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Significance of Rib Fractures Potentially Caused by Blunt-Impact Non-Lethal Weapons

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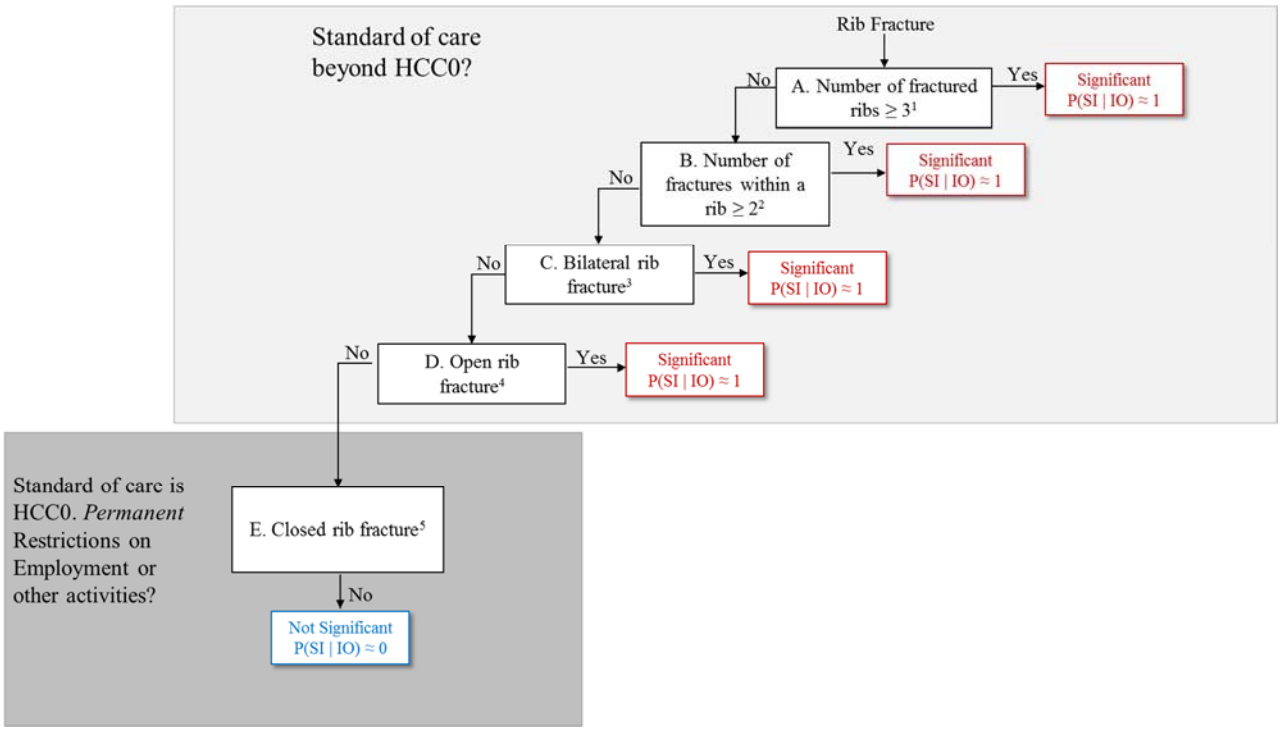
Executive Summary

Department of Defense Directive (DoDD) 3000.3E defines Non-Lethal Weapons (NLWs) as "weapons, devices, and munitions that are explicitly designed and primarily employed to incapacitate targeted personnel or material immediately, while minimizing fatalities, permanent injuries to personnel, and undesired damage to property in the target area or environment" (DoD 2013, 12). In addition, "NLWs are intended to have reversible effects on personnel and material" (DoD 2013, 12).

This document considers effects from non-lethal blunt-impact munitions, such as rubber bullets and bean bags. Often employed in crowd dispersal, these munitions serve as a deterrent by inducing pain or muscle spasm at the site of impact of the affected individual. These weapons may induce rib fractures—the focus of this document.

During the Department of Defense (DoD) technology development acquisition process, developers compare the capabilities of novel NLW systems to requirements, including the key performance parameters (KPPs) and key system attributes (KSAs) discussed in capability documents (DoD 2015, B-24). Counter-personnel NLW requirements often include a KPP or KSA pertaining to RSI. The RSI metric estimates the reversibility of a system's effect on targeted personnel (DoD 2012, 14). During the development acquisition process, developers must quantify the NLW's total RSI (DoD 2012), demonstrating a RSI less than or equal to a numerical threshold value. DoD Instruction (DoDI) 3200.19 defines a significant injury as death, permanent injury, or injury that requires medical treatment with a Health Care Capability (HCC) index of 1 (HCC1) or higher (HCC1+) (DoD 2012, 14). A HCC index of 0 (HCC0) medical treatment requires "limited first-responder capability including self-aid, buddy-aid, and combat lifesaver skills" (DoD 2012, 13).

This study searched the literature to identify attributes of rib fractures that quantitatively, accurately, and precisely approximate the significance of the rib fracture type according to the definitions established in DoDI 3200.19 (DoD 2012) and consider how these predictive attributes can be estimated during the development acquisition phase for a novel blunt-impact NLW. The results of our analysis are illustrated in Figure ES-1 and are summarized in the findings and recommendations that follow.



Legend for Figure ES-1

[1] Lee et al. (1990, 689); Sirmali et al. (2003, 135); Karmy-Jones and Jurkovich (2004, 248); Sharma et al. (2008, 313); Shields et al. (2010, e117).

[2] U.S. Army Medical Department Center and School (n.d., 1-4).

[3] Easter (2001); Pressley et al. (2012); Chapman et al. (2016).

[4] Lafferty et al. (2011, 102); Aetna (2016).

[5] Kerr-Valentic et al. (2003); Easter (2001); Middleton et al. (2003); Mayberry et al. (2009); Kouritas et al. 2013; Lube (2013); Fathi (2012)

Figure ES-1. Decision Flow Diagram:
Classifying Rib Fractures as Significant Based on Rib Fracture Type

Findings

- Most blunt-impact trauma data are derived from motor vehicle accidents, falls, assaults, and industrial accidents which present different injury mechanisms than blunt NLWs. Our analysis considers all data regardless of mechanism of injury.
- The elderly are more vulnerable to rib fractures. Children are more vulnerable to intrathoracic injuries. Our analysis assumes equal vulnerability to blunt trauma injuries, regardless of age and/or pre-existing cardiac and/or pulmonary conditions.
- The medical literature does not study rib fractures in isolation. When rib fractures are reported, clinicians and medical researchers rarely capture data on rib fractures in isolation, and the data that do exist rarely indicate the characteristic of the fracture (e.g., transverse, oblique, overriding, and so forth), how many fractures within one rib, location within the rib, or which rib. This

challenged our study's ability to quantify the likelihood and consequence of each injury and complication.

- The human thoracic region is complex, composed of different soft and hard tissues. This added complexity challenged the team to evaluate a broader set of injuries and potential complications (compared to prior IDA studies).
- Little is known about a rib fractures' contribution to chronic pain and long term disability (Gordy et al. 2014). Nor does the literature provide consistent association between fractures and chronic disability/pain.
- A study by Mayberry et al, concluded that patients with two or fewer fractures and no additional injuries and/or complications were able to return to work or usual activity sooner than patients with additional injuries and/or complications (Kerr-Valentic et al. 2003).

Recommendations

Based on our findings, our recommendations for NLW developers are as follows:

- Classify the following rib fracture types as significant because the medical treatment for the injuries or the complications have HCC1+ standards of care:
  - Three or more simultaneously fractured ribs, or
  - Two or more simultaneous fractures within one rib, or
  - Bilateral rib fracture, or
  - Open rib fracture.
- Classify the following rib fractures as not significant because the literature suggests HCC0 standard of care, with low likelihood of permanent disability:
  - Closed rib fracture with one or two simultaneously fractured ribs, and
  - Each rib only fractured once, and
  - Not a bilateral fracture and not an open fracture.
- For future study of permanent injury, promote investigation of metrics which evaluate blunt force impact effects on long term pain, mobility, and lung capacity. This includes the Mayberry group's effort to determine rib fracture attributes which predict long term disability (see Appendices A and B to this document).
- Investigate whether existing models, such as Advanced Total Body Model (ATBM) may predict two of the rib fracture classes we identify as significant, which include:
  - Three or more simultaneously fractured ribs and

– Bilateral rib fracture.

At present, we conclude that existing models have no capability to model the remaining *significant* rib fracture types:

- Two or more fractures in a single rib, and
- Open rib fracture.

Due to the ongoing need for experimental validation of the existing models, we recommend an optimization of future experiments to collect rib fracture prediction data and characterization of the fracture. Existing data (if x-rays were maintained) may support this purpose. This effort must predict the conditions under which multiple fractures in a single rib or in open rib fractures result. Given that experimentation to develop and validate the model is already necessary, additions to the testing should be made to gain understanding of the conditions that might cause the rib fracture attributes found to be significant in this report. In the event that multiple, bilateral, or open fractures are found to occur under expected weapon use conditions, a modeling capability with increased fidelity on fracture type should be pursued.

Contents

1. Introduction

A. Non-Lethal Weapons (NLWs)

Department of Defense Directive (DoDD) 3000.3E defines NLWs as "weapons, devices, and munitions that are explicitly designed and primarily employed to incapacitate targeted personnel or material immediately, while minimizing fatalities, permanent injuries to personnel, and undesired damage to property in the target area or environment" (DoD 2013, 12). In addition, "NLWs are intended to have reversible effects on personnel and material" (DoD 2013, 12).

Counter-personnel NLWs deliver many different types of stimuli. This document considers effects from non-lethal blunt-impact munitions, such as rubber bullets and bean bags. Often employed in crowd dispersal, these munitions serve as a deterrent by inducing pain or muscle spasm at the site of impact of the affected individual. These weapons may also induce rib fractures—the focus of this document.

B. Why Assess Rib Fracture Significance?

This document informs the Joint Non-Lethal Weapons Directorate (JNLWD) of the risk of significant injury (RSI) (see Section 1.C) from blunt-impact NLWs by categorizing the injuries that are associated with the weapons as either significant or not significant. Those injuries that are deemed significant may require the development of a predictive capability via modeling.

Previous analyses of field-use statistics of blunt-impact NLWs indicate that approximately half of reported injuries occur to the abdomen and chest regions, which is to be expected since most weapons call for targeting the torso. In addition, Kenny and Bovbjerg (2013) and Hubbs and Klinger (2004) report that the vast majority of injuries that occur are bruises and abrasions (57%–91% of reported injuries), and, less frequently, lacerations (6.2%–11.8%), fractures (1.5%–3.9%), and penetrations (1.7%–2%) occur. Analyses of case studies, which are, by nature, focused on the most severe injuries from blunt-impact NLWs, indicate that lung contusion (44 of 123 reports) and rib fracture (22 of 123 reports are predominant injuries (Rezende- Neto et al. 2009).

Rib fractures come in many forms which span the scale of severe and non-severe injuries. The JNLW tasked IDA to clarify the attributes that determine when a rib fracture constitutes a significant injury.

