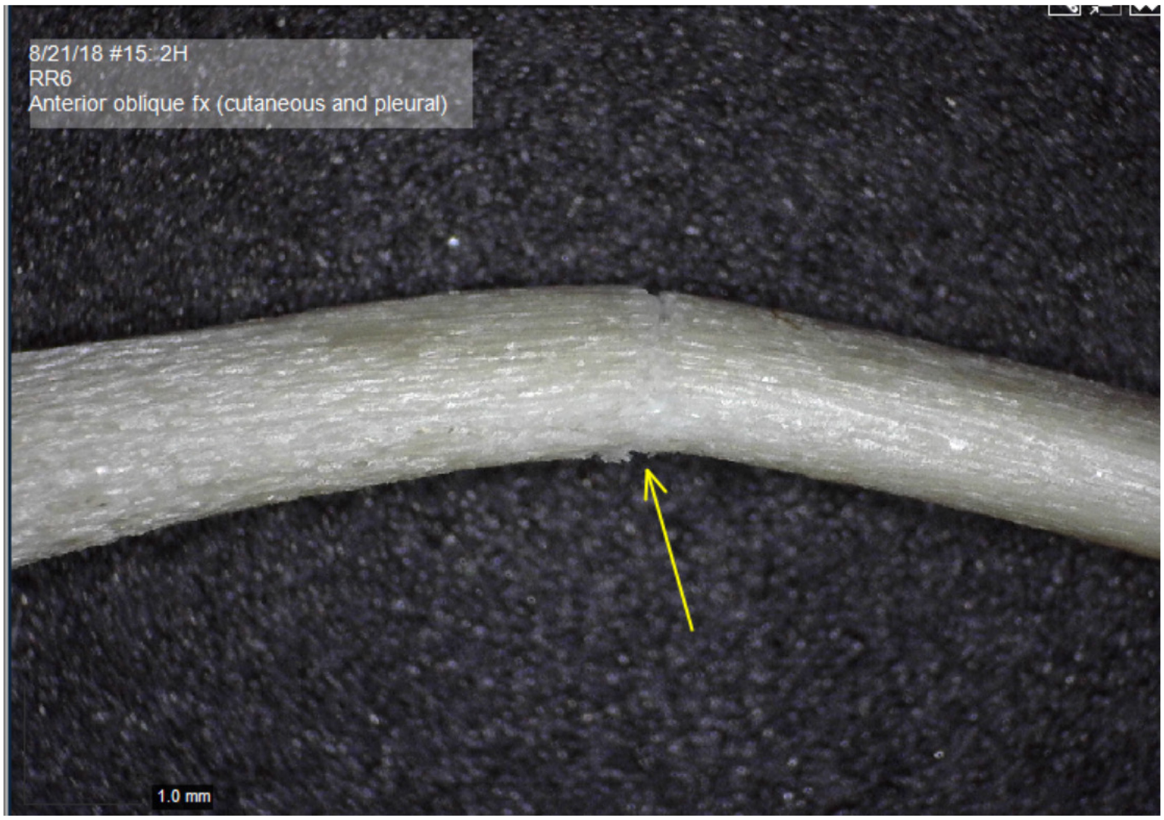
APPENDIX D: OBSERVED BUCKLE FRACTURE: PIGLET SAMPLE

APPENDIX E: OBSERVED OBLIQUE FRACTURE: PIGLET SAMPLE



APPENDIX F: OBSERVED TRANSVERSE FRACTURE: PIGLET SAMPLE

APPENDIX G: OBSERVED UNDETERMINED FRACTURE: PIGLET SAMPLE



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