C. Risk of Significant Injury (RSI)

During the Department of Defense (DoD) technology development acquisition process, developers compare the capabilities of novel NLW systems to requirements, including the key performance parameters (KPPs) and key system attributes (KSAs) discussed in capability documents (DoD 2015, B-24). Counter-personnel NLW requirements often include a KPP or KSA pertaining to RSI. The RSI metric estimates the reversibility of a system's effect on targeted personnel (DoD 2012, 14). During the development acquisition process, developers must quantify the NLW's total RSI (DoD 2012), demonstrating a RSI less than or equal to a numerical threshold value.[1]

To estimate the RSI metric for a particular injury (e.g., rib fracture), one must first consider the term "significant." DoD Instruction (DoDI) 3200.19 defines[2] a significant injury as death, permanent injury, or injury that requires medical treatment with an HCC index of 1 (HCC1) or higher (HCC1+) (DoD 2012, 14), defined as follows:

- Permanent injury constitutes "physical damage to a person that permanently impairs physiological function and restricts the employment or other activities of that person for the rest of his or her life" (DoD 2012, 14).
- Medical treatment with an HCC index of 1 (HCC1) is defined as "first responder capability including resuscitation, stabilization, and emergency care" (DoD 2012, 13). Medical treatment with an HCC index of 2 (HCC2) is defined

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[1] The total RSI for an NLW system is the probability that, when used as intended, the system will cause *any* significant injury:

$$RSI_{tot} = P(any\ significant\ injury\ occurs).$$

Note, however, that an NLW system can cause more than one significant injury. For example, it may be possible that a rubber bullet could cause a shattered rib *and* a severe concussion. One can estimate the total RSI of the NLW system by aggregating the probabilities that the system causes each particular significant injury (Burgei et al. 2014). These injuries may be correlated with each other; therefore, statistical methods must be employed to aggregate the individual probabilities without double counting. Such statistical aggregation techniques are beyond the scope of this document.

Instead, this document focuses on estimating the probability that an NLW system causes a particular significant injury

$$RSI_{injury} = P(a\ particular\ significant\ injury),$$

regardless of whether any other significant injuries also occur. Specifically, this document focuses on estimating the probability that a non-lethal, blunt-impact munition causes a significant rib fracture

$$RSI_{rib\ fracture} = P(a\ significant\ rib\ fracture),$$

regardless of whether a significant concussion—or any other significant injury—also occurs. Therefore, throughout this document, we use the term RSI to mean RSI_{injury} (e.g., $RSI_{rib\ fracture}$), as opposed to the aggregated RSI_{tot}.

[2] DoDI 3200.19 explicitly defines "risk of significant injury" but not "significant injury." Therefore the definition of "significant injury" provided here is our extrapolation from DoDI 3200.19's definition of "risk of significant injury" (see DoD 2012, 14).

as "forward resuscitative and theater hospitalization capabilities including advanced emergency, surgical, and ancillary services" (DoD 2012, 13).

- In contrast, medical treatment with an HCC index of 0 (HCC0) falls below the threshold for significance. It is defined as "limited first-responder capability including self-aid, buddy-aid, and combat lifesaver skills" (DoD 2012, 13).

In summary, DoD classifies an injury as significant if the injury requires HCC1+ medical treatment and/or leads to permanent injury.[3]

One must use these definitions to estimate RSI for a given injury. A multi-step estimation process can be used (Burgei et al. 2014). The first step estimates *P*(*injury occurs*), the probability that an injury (e.g., rib fracture) occurs when using the NLW as intended. This metric is commonly estimated via modeling and simulation or cadaver experimentation. Another step estimates *P*(*injury is significant | injury occurred*), the probability that the injury (e.g., rib fracture) is significant, given that it occurred. The final RSI estimate is the product of these terms:

$$RSI = P(injury\ occurs) \times P(injury\ is\ significant \mid injury\ occurred),$$

where the *injury* represents any injury under investigation (e.g., rib fracture, concussion, tympanic membrane rupture, photothermal retinal lesion, etc.).

This document focuses on the second RSI quantity, *P*(*injury is significant | injury occurred*), with the first quantity, *P*(*injury occurs*), considered beyond the scope of this project.

Our framework considers multiple types of rib fractures. The RSI equation for the injury can then be rewritten as follows:

$$RSI = \sum_{all\ types} P\left(injury_{type}\ occurred\right) \times P\left(injury_{type}\ is\ significant \mid injury_{type}\ occurred\right).$$

This equation is true provided that the injury types are mutually exclusive and collectively exhaustive (MECE). The MECE caveat means that any instance of the injury (e.g., any instance of "rib fracture") must fit within one and only one pre-defined type (e.g., "three or more ribs fractured" vs. "one or two ribs fractured").

For example, consider the more general case in which the injury in question is binned into three MECE types. Then, the RSI equation for that particular injury can be written using six individual terms:

$$RSI = \left[P(injury_{type1}\ occurred) \times P\left(injury_{type1}\ is\ significant \mid injury_{type1}\ occurred\right)\right]$$

[3] In this document, we treat "death" as a subset of "permanent injury."

$$+ [P(injury_{type2}\ occurred) \times P(injury_{type2}\ is\ significant \mid injury_{type2}\ occurred)]$$
$$+ [P(injury_{type3}\ occurred) \times P(injury_{type3}\ is\ significant \mid injury_{type3}\ occurred)].$$

To simplify RSI estimation, we approximate $P(injury_{type}\ is\ significant \mid injury_{type}\ occurred)$ as either 1 or 0, based upon the definitions of "HCC" and "permanent injury" in DoDI 3200.19 (DoD 2012). Approximations are based upon literature review, showing which injury types do/don't require HCC1+ medical treatment or lead to permanent injury. Our previous work used this approach (Hirsch et al. 2015; King and Cazares 2015; and Cazares et al. 2016). The Naval Surface Warfare Center Dahlgren Division (NSWCDD) also employed the method (NSWCDD 2015).

To continue our previous example, consider the case in which the literature indicates that the injury in question can be binned into three MECE types and that

- The first type almost always requires HCC1+ medical treatment;
- The second type almost never requires HCC1+ medical treatment and almost never leads to permanent injury; and
- The third type almost always leads to permanent injury, regardless of the HCC level of medical treatment.

In such a case, we can approximate $P(injury_{type}\ is\ significant \mid injury_{type}\ occurred)$ as either 1 or 0 for each of the three types. In this way, we can approximate each type of injury as either significant or not significant, based on the definitions in DoDI 3200.19 (DoD 2012):

$$P(injury_{type1}\ is\ signficant \mid injury_{type1}\ occurred) \approx 1 \text{ (significant)},$$
$$P(injury_{type2}\ is\ signficant \mid injury_{type2}\ occurred) \approx 0 \text{ (not significant), and}$$
$$P(injury_{type3}\ is\ signficant \mid injury_{type3}\ occurred) \approx 1 \text{ (significant).}$$

Substituting these 1 and 0 approximations into the example RSI equation leads to the following:

$$\begin{aligned} RSI \approx\ & [P(injury_{type1}\ occurs) \times 1] \\ & + [P(injury_{type2}\ occurs) \times 0] \\ & + [P(injury_{type3}\ occurs) \times 1], \end{aligned}$$

which reduces to:

$$RSI \approx P(injury_{type1}\ occurs) + P(injury_{type3}\ occurs).$$

In this example, we reduced the RSI estimate to two quantities: probability that the first type of the injury occurs plus the probability that the third type of the injury occurs.

Developers need not waste resources considering the second injury, since that type was approximated as not significant.

To enable the framework previously described, the injury classification must comply with the following:

- Injury types are MECE to permit RSI equation summation over different types;
- Each type is based upon objective and quantifiable attributes to permit consistently binning into the same type;
- The significance of each type of the injury (given that it occurred) should approximate to either 1 or 0, reducing the RSI equation to a sum of the probabilities that injury types occur.

To predict the onset of injury and attributes like those listed above, the JNLWD seeks computational modelling approaches in lieu of empirical methods to avoid the constraints placed upon animal and human cadaver experimentation.

D. Objective

This study searched the relevant academic and medical literature to

- Identify physical attributes of rib fractures to consistently bin a rib fracture into a set of MECE types to quantitatively approximate each rib fracture type as either non-significant or significant according to the definitions established in DoDI 3200.19 (DoD 2012); and
- Consider how these attributes can be estimated during the development acquisition phase for a novel blunt-impact NLW.

E. Overview

In this document, we review the anatomy of the thoracic cage and blunt-impact injuries, including rib fractures and other potential injuries and complications. We summarize the literature's data on rib fractures and propose recommendations for approximating a rib fracture as significant or not significant, based on the definitions established in DoDI 3200.19. (DoD 2012). Finally, we review relevant modeling capabilities and conclude with our recommendations for how NLW developers might further develop computational modeling to estimate the likelihood of rib fracture for blunt-impact NLWs.

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2. Injuries and Complications of Blunt-Impact NLWs

A. Defining Injuries and Complications

Thoracic conditions described fall into two categories: injuries and complications. An injury is "damage, harm, or loss to a person, particularly as a result of external force" (Stedman 2012, 868). A complication is a "morbid process or event occurring during a disease [or injury] that is not an essential part of the disease [or injury], although it may result from it or from independent causes" (Stedman 2012, 375). We consider rib fracture a primary injury, and complications that may result from rib fracture as secondary (causal). We also consider other primary injuries and complications that are associated with blunt trauma because the literature does not often distinguish whether such injuries are caused by the rib fracture or the original insult. In Chapter 3, the distinction between "rib fracture" injuries and complications (those likely caused by the fracture itself) and "associated" co-injuries and co-complications is discussed.

B. Blunt-Impact NLW Injuries: Review of Field-Use Data and Medical Case Studies

As reported by Kramer, Macheret, and Teichman (2016), non-lethal blunt-impact weapons are currently used by U.S. law enforcement and corrections personnel, with many attempts to characterize injuries from field use. We leverage these studies to identify common thoracic injuries. Field-use data are constrained by officers' observations at the time of reporting, and lack medical sequelae such as lung contusion or pneumothorax that may take time to develop. We therefore supplement the field-use data with medical case studies to shed light on the more serious injuries.

Reported injuries include abrasions, lacerations, rib fractures, skull fractures, and heart and pulmonary contusions (Kobayashi and Mellen 2009; Pavier et al. 2015). Each part of the body responds differently to blunt impact, requiring tailored analyses to each region of interest (Pavier et al. 2015).

Two sources documenting the injuries from field use of blunt-impact NLWs are as follows:

- A 2013 study (Kenny and Bovbjerg) conducted by Penn State University and funded by the Joint Non-Lethal Weapons Program (JNLWP) focused on use-of-force records detailing 1,398 non-lethal blunt-impact weapon uses between 1995 and 2010, as maintained by the Los Angeles Sheriff's Department (LASD).

Weapons reported were Stinger (37 mm round containing 0.32 caliber rubber balls), flash-bang, Sting-ball grenades, and 12-gauge beanbag.

- A 2004 study (Hubbs and Klinger) conducted by the National Institutes of Justice (NIJ) analyzed case studies from 106 agencies nationwide after a targeted data call, resulting in 373 separate case reports during which 979 blunt-impact weapon munitions were fired. Weapons reported in these case reports were 37 mm plastic batons, 12-gauge bean-bag, 12-gauge "super-sock", and 40 mm "eXact iMpact™" rounds.

Injuries to the abdomen, chest, and back[4] made up between 45 and 66% of the reported injuries (compared to ~30% to extremities and up to 12% to the head face and neck). Hubbs and Klinger (2004) reported injury type and body part (Table 2-1). Of the thoracic injuries, 89% are bruises and abrasions, and 4% are fractures.

Table 2-1. Injuries to the Chest and Abdomen from Blunt-Impact NLWs

Injury Type	Injury Count	Percent
Bruise	227	60%
Abrasion	111	29%
Fracture	15	4%
Laceration	11	3%
Penetration	8	2%
Death	5	1%
Total	377	100%

Source: Hubbs and Klinger (2004).

To identify potentially overlooked injuries from field use, we turn to medical case studies such as that by Rezende-Neto et al. (2009), which summarize medical case studies of thoracic injuries from rubber and plastic bullets between 1972 and 2009. Out of 19 sources reporting 865 total cases, 123 cases reported injuries to the thoracic region (Table 2-2).

Case studies, which tend to focus on more severe injuries, indicate present lung contusion (44 of 123 reports) and rib fracture (22 of 123 reports) as predominant injuries (Rezende-Neto et al. (2009). Based on our own and prior analyses (Kenny and Bovbjerg 2013), we believe that lung contusion will be classified as a significant injury and therefore chose to focus on an injury that may or may not be significant to improve the fidelity of current RSI predictions.[5] We chose to focus this document on rib fractures and to identify the physical attributes of such fractures that can be used to determine the significance based

[4] The LASD dataset did not distinguish between chest and back impacts.

[5] In this report, we only consider lung contusion when it is a complication that *results* from rib fracture.

on several rib fracture types. For reasons of scoping, we do not include analysis of lacerations or penetrating injuries.

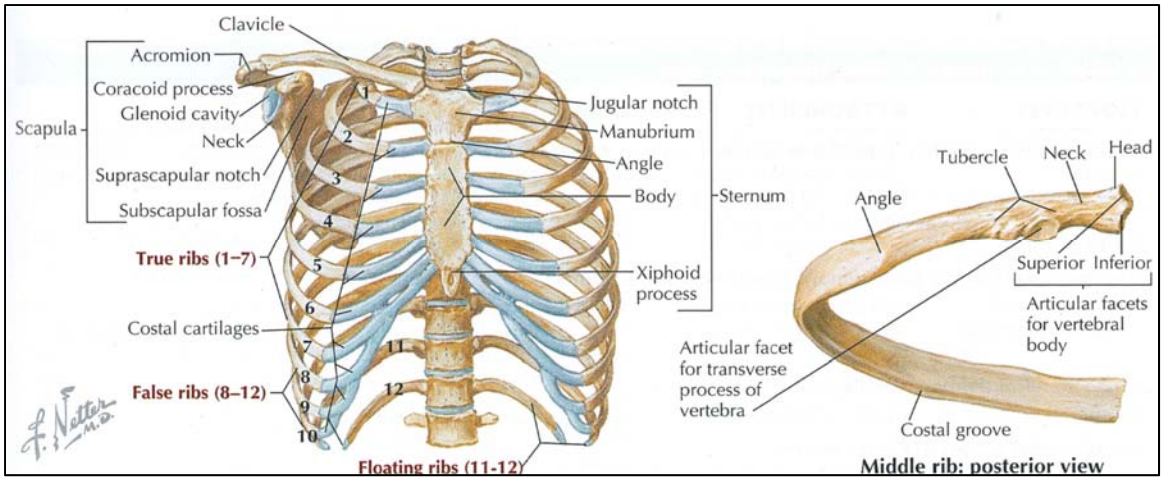
Table 2-2. Types and Numbers of Thoracic Injuries from 19 Sources of Case Studies Describing Thoracic Injury Due to Rubber and Plastic Bullets

Thoracic Injury	Number Out of 123 Reported Thoracic Injuries
Lung contusion	44
Rib fracture	22
Pneumothorax	16
Hemothorax	15
Heart laceration	7
Vascular injury	6
Lung laceration	5
Cardiac tamponade	2
Sternum fracture	1
Soft tissue injury	1
Scapula fracture	1
Myocardial contusion	1
Esophageal injury	1
Arterial embolization	1

Source: Adapted from information in Rezende-Neto et al. (2009, Table 1).

C. Thoracic Cage and Pulmonary Anatomy

The *thorax* occupies the region between the neck and abdomen. It contains several vital organs (Hansen 2014) inclding the heart and lungs as well as partially encased organs such as the liver and kidneys. These organs are protected by a portion of the axial skeleton known as the *thoracic cage* (see Figure 2-1). Twelve pairs of ribs, the *costal cartilages*, the sternum, and the thoracic vertebrae comprise the thoracic cage. The structures and organs of the thorax, such as the heart and lungs, are encircled and protected by the thoracic cage. Anteriorly, the ribs articulate (connect loosely to allow motion such as a joint) through the costal cartilages with the *sternum* (commonly known as the breastbone). Posteriorly, the ribs articulate with 12 corresponding vertebrae of the spine. The joints between the sternum, costal cartilages, and the ribs are fairly rigid due to the support of cartilage, ligaments, and muscles of the thoracic cage.



Source: Hansen (2014, 89).

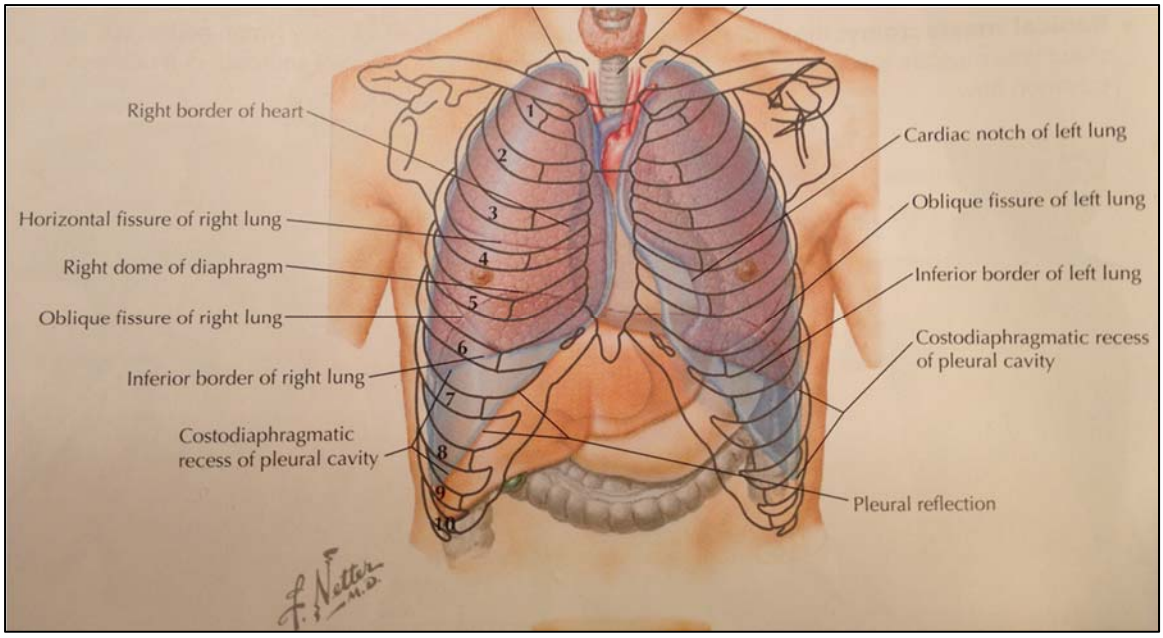
Note for Figure 2-1: Left: The bone structure of the thoracic cage showing the sternum, ribs, costal cartilage, and thoracic vertebrae. The ribs are numbered sequentially. Right: The structure of a single rib.

Figure 2-1. The Thoracic Cage

The 12 ribs are divided into 3 types. Starting at the top of the thoracic cage, the first seven ribs (ribs 1–7) are known as true ribs because they articulate directly with the sternum. Ribs 8 through 12 do not articulate with the sternum and are known as false ribs. Ribs 8, 9, and 10 articulate with the costal cartilage of the rib directly above, while ribs 11 and 12 do not articulate anteriorly and are known as floating ribs. All 12 pairs of ribs articulate with their corresponding vertebrae in the posterior portion of the thoracic cage.

The space containing the heart and the lungs, known as the *thoracic cavity*, is inside the thoracic cage. This cavity is further divided into three compartments called the *right pleural space*, the *left pleural space*, and the *mediastinum*. Each lung lies within the left and right pleural spaces and is enveloped by a membrane structure called the pleura (Hansen 2014, 100) (see Figure 2-2).

The mediastinum is the "middle" section of the chest cavity. The mediastinum contains all of the chest organs except the lungs. Organs located in the mediastinum include the heart, the aorta, the thymus gland, the chest portion of the trachea, the esophagus, lymph nodes, and important nerves (University of Southern California, n.d.). The left and right pleural cavities normally contain a small amount of fluid that serves to lubricate the surfaces to prevent friction during respiration. The heart and its great vessels (the venae cavae, pulmonary artery, pulmonary veins, and aorta) (Stedman 2012) occupy the space between the left and right pleural cavities in the mediastinum.



Source: Hansen (2014, 100).

Figure 2-2. Pleural Spaces and the Lungs

D. Blunt-Impact Injuries of the Thoracic Cage and Their HCC Level of Care

We separate thoracic blunt-impact injuries into four categories: bruises and abrasions, rib and sternum fractures, pulmonary injuries, and solid organ injuries. Below, we review each injury type and the associated HCC level of care. We expanded our literature survey beyond NLWs because there was so little literature pertaining specifically to NLW injuries. We found that most of our sources come from automotive accidents, which differ from NLW blunt impact use we address in Appendix D to this document. We also found that under such circumstances, multiple injuries are often co-occurring and that diagnostics and protocols for care are often agnostic to the relationship (causal or otherwise) between the different injuries.

1. Bruises and Abrasions

A bruise (also known as a contusion) results from damage to blood cells beneath the skin. Bruising often results from blunt-impact NLWs. The treatment protocol is known as the RICE (rest, ice, compression, elevation) method. We conclude that bruises require an HCC0 standard of care (Mayo Clinic 2017).

More severe impacts may produce a subcutaneous hematoma (a lump produced by the pooled blood), which often resolves without assistance. On rare occasion, a hematoma requires aspiration (draining). Further analysis is required to establish the attributes that determine a given hematoma's needed level of care (Mayo Clinic 2017). We found no

reports of NLW hematomas requiring surgical treatment, while noting these sources did not follow patients for multiple weeks (the time scale over which such a diagnosis would be made).

Abrasions result from superficial damage to the skin, typically classified as either level 1 (epidermal only) or level 2 (also involving the dermis). If all layers of the skin are removed due to the trauma, the injury is known as an avulsion. Level 1 and 2 abrasions must be cleaned, and topical antibiotics can be used to prevent infection and promote healing. (WebMD 2015a) which are HCC0 standards of care. Avulsions may require stiches or skin grafting which are HCC1+ standards of care, but these types of abrasions are never reported in NLW field use.

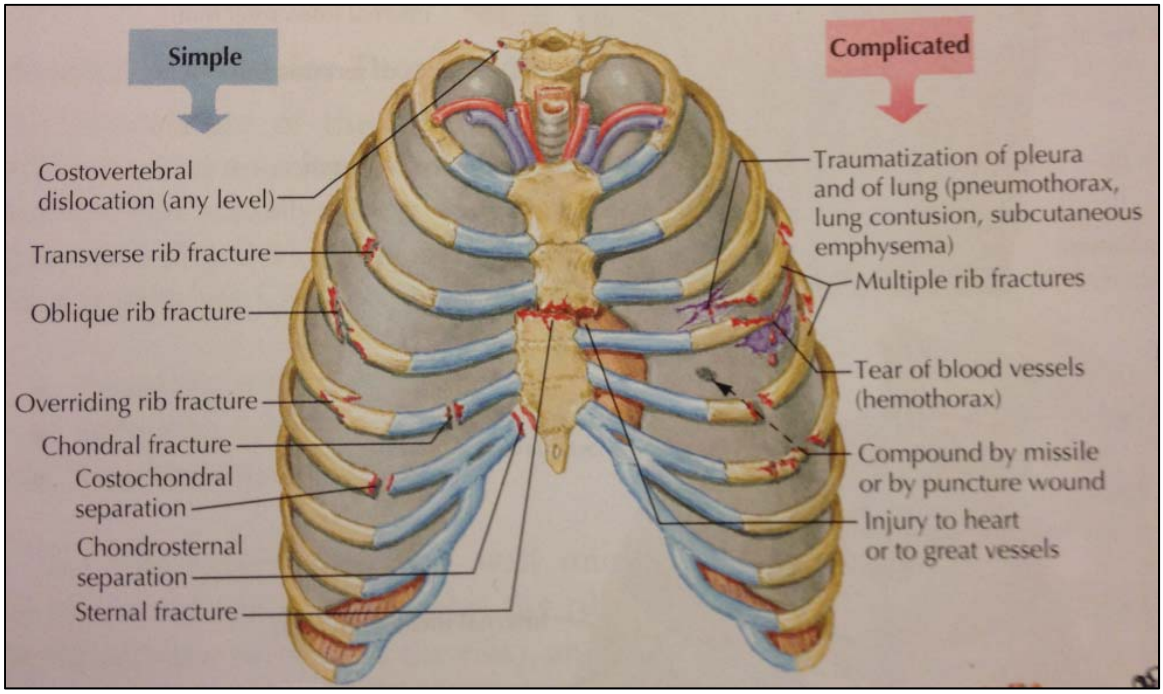
2. Rib and Sternum Fractures

Rib fractures are the most common chest trauma injuries reported by trauma centers (Sharma et al. 2008). Over two-thirds of patients who experience chest trauma suffer some kind of rib fracture. Rib fractures range from simple fractures, with a single rib fractured transversely or obliquely, to more complicated fractures (as defined in Hansen 2014; Figure 2-3, taken from Hansen, 2014). A transverse fracture describes a broken piece of bone at a right angle to the bone's axis. An oblique fracture describes a break with curved or sloped pattern (Hansen 2014; WebMD 2015b). A simple fracture, also known as a hairline fracture, is where there is no separation of the fragments (Stedman 2012, 738). If the ends of a fractured rib overlap each other, an overriding fracture results. The most common ribs fractured are ribs 3–10 (Hansen 2014, 92). Ribs 1, 2, 11, and 12 are more protected during a blunt force impact with less likelihood of injury (Hansen 2014, 92). Costal cartilage fractures and cartilage separation from the ribs or the sternum also occur. Sternal fractures[6] are also fairly simple injuries that can occur from anterior (front) thoracic trauma, including deceleration injuries resulting from motor vehicle accidents (Khorati, Rajakulasingam, and Shah 2013).

Simple rib fractures, also known as closed fractures, do not break through the skin. Most simple fractures are treated on an outpatient basis (Easter 2001; Middleton et al. 2003; Mayberry et al. 2009; Kouritas et al. 2013), with an HCC0 standard of care if over-the-counter (OTC) pain medicine is adequate for pain relief and respiration. Rib fractures are very painful since the mechanics of breathing expands and contracts the area around the injury, causing the fractured ends of the bones to rub against each other and against the nerve-rich surrounding tissue. A common marker for adequate management of rib fractures is the patient's respiration. The pain of a rib fracture can interfere with breathing and prevent adequate gas exchange in the lungs. Respiratory failure can result with the buildup of carbon dioxide in the peripheral blood and a decrease in oxygen tension (hypoxemia).

[6] Sternal fractures, although mentioned, are beyond the scope of this project.

Mechanical ventilation may become necessary if rib fracture pain prevents normal breathing (HCC1+). Studies indicate effective pain management produce positive outcomes from thoracic cage fractures (Jensen et al. 2016).



Source: Hansen (2014, 92).

Figure 2-3. Fractures of the Thoracic Cage

The HCC level required to treat rib injuries is often associated with the physical integrity of the rib cage (Easter 2001). The ribs and the thoracic cage provide attachment points for muscles that are involved in the respiration process (Vassilakopoulos 2012). Rib fractures can compromise support for respiratory muscles, disrupting respiratory mechanics. Simple single rib fractures that do not interfere with respiration can be treated conservatively with OTC pain medications and allowed to heal on their own (HCC0). However, if rib injuries damage the thoracic cage sufficiently such that the patient is unable to physically breathe on his or her own, mechanical ventilation and pain management treatments are required (HCC1+) to support healing. The clinician can monitor blood gases and lung capacity to determine level of care (Goldsworthy and Graham 2014). Spirometry[7] provides a common measure of lung capacity, which measures an individual's rate and volume of respired gases (Stedman 2012)

With more severe trauma, more complicated injuries may result. Multiple rib fractures can occur, and the number of fractured ribs correlates with *associated* co-injuries and

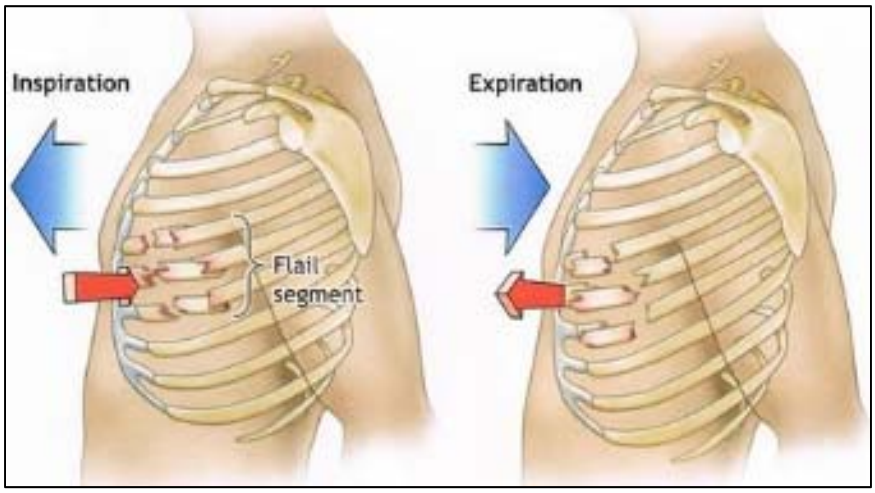
[7] Refer to Appendix C of this document under the subsection titled "Vital Capacity (VC)" for a detailed explanation of spirometry.

mortality with thoracic trauma patients (Sirmali et al. 2003; Flagel et al. 2005, Sharma et al. 2008; Al-Hassani et al. 2010; Karadayi et al. 2011).

Multiple rib fractures with two or more fractures on each rib, known as *flail chest*, can severely degrade the integrity of the chest wall, interfering with respiration. Flail or crushed chest has an anatomical and a clinical definition. Anatomically, it occurs when consecutive ribs are fractured such that a segment of the thoracic cage becomes detached from the rest of the cage (Dehghan et al. 2013). Detachment can occur when

- Three or more consecutive ribs are fractured in two or more locations,
- Three or more bilateral[8] consecutive ribs are fractured, or
- Three or more rib fractures are associated with a sternal fracture.

Clinically, flail chest is diagnosed when the detached segment of the rib cage leads to a weakening of the thoracic wall (Nirula et al. 2009). Flail chest can weaken the chest wall significantly so that when the patient inspires, the chest near the flail segment recedes due to negative intrathoracic pressure and when the patient expires, the segment protrudes (a condition known as *paradoxical respiration* (see Figure 2-4). Pulmonary *complications* of flail chest include decreased lung volume, pneumonia, and atelectasis (complete or partial collapse of a lung or lobe of a lung).



Source: National Association of Emergency Medical Technicians (NAMET) (2016, 342)

Figure 2-4. Flail Chest and Paradoxical Respiration

Management of flail chest is aimed at supporting the damaged thoracic wall, and the treatment requires hospitalization. A study based upon flail chest injury entries in the National Trauma Data Bank® (NTDB) shows that the vast majority of blunt trauma patients

[8] Occurring on both sides.

with flail chest (82%) had a mean Intensive Care Unit (ICU) stay of 11.7 days and that 59% of the flail chest patients required mechanical ventilation (Dehghan et al. 2013). Surgical stabilization is also being considered as a technique to manage flail chest (Nirula and Mayberry 2010). From these data, we conclude that flail chest management requires HCC1+ care.

3. Pulmonary Injuries

a. Pneumothorax

Pneumothorax occurs when air invades the pleural space (Harrison 2014), which is a membrane interface between the lungs and rib cage. In healthy patients, the pleural space is empty except for a small amount of lubricating fluid. The pressure is normally higher in the lungs, allowing the lungs to inflate fully. The sharp edges of a fractured rib can puncture the pleural membrane, allowing air to enter the pleural space. This increase in pleural space pressure interferes with normal respiration (Zarogoulidis et al. 2014). Pneumothorax result in hypoxia (low blood oxygen). In severe cases, a tension pneumothorax may lead to respiratory arrest, and eventual death, if untreated (Leigh-Smith and Harris 2005). Increasing amounts of air accumulate in the pleural space and, with inspiration, can cause the pleura to shift the mediastinal structures, constricting the great vessels of the heart leading to a possible fatal hypotension (i.e., low blood pressure).

Pneumothorax can result from rib fractures (Baumann and Noppen 2004). It is the second most common sign of traumatic chest injury (behind rib injury). Occurrences have been quoted in 30%–50% of chest trauma cases (Harrison 2014; Zarogoulidis et al. 2014).

Prehospital treatment guidelines recommend that any open chest wound be sealed with supplemental oxygen supplied, if necessary (National Association of Emergency Medical Technicians (NAMET) 2016, 344). Care should be taken with supplemental oxygen since it may increase the amount of air accumulating in the pleural space and worsen the condition. If a tension pneumothorax develops and immediate lifesaving techniques are required, a needle thoracostomy could be performed in a prehospital setting.

No recognized guidelines or standards are available for the management of pneumothorax (Harrison 2014). Generally, the patient is monitored by the clinician to determine whether invasive draining of trapped air is necessary. If surgical intervention is necessary, a chest drain or needle (thoracentesis) is inserted into the pleura cavity in the "safe triangle," which is located on the side of the patient and just under the armpit, to minimize any potential damage to structures (Fontaine and Page 2011). In the case of a tension pneumothorax, an immediate needle thoracentesis is performed in the second intercostal space, followed by an insertion of a chest drain. In practice, pneumothorax is nearly always treated by the insertion of a tube drain into the pleural spaces to drain the accumulated air (Fontaine

and Page 2011; Mowery et al. 2011; Broderick 2013) and, therefore, HCC1+ is the standard of care.

Clinical studies advocate for different pneumothorax management strategies (Knottenbelt and van der Spuy 1990; Yadav, Jalili, and Zehtabchi 2010; Kaneda et al. 2013). With complications that arise from thoracentesis (Bailey 2000) and rapid expansion of collapsed lungs, clinical studies are geared toward understanding which pneumothoraces can be managed conservatively (Harrison 2014). Several researchers are advocating a non-surgical, observational approach for those patients who have pneumothorax and are "clinically stable" and have less than 10% of their lung collapsed (Baumann and Noppen 2004; Sahota et al. 2016). It is possible in the future that treatment of pneumothoraces will be more conservative and surgery may be minimized and the standard of care may become HCC0 in the future.

b. Hemothorax

Hemothorax occurs when blood accumulates in the pleural spaces (Davies and Lee 2008; Boersma, Stigt, and Smit 2010). A patient's hematocrit value is used to diagnose a hemothorax. The hematocrit value is the percentage of fluid volume that contains red blood cells. If hematocrit values in the pleural space exceeds 50%, the effusion is considered a hemothorax (Broderick 2013, 93). A hemothorax is usually the result of chest trauma, such as rib fracture, that involves injury to blood vessels or lung tissue (Khandhar, Johnson, and Calhoon 2007). Misthos et al. (2004) and Plourde et al. (2014) found that blunt thoracic trauma that included at least one rib fracture is a significant risk factor for delayed hemothorax. Like pneumothorax, the treatment is also invasive (Broderick 2013). A chest tube is inserted into the pleura in the intercostal spaces to drain accumulated blood. Further surgical intervention may be required to repair blood vessels or lung tissue if blood continues to accumulate after initial drain (retained hemothorax). We conclude that a hemothorax requires HCC1+ level of care.

c. Lung contusion

Lung contusion, or pulmonary contusion, can arise from blunt impact damage of bony or cartilaginous structures in the thorax (e.g., a rib) which tears lung tissue (Cohn and DuBose 2010). The injury leads to delayed pathophysiological changes in the lung, hours after injury. These changes include bleeding, mucus, and edema (i.e., excessive fluid accumulation). The changes may produce shortness of breath, coughing, and pain. Hypoxia (i.e., deficiency in the amount of oxygen reaching the tissues) is the primary symptom to manage (Cohn and DuBose 2010; Pharaon, Marasco, and Mayberry 2015).

Prehospital care (National Association of Emergency Medical Technicians (NAMET) 2016, 342) involves the monitoring of peripheral blood gases by pulse oximetry (Culver

2012) and administration of supplemental oxygen. Depending on the severity of the contusion, mechanical ventilation or surgery may be required to treat the injury. Pulmonary toilet (i.e. cleaning pulmonary airways of excess fluids and obstructions) and fluid management are also important to keep airways clear. If respiratory distress occurs, intubation and mechanical ventilation become necessary. Treatment of a lung contusion injury should be considered HCC1+.

4. Solid Organ Injuries (SOIs)

a. Abdominal solid organ injuries (ASOIs): Liver, kidneys, and spleen

While generally regarded as organs of the abdomen, the liver, kidneys, and spleen are subject to injury from thoracic trauma (Sirmali et al. 2003; Sharma et al. 2008). These organs are placed close to the lower ribs. The incidence of ASOI associated with rib fracture is reported c.a. ~10%–16% (Rostas et al. 2016). While ASOI does not necessarily correlate with the number of fractured ribs (Swaid et al. 2015), it correlates with the pattern of breakage. Lower rib fractures (9–12) correlate with ASOI in thoracic trauma patients (Al-Hassani et al. 2010). Later studies indicate fractures in the middle and lower rib sections (ribs 5–12) are better predictors of ASOI (Rostas et al. 2016) than lower ribs alone. Individual rib fractures do not correlate with injury to a specific abdominal organ. For example, no repertoire of rib fractures predicts a liver injury over a spleen injury.

ASOI treatment depends on many medical indications (Schroeppel and Croce 2007). If hemodynamically stable[9], awake, and alert, the patient is generally discharged from a medical facility. If the patient is hemodynamically unstable, indicating abdominal bleeding, then surgical intervention (HCC 1+ care) is warranted. Alternatively, a patient with ASOI injuries who is diagnosed as hemodynamically stable via computed tomography (CT) scan is generally treated nonoperatively in a trauma center. We assume that nonoperative treatment in a trauma center is HCC1+ level of care.

b. Heart and thoracic vascular injuries

Blunt cardiac injury (BCI) is an infrequent but potentially fatal thoracic injury (Joseph et al. 2016). The prevailing clinical assessment is that rib injuries—in particular, first and second rib fractures—are markers for BCI and great vessel injuries. However, this idea remains controversial. Studies indicate that rib fractures are not good predictors of fatal BCI (Joseph et al. 2016). Thoracic vascular injuries have been found to be associated with rib fractures in thoracic trauma patients. However, not enough evidence is available to support the idea that rib fractures would be suitable markers for great vessel or other vascular injuries (Woodring et al. 1982; Sakellaridis et al. 2004). It is unclear from current

[9] A lack of bleeding or a normally functioning intact circulatory system (Ref: Stedman's).

data that a particular rib fracture could predict these injuries or if the rib fracture itself can cause BCI or great vessel injury. In the opinion of many clinicians, an assessment of thoracic vascular injury is not indicated for patients with first and second rib fractures alone. Other supporting information is needed for an indication of vascular injury (Gupta, Jamshidi, and Rubin 1997).

Blunt trauma cardiac injuries take many forms including cardiac rupture, cardiac valve injuries, pericardial abnormalities, and vascular injuries (El-Chami, Nicholson, and Helmy 2008). Cardiac rupture is usually fatal, while cardiac contusion are managed with ICU care or surgical intervention (Navid and Gleason 2008). Hemodynamically unstable patients with either cardiac or great vessel injury require immediate surgical intervention, while hemodynamically stable patients with similar injury may warrant ICU care and monitoring. There are no specific clinical trials defining a standard of care for these injuries. Even though there is a lack of current evidence that rib fractures cause BCI or great vessel injuries, future research may prove otherwise. Therefore, we will take a conservative approach and assume all rib-fracture-induced cardiac or great vessel injuries have an HCC1+ level of care.

E. Pulmonary Complications of Thoracic Trauma

The mechanism of respiration requires the concerted movement of the muscles and bony structures of the thoracic cage (Easter 2001). Blunt trauma to the thorax and rib fracture can disrupt this mechanism, reducing air flow into and out of the lungs. Rib fractures may decrease respiratory volume by causing pain and splinting,[10] contributing to atelectasis and pneumonia.

Inadequate respiration not only leads to insufficient gas exchange in the lung (Wagner 2012), but also prevents lung secretions, such as surfactants (Culver 2012), involved in gas exchange and mucus from circulating in and out of the lung. Pain discourages a patient from coughing these secretions out, and they become trapped in collapsed localized or extensive areas of the lung, which can lead to atelectasis. Retained secretions also promote microbe growth and can lead to the development of pneumonia (Easter 2001).

With rib fractures, pain management becomes crucial to dampen the development of pulmonary complications (Jensen et al. 2016). Generally, patients with three or fewer fractured ribs can manage pain with non-opioid analgesics (Jensen et al. 2016), which is an HCC0 standard of care. However, as the complexity of damage from blunt thoracic trauma increases, the use of opioids or more intrusive forms of pain management, such as nerve blocks, may be necessary. If pain persists and prevents the patient from breathing adequately, applying mechanical ventilation may be necessary to assist the patient's natural

[10] Stiffening of the thorax in response to the pain of the rib fracture. Splinting discourages taking full breaths.

breathing (Easter 2001). The use of opioids and nerve blocks for pain and mechanical ventilation for assistance with breathing are HCC1+ standards of care.

a. Pneumonia

Pneumonia is a condition of inflammation of the lung parenchyma (i.e., tissue) in which the alveolar sacs fill with fluid (Stedman 2012). Insufficient breathing and coughing caused by the pain of rib fracture may lead to mucus and fluid buildup within the airways. This buildup promotes microorganism growth, leading to infection. Bacterial pneumonial infections are treated with antibiotics (Rabbat and Huchon 2008a). Non-bacterial infections are treated with antiviral therapy or fungicides depending upon the infectious microbe (Rabbat and Huchon 2008b). Hospitalization is appropriate in severe cases requiring mechanical ventilation, chest pain or contusion (Rabbat and Huchon 2008a). Other indicators of severity include extremes in temperature (below 95°F or above 104°F), a respiratory rate greater than 30 breaths per minute, or low blood pressure (< 90/60 millimeters of mercury (mmHg)).

Because pneumonia is treated with prescription medication and may progress to the point of needing mechanical ventilation, we presume pneumonia requires HCC1+ standards of care.

b. Atelectasis

Atelectasis is a condition of the lung in which the airways and alveoli collapse, causing gases to be trapped inside the lung (Peroni and Boner 2000). Atelectasis occurs in areas of the lung that are usually undamaged. However, injuries such as thoracic trauma can cause airway obstruction or an increase in surface tension that cause the alveoli to collapse. Atelectasis can occur if rib fractures interfere with efficient breathing and coughing. Insufficient breathing and coughing can lead to accumulations of excess fluid and sputum. Obstructions in airways are not cleared efficiently through coughing.. Surfactants, which are fluids that reduce the surface tension within alveoli and allow their inflation under normal breathing conditions, can decrease, leading to lung collapse and atelectasis. If the condition is severe, respiration and gas exchange can become affected. Severe atelectasis is known as pulmonary collapse. Atelectasis is a common complication in blunt thoracic trauma (Shorr et al. 1987) and has been seen as a complication in rib fractures on the order of 3%–7% of the time (Sirmali et al. 2003; Plourde et al. 2014).

No specific, evidence-based protocol exists for the treatment of atelectasis (Schindler 2005). However, the most common treatment for less severe cases of atelectasis is chest physiotherapy (Peroni and Boner 2000)—specifically, the removal of mucus and sputum plugs by coughing or clapping the patient on the back. This treatment for atelectasis appears to be an HCC0. However, if rib fracture pain and damage prevent chest physiotherapy treatment, the application of pain management treatments can become necessary. Also,

invasive bronchoscopy[11] to find and clear sputum plugs in the nasal, tracheal, and bronchial passages as well as nasotracheal aspiration are common treatments of atelectasis due to rib fractures (Karadayi et al. 2011). Therefore, the treatment for atelectasis as a complication from rib fracture is considered HCC1+.

[11] Inspection of the interior of the tracheobronchial tree through a bronchoscope (Stedman 2012).

3. Assessing Rib Fracture Significance

In this chapter, we discuss methods to classify rib fractures into different types and then estimate whether $P(rib\ fracture_{type}\ is\ significant \mid rib\ fracture_{type}\ occurred)$, the probability that a rib fracture type is significant, given that it has occurred. We first discuss some of the challenges inherent with the available rib fracture data. We then evaluate rib fracture significance in light of these challenges.

A. Challenges in Estimating the Significance of Rib Fractures

Approximately 300,000 patients are treated annually in the United States for rib fractures (Shauib et al. 2014, 159), and the medical literature contains an abundance of rib fracture data. However, applying the reported data to our statistical framework described in the Introduction proved challenging for the following reasons:

- Most blunt-impact trauma data, including rib fracture data, are from motor vehicle accidents, falls, assaults, and industrial accidents (Sirmali et al. 2003, 135), which provide injury mechanisms that may differ from blunt-impact NLWs (i.e., low mass/high velocity vs. high mass/low velocity). For our analysis, we treated all data the same, regardless of mechanism of injury.
- Certain populations are more vulnerable to rib fractures than others, particularly the elderly (≥ 65 years of age) as a result of decreased bone density (Pressley et al. 2012, 911). Older patients with even a single fracture or those patients with cardiac and/or pulmonary conditions have greater susceptibility to complications than younger adults (Middleton et al. 2003, 30). Furthermore, children display greater vulnerability than adults to intrathoracic injuries via blunt trauma. Their chest walls are more pliant, which protects their ribs from fracture but allows for greater energy transfer to the intrathoracic organs and greater incidence of complications (hemothorax, pneumothorax, and lung contusion) (Sirmali et al. 2003, 136; Kessel et al. 2014, 834). This difference in vulnerability to rib fracture is a challenge because some data sets do not consider age and/or pre-existing conditions when reporting rib fracture data. For our analysis, we assume that every person is equally vulnerable to rib fractures, regardless of age and/or pre-existing cardiac and/or pulmonary conditions.
- When reporting rib fractures, clinicians and medical researchers rarely capture data on rib fractures in isolation, and the data that do exist rarely indicate the characteristic of the fracture (e.g., transverse, oblique, overriding, and so forth; see Figure 2-3), how many fractures within one rib, location within the rib, or

which rib. Investigating the mechanisms of rib fractures, their effects, and complications is not generally a concern in the medical literature since clinicians treat the patient as a whole system and not as a series of unrelated (or loosely related) subsystems (rib fractures, thoracic cage injuries, pulmonary injuries, organ injuries, and so forth). In Gordy et al., Dr. Morad Hameed eloquently states the data complexity: "Chest well trauma is an extremely heterogeneous clinical entity with many characteristics including multiple fractures, displacement, flail chest and thoracic deformity, underlying lung contusion and [other] associated injuries" (Gordy et al. 2014, 662).

Flagel et al. states, "the effect of fractured ribs on mortality and morbidity either independently or synergistically in conjunction with other injuries is difficult to determine" (Flagel et al. 2005, 717). Of rib fracture patients, "90% will have associated injuries, 50% will require operative and intensive care unit care, 33% will require discharge to an extended care facility, and 12% die before hospital discharge" (Chapman et al. 2016, 96). Patients can develop complications (e.g., pneumonia, respiratory failure, delayed hemothorax) (Easter 2001, 320; Shields et al. 2010, e119), and most patients who develop complications will do so within 2 weeks (Shields et al. 2010, e117). It is often difficult to determine whether these complications are caused by the rib fracture or by the blunt impact. We would like to assess rib fractures in isolation, without considering other injuries or complications or, at a minimum, only focus on those injuries or complications that are causal, but this type of assessment is not always possible. For our analysis, we break down the terms in our statistical framework to explicitly consider the likelihood and consequence of each potential injury or complication given that a particular rib fracture type occurs.

- This analysis encompasses potential injuries to many bodily structures, including the 24 ribs of the thoracic cage and internal organs. In addition, the human thoracic region is composed of a large number of different soft and hard tissues, each with its own properties. This complexity contrasts with our previous significant injury studies in which the biomechanical system was a small well-defined system with well-defined responses. The complexities for this study required the analysis of a broad set of injuries and potential complications.
- Finally, we found a near-total lack of standards for quantifying rib fracture as a permanent disability, despite recent reports indicating that long-term pain and disability are more likely than previously expected (see Appendix B). In the absence of such standards, we attempt to determine rib fracture severity significance by examining the potential of long-term effects of chronic pain.

Where necessary, due to insufficient data, we make assumptions from the medical literature to assess the significance of rib fractures and/or the significance of any causal

complications.[12] The following sections describe our results in the form of a statistical framework utilizing HCC standards of care and restrictions on life.

B. HCC Standard of Care to Treat Rib Fractures

As explained in the Introduction, one way we interpret DoDI 3200.19's definition of significant injury is one for which HCC1 or higher treatment is the standard of care (DoD 2012, 13).

In a previous project for JNLWD on blunt-impact RSI, Kenny and Bovbjerg (2013) state that the standard of care for a fracture is always HCC1+, regardless of the weapon causing the fracture or the location of the fracture of the body. We find this statement overly conservative since certain types of rib fractures have an HCC0[13] standard of care (Middleton et al. 2003, 2; Fathi 2012).

The following probability expressions are a review of information presented in the Introduction. The expression for the probability that a rib fracture type is significant, given that a rib fracture type occurred is as follows:

$$P(\textit{rib fracture}_{\textit{type}}\ \textit{is significant} \mid \textit{rib fracture}_{\textit{type}}\ \textit{occurred}).$$

We bin each rib $\text{fracture}_{\text{type}}$ as either 0 (non-significant) or 1 (significant).

We bin a rib $\text{fracture}_{\text{type}}$ as "0" (not significant) when the literature suggests that the standard of care for this type of rib fracture is only HCC0 and this type of rib fracture does not result in permanent injury that restricts employment or other activities for the rest of one's life. That is,

$$P(\textit{rib fracture}_{\textit{type}}\ \textit{is significant} \mid \textit{rib fracture}_{\textit{type}}\ \textit{occurred}) = 0.$$

However, we bin a rib $\text{fracture}_{\text{type}}$ as "1" (significant) when the literature indicates that the standard of care for this type of rib fracture is HCC1+ medical treatment or this type of rib fracture results in permanent injury. That is,

$$P(\textit{rib fracture}_{\textit{type}}\ \textit{is significant} \mid \textit{rib fracture}_{\textit{type}}\ \textit{occurred}) = 1.$$

---

[12] We refer to any thoracic condition (injury or complication) *caused* by a rib fracture as a "complication." We refer to any condition (injury or complication) resulting from blunt impact, but not necessarily from rib fracture, as an "associated injury."

[13] Patients with one rib fracture without any complications can be treated on an outpatient basis with non-steroidal anti-inflammatory drugs (NSAID). Since NSAIDs can be OTC drugs, we equate this treatment with HCC0 medical treatment defined as "self-aid, buddy aid, and combat lifesaver skills" (DoD 2012, 13).

Furthermore, $P(rib\ fracture_{type}\ is\ significant \mid rib\ fracture_{type}\ occurred)$ for a rib fracture$_{type}$ that includes any causal complication(s) is the product of two expressions that should be evaluated for significance independently:

$$P(rib\ fracture_{type}\ is\ significant \mid rib\ fracture_{type}\ occurred)$$
$$= P(complication\ is\ significant \mid complication\ occurred)$$
$$\times P(complication\ occurs \mid rib\ fracture_{type}\ occurred).$$

We systematically assess rib fracture type significance using HCC standards of care and visually depict this process in a decision flow diagram. Each rectangular box in the decision flow diagram is a rib fracture$_{type}$, and each rib fracture$_{type}$ is discussed in the context of this framework. The decision flow diagram is broken down into sequential steps, and each new step also includes all preceding steps to logically guide the reader through this framework. The decision flow diagram is presented in its entirety in the concluding chapter.

We begin our analysis by assessing the significance of "three or more simultaneously fractured ribs."

1. Three or More Simultaneously Fractured Ribs Is a Significant Injury

We propose that three or more simultaneously fractured ribs is a significant injury because of increased mortality and increased risk of causal complications that have an HCC1+ standard of care. See Figure 3-1.

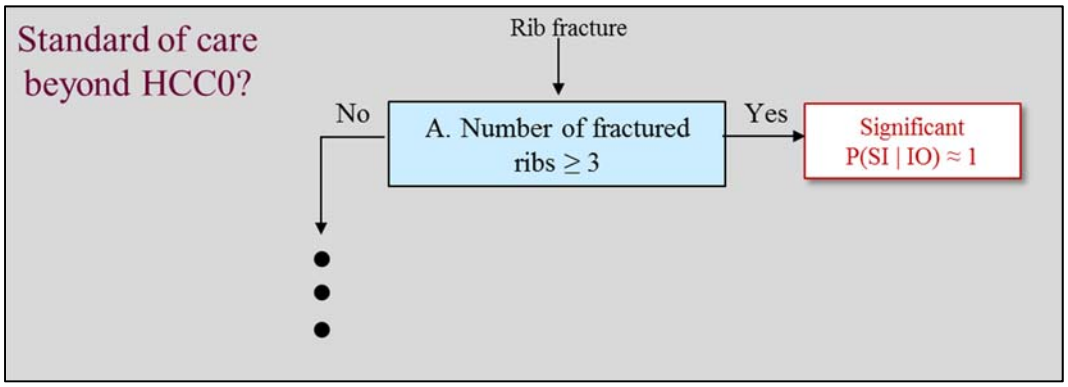


Figure 3-1. Decision Flow Diagram:
Three or More Simultaneously Fractured Ribs Is a Significant Injury

In the first rectangular box (labeled "A" and shaded blue) of the decision flow diagram (see Figure 3-1), we consider the HCC standard of care to treat three or more fractured ribs. To complicate matters, the terms "number of fractured ribs" and "number of rib fractures" are used interchangeably throughout the medical literature, often referring to the same data set (Lee et al. 1990, 690; Karmy-Jones and Jurkovich 2004, 248; Flagel et al. 2005, 719).

"Number of fractured ribs" means the number of ribs fractured out of a possible 24 ribs. "Number of rib fractures" could mean "number of fractured ribs," but it could also mean the "total number of fractures within all ribs." A closer examination of the data sources reveal that the research groups pull data from the NTDB using International Classification of Disease Codes, 9th revision (ICD-9) to identify patients with one or more *fractured* ribs (Lee et al. 1990, 689; Flagel et al. 2005, 718).[14] ICD-9 codes do not capture number of fractures within one rib or total number of rib fractures within all ribs, which further supports that "number of fractured ribs" is the intended statement. Furthermore, some researchers explicitly state that their analysis involves number of *fractured* ribs (Sirmali et al. 2003, 133). For our analysis, we will assume that papers that use either term mean "number of fractured ribs."

No specific statements in the medical literature indicate an HCC1+ standard of care for three or more fractured ribs in isolation. However, a comprehensive literature review in 2012 found that seven studies reported that patients with three or more fractured ribs faced a statistically significant increased likelihood of mortality, four studies indicated that patient mortality increased with an increase in "ribs fractured" (which we interpret as "number of fractured ribs"), and four studies found no correlation between number of fractured ribs and patient mortality (Battle, Hutchings, and Evans 2012, 11). We were unable to obtain the references cited in Battle that indicated no correlation between mortality and number of fractured ribs; however, based on the paper titles, the four studies focus on age. Battle, Hutchings, and Evans performed a meta-analysis of all available data and determined a correlation between three or more fractured ribs and increased mortality.[15] The odds of mortality for three or more fractured ribs is "[statistically] significantly higher when compared with patients with less than three rib[s] fracture[d]" (odds ratio 2.02 (1.89–2.15, 95% confidence interval); $p < 0.00001$) (Battle, Hutchings, and Evans 2012, 12–13).

We hypothesize that this increased mortality rate could result from increased complications. Patients with three or more fractured ribs have increased likelihood of splenic injury and liver injury (i.e., solid organ injuries), and three or more fractured ribs can be "a useful triage tool" for determining patients who should be transferred to a trauma center (Karmy-Jones and Jurkovich 2004, 248). This statement—"a useful triage tool"—can be traced back to a retrospective study done in 1990 by Lee and fellow clinicians and has been widely adopted as an indicator of serious injury (Lee et al. 1990, 689; Karmy-Jones and

---

[14] ICD-9 codes 807.00–807.19 classify rib fractures with the fifth number, indicating number of fractured ribs. For the fifth number, "0" indicates number of fractured ribs unspecified and "9" indicates multiple fractured ribs, but number of fractured ribs is unspecified (Lee et al. 1990, 690).

[15] A paper in 2013, a year after Battle, Hutchings, and Evans, states that overall trauma burden and age are better predictors than number of fractured ribs when determining outcome (Whitson et al. 2013, 140). Unfortunately, Whitson's analysis of data from the NTDB is presented in a way that is not helpful to our analysis (i.e., number of fractured ribs not specified).

Jurkovich 2004, 248; Sharma et al. 2008, 313). Another retrospective study by Sirmali et al. (2003), which does not cite Lee et al., recommends that patients with three or more fractured ribs should be hospitalized due to increased risk of flail chest and other pulmonary complications that are sometimes delayed (i.e., pneumothorax, hemothorax, pulmonary contusion, pneumonia, and atelectasis) (Sirmali et al. 2003, 135).

We can now write the following equation:

$$\begin{aligned} &P(\textit{rib fracture}_{\geq 3\ \textit{ribs}}\ \textit{is significant} \mid \textit{rib fracture}_{\geq 3\ \textit{ribs}}\ \textit{occurred}) \\ &\quad = P(\textit{complication is significant} \mid \textit{complication occurred}) \\ &\quad \times P(\textit{complication occurs} \mid \textit{rib fracture}_{\geq 3\ \textit{ribs}}\ \textit{occurred}), \end{aligned}$$

where "complication" can be solid organ injuries, flail chest, pneumothorax, hemothorax, pulmonary contusion, pneumonia, or atelectasis.

For the first term in the preceding equation, we know that the probability that the complication is significant given that the complication occurred is 1 because HCC1+ is the standard of care for each potential complication. Solid organ injuries, flail chest, pneumothorax, hemothorax, pulmonary contusion, pneumonia, and atelectasis are complications with an HCC1+ standard of care, as discussed in Chapter 2.

Therefore, we state that

$$P(\textit{complication is significant} \mid \textit{complication occurred}) = 1.$$

For the second term in the equation, we do not know the probability that a complication occurs, given that three or more fractured ribs occurred. The literature does not provide adequate detail to independently quantify the conditional likelihood of these complications. Therefore, we err on the side of caution and approximate this term as 1:

$$P(\textit{complication occurs} \mid \textit{rib fracture}_{\geq 3\ \textit{ribs}}\ \textit{occurred}) \approx 1.$$

Multiplying these terms together, we find that we can approximate the probability that three or more fractured ribs is significant, given that three or more fractured ribs occurred as follows:

$$P(\textit{rib fracture}_{\geq 3\ \textit{ribs}}\ \textit{is significant} \mid \textit{rib fracture}_{\geq 3\ \textit{ribs}}\ \textit{occurred}) = 1 \times (\approx 1) = \approx 1.$$

That is, we bin three or more fractured ribs as a significant injury.

2. Two or More Simultaneous Fractures within One Rib Is a Significant Injury

We propose that one or two simultaneously fractured ribs, with two or more simultaneous fractures within one rib is a significant injury because of the increased risk of causal complications that have an HCC1+ standard of care. See Figure 3-2.

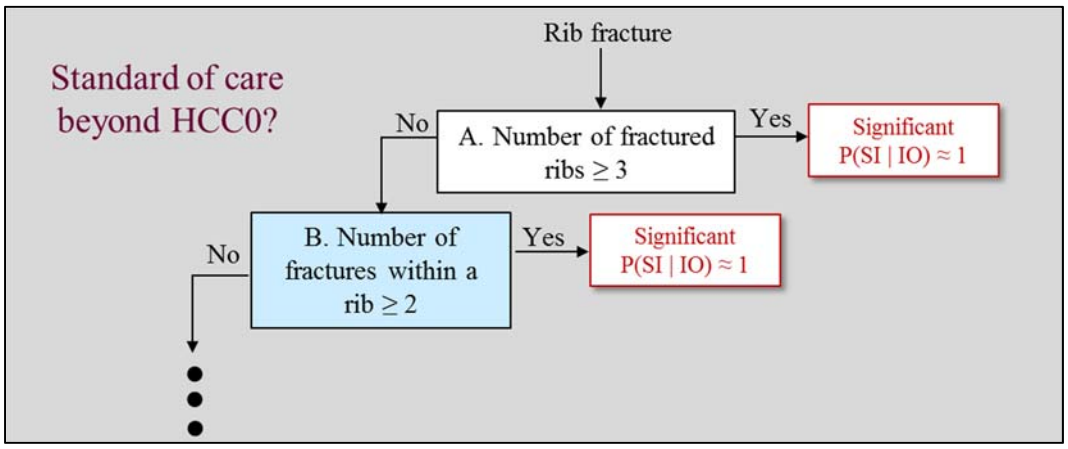


Figure 3-2. Decision Flow Diagram:
Two or More Fractures within One Rib Is a Significant Injury

In the second rectangular box (labeled "B" and shaded blue) of the decision flow diagram (see Figure 3-2), we consider the HCC standard of care to treat two or more simultaneous fractures within one rib. When fractures occur in two places within one rib, the segment of bone between the two fractures is called a floating rib. This floating rib could puncture an organ (e.g., the heart or lung) or a major blood vessel (e.g., the aorta) (U.S. Army Medical Department Center and School, n.d., 1–4) and lead to other pulmonary complications including, but not limited to, hemothorax, pneumothorax, and pulmonary contusion.

Therefore, P(rib fracture $\geq$ 2 fractures within one rib is significant | rib fracture $\geq$ 2 fractures within one rib occurred) is the product of two expressions and can be written as follows:

$$P(\textit{rib fracture}_{\geq 2 \textit{ fractures within one rib}} \textit{ is significant} \mid \textit{rib fracture}_{\geq 2 \textit{ fractures within one rib}} \textit{ occurred})$$
$$= P(\textit{complication is significant} \mid \textit{complication occurred})$$
$$\times P(\textit{complication occurred} \mid \textit{rib fracture}_{\geq 2 \textit{ fractures within one rib}} \textit{ occurred}).$$

HCC1+ treatments are the standard of care for damage to an organ, major vessel, hemothorax, pneumothorax, and pulmonary contusion, as discussed in Chapter 2. Therefore, the probability that a complication is significant, given that the complication occurred is 1:

$$P(\textit{complication is significant} \mid \textit{complication occurred}) = 1,$$

where "complication" is damage to an organ or vessel, hemothorax, pneumothorax, or pulmonary contusion.

The literature does not describe the probability of a complication occurring given two or more simultaneous fractures within one rib. In the absence of quantitative data, we err on the side of caution and approximate this term as 1:

$$P(\textit{complication occurred} \mid \textit{rib fracture}_{\geq 2 \text{ fractures within one rib}} \textit{ occurred}) \approx 1.$$

So,

$$P(\textit{rib fracture}_{\geq 2 \text{ fractures within one rib}} \textit{ is significant} \mid \textit{rib fracture}_{\geq 2 \text{ fractures within one rib}} \textit{ occurred}) = 1 \times (\approx 1) = \approx 1.$$

At this point in the decision flow diagram, three or more simultaneously fractured ribs is a significant injury (see Figure 3-1), and two or more simultaneous fractures within any one rib is also a significant injury (see Figure 3-2).

3. Bilateral Rib Fracture Is a Significant Injury

We propose that bilateral rib fracture is a significant injury due to potential chest wall destabilization and the increased risk of causal complications including pulmonary complications like respiratory failure and pneumonia, which will have HCC1+ standards of care. See Figure 3-3.

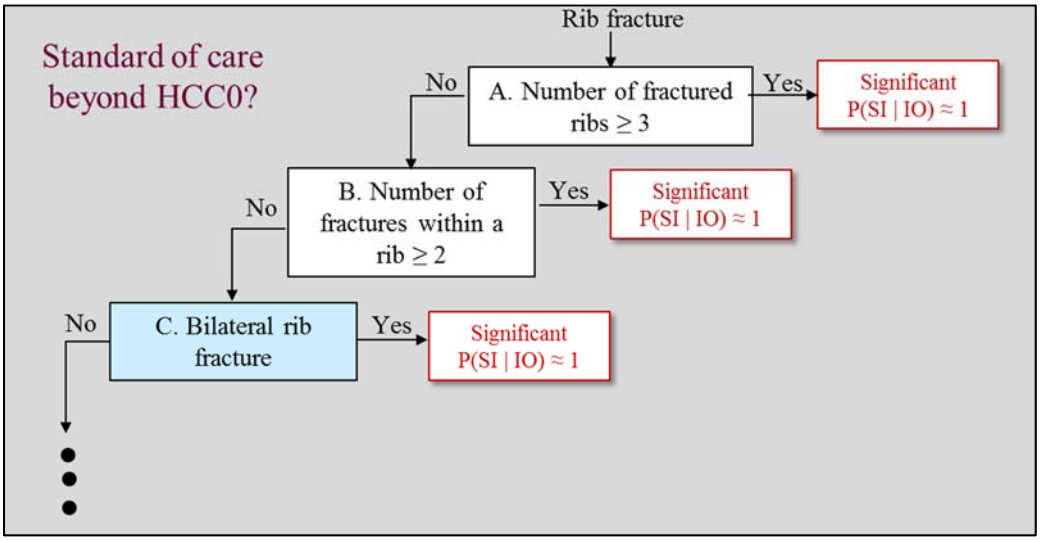


Figure 3-3. Decision Flow Diagram:
Bilateral Rib Fracture Is a Significant Injury

In the third rectangular box (labeled "C" and shaded blue) in the decision flow diagram (see Figure 3-3), we consider the HCC standard of care to treat bilateral rib fracture. We need to first define "bilateral fracture" since it is poorly defined in the medical literature (Easter 2001; Pressley et al. 2012; Chapman et al. 2016). Stedman's Medical Dictionary defines "bilateral" as "relating to, affecting, or having, two sides" (Stedman 2012, 209) but does not define the term "bilateral fracture." Chapman et al. (2016) and Pressley et al. (2012) do not define bilateral fracture, and Easter defines it as both "sides" (Easter 2001,

326). We interpret "bilateral rib fracture" as at least one fractured rib on each side of the thorax (right, left) with the sternum in between.

Bilateral fractures can result in chest wall destabilization and pulmonary complications. Several chest wall trauma scoring systems use bilateral fracture as a risk factor variable. These chest wall trauma scoring systems include the Rib Fracture Score (RFS), Organ Injury Scale (OIS) Chest Wall grade, Chapman et al.'s RibScore, and Pressley et al.'s Chest Wall Trauma Scoring System[16] (Easter 2001, 326; Chapman et al. 2016, 96). Chapman et al.'s RibScore and Pressley et al.'s Chest Wall Trauma Scoring System use bilateral fracture as one of the risk factors to predict pulmonary complications[17] (e.g., respiratory failure, pneumonia) in rib fracture patients (Chapman et al. 2016, 97). Bilateral fractures are associated with increased[18] morbidity and mortality (Pressley et al. 2012, 911; Chapman et al. 2016, 96). In the Chapman et al. and Pressley et al. studies, it is difficult to parse the individual contribution of bilateral fracture to risk of pulmonary complications since both studies use bilateral fracture in a point-scoring system that uses multiple factors to assess risk.

Therefore, $P(\textit{rib fracture}_{\textit{bilateral}}\ \textit{is significant} \mid \textit{rib fracture}_{\textit{bilateral}}\ \textit{occurred})$ is the product of two expressions and can be written as follows:

$$\begin{aligned} &P(\textit{rib fracture}_{\textit{bilateral}}\ \textit{is significant} \mid \textit{rib fracture}_{\textit{bilateral}}\ \textit{occurred}) \\ &\quad = P(\textit{complication is significant} \mid \textit{complication occurred}) \\ &\quad \times P(\textit{complication occurred} \mid \textit{rib fracture}_{\textit{bilateral}}\ \textit{occurred}). \end{aligned}$$

Both chest wall destabilization[19] (Dittmann et al. 1982) and pulmonary complications are significant because they have HCC1+ standards of care (see Chapter 2). Therefore,

$$P(\textit{complication is significant} \mid \textit{complication occurred}) = 1.$$

We do not know the probability that chest wall destabilization or pulmonary complications will occur, given that a bilateral fracture occurred. Chapman et al. describes the percentage of patients with bilateral fracture who also have respiratory failure (42.5%) or

---

16 Pressley et al.'s (2012) Chest Wall Trauma Scoring System is referred to as Chest Trauma Score (CTS) in Chapman et al. (2016, 96).

17 Chapman et al.'s RibScore factors include ≥ 6 ribs fractured, flail chest, bilateral fractures, first rib fracture, ≥ 3 displaced fractures, and one fracture in each of three anatomic areas (anterior, lateral, and posterior) (Chapman et al. 2016, 97). Pressley et al.'s Chest Wall Trauma scoring factors include age, pulmonary contusion, and number of ribs fractured to identify the risk of respiratory failure (Pressley et al. 2012, 911).

18 "Increased" morbidity and mortality is not quantified in the Chapman et al. (2016) or the Pressley et al. (2012) reports.

19 Chest wall destabilization is treated with surgery and possibly epidural pain medication, and both treatments are HCC1+ standards of care (Dittman 1982).

pneumonia (19.2%) (Chapman et al. 2016, 97). Unfortunately, this data set does not provide a way to determine whether these complications are a direct consequence of the bilateral fracture (causal). The data set includes patients with a bilateral fracture, but these patients may or may not have other risk factors contributing to an increased likelihood of chest wall destabilization or pulmonary complications, including ≥ 6 ribs fractured, flail chest, first rib fracture, ≥ 3 displaced fractures, and one fracture in each of three anatomic areas (anterior, lateral, and posterior) (Chapman et al. 2016, 97). In the absence of meaningful quantitative data, we err on the side of caution and approximate as 1:

$$P(\textit{complication occurred} \mid \textit{rib fracture}_{\textit{bilateral}}\ \textit{occurred}) \approx 1.$$

The product of these two expressions yields the following:

$$P(\textit{rib fracture}_{\textit{bilateral}}\ \textit{is significant} \mid \textit{rib fracture}_{\textit{bilateral}}\ \textit{occurred}) = 1 \times (\approx 1) = \approx 1.$$

At this point in the decision flow diagram, three or more simultaneously fractured ribs is a significant injury (see Figure 3-1), two or more simultaneous fractures within any one rib is a significant injury (see Figure 3-2), and a bilateral rib fracture is a significant injury (see Figure 3-3).

4. Open Rib Fracture Is a Significant Injury

An open fracture, also known as a compound fracture, is a complex fracture in which the bone protrudes from the skin's surface, resulting in an open wound (Stedman 2012, 1198). We propose that an open rib fracture is a significant injury because of the need for surgical intervention and infection prevention and control, which have HCC1+ standards of care. See Figure 3-4.

In the fourth rectangular box (labeled "D" and shaded blue) in the decision flow diagram (see Figure 3-4), we consider the HCC standard of care to treat an open fracture.

Lafferty and researchers at the University of Minnesota-Regions Hospital investigated the operative treatment of chest wall injuries and found no studies that addressed the treatment of open rib fractures (Lafferty et al. 2011, 102). We have reached the same conclusion. Lafferty et al. suggest that one could apply the same treatment procedures used for any open fracture to procedures used for open rib fractures. These procedures include surgical irrigation,[20] debridement,[21] and infection prevention and control (Lafferty et al. 2011, 102). Lafferty et al. suggest that internal fixation of open rib fractures, which is surgical stabilization of the fracture using hardware such as plates, screws, and splints, could be a

[20] Irrigation is a surgical term for washing a "body cavity, space, or wound" with a liquid (Stedman 2012, 900).

[21] Debridement is removal of dead tissue and foreign matter from a wound (Stedman 2012, 442–443).

treatment for open rib fractures (Lafferty et al. 2011, 102). However, Aetna's 2016 insurance coverage policy, which references Lafferty et al., still considers this treatment experimental (Aetna 2016). Regardless, open rib fractures are significant because surgical irrigation, debridement, and infection prevention and control with a prescription antimicrobial drug are HCC1+ treatments. We stop the analysis at this step because the injury, open rib fracture, is already significant, regardless of the complications. That is,

$$P(\textit{rib fracture}_{\textit{open}}\ \textit{is significant} \mid \textit{rib fracture}_{\textit{open}}\ \textit{occurred}) = 1.$$

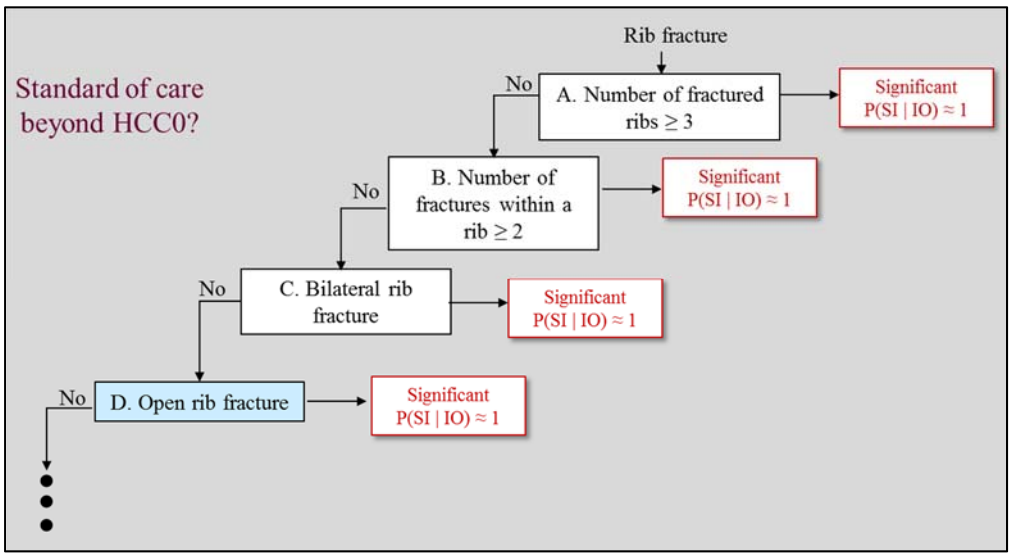


Figure 3-4. Decision Flow Diagram: Open Rib Fracture Is a Significant Injury

At this point in the decision flow diagram, three or more simultaneously fractured ribs is a significant injury (see Figure 3-1), two or more simultaneous fractures within any one rib is a significant injury (see Figure 3-2), a bilateral rib fracture is a significant injury (see Figure 3-3), and an open rib fracture is a significant injury (see Figure 3-4). Our analysis of types of rib fractures that have HCC1+ standards of care concludes.

5. Closed Rib Fractures (2 or fewer) are treated with HCC0 care

The classes of fractures not yet considered include fractures in one or two ribs, with each rib only fractured once—not a bilateral fracture and not an open fracture. The only type of rib fracture that fit these criteria is a closed rib fracture.

A closed rib fracture, commonly known as a simple rib fracture, occurs when the fractured bone does not break the skin (Hansen 2014; Stedman 2012, 1542). Closed rib fractures include transverse, oblique, and overriding and are categorized according to the

characteristic of the break (see Figure 2-3). A transverse rib fracture is a break that is perpendicular to the long axis of the bone; an oblique rib fracture is an angled break across the bone; and an overriding fracture is one in which one fragment of the fractured bone is positioned so it overlaps with the other fragment (Hansen 2014).

The general consensus among clinicians is that most patients with closed rib fractures without other complications can be treated on an outpatient basis (Easter 2001; Middleton et al. 2003; Mayberry et al. 2009; Kouritas et al. 2013) if OTC pain medicine is adequate for pain relief and respiration. Most closed rib fractures are "treated non-operatively using pain control and pulmonary hygiene," and most "heal spontaneously without major complications" (Lube 2013, 1). Often, fractured ribs are broken in one place. Most are not displaced, which allows for proper alignment during healing. Fractures can be "managed conservatively with simple pain control and time" (Fathi 2012). Since the type of pain medication in Lube and Fathi is not stated, we assume that the treatment is nonprescription, and therefore, an HCC0 treatment.

C. Restrictions to Life Caused by Closed Rib Fracture

In the previous section, we determined types of fractures that are significant injuries according to HCC standards of care. For those remaining rib fractures that do not have an HCC1+ standard of care, DoDI 3200.19 specifies a second way in which an injury, such as rib fracture type, can be considered significant: the injury results in death or "physical damage … that … restricts the employment or other activities of the person for the rest of his or her life" (DoD 2012, 14).

At present, few standards exist for grading disability or quality of life after rib injury (see Appendix B). Little is known about a rib fractures' contribution to chronic pain and long term disability (Gordy et al. 2014). Nor does the literature provide consistent association between fractures and chronic disability/pain. A study by Mayberry et al, concluded that patients with two or fewer fractures and no additional injuries and/or complications were able to return to work or usual activity sooner than patients with additional injuries and/or complications (Kerr-Valentic et al. 2003).

Absent any convincing evidence to the contrary, we therefore conclude that the remaining class of HCC0 fractures (fractures in one or two ribs, each rib only fractured once, not bilateral, not an open fracture) do not present a significant risk of permanent injury.

However, given the lack of studies relating rib fractures to permanent injury, we recommend future investigation of metrics which evaluate blunt force impact effects on long term pain, mobility, and lung capacity. This includes the Mayberry group's effort to determine rib fracture attributes which predict long term disability (see Appendices A and B to this document).

Figure 3-5 shows the final step in the decision flow diagram.

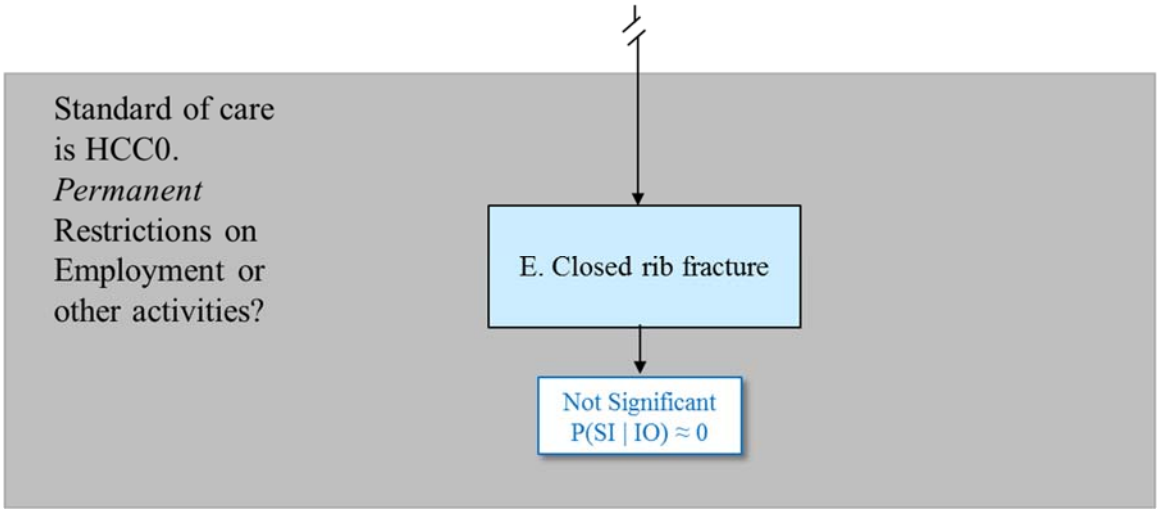


Figure 3-5. Decision Flow Diagram:
One or Two Simultaneously Fractured Ribs (Each Rib Only Fractured Once, Not a Bilateral Fracture, and Not an Open Fracture) Is Not Significant

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4. Computational Modeling

Due to the limitations of live-human, cadaveric, and animal testing for RSI assessment, the JNLWP has invested in the development of computational models to quantify the RSI for its fielded weapons and its weapons under development. For assessment of the RSI of blunt-impact NLWs, JNLWP has developed a collection of finite element models designed to calculate the human body's response to blunt impacts from the delivery of projectiles. The models developed thus far are known as the Advanced Total Body Model (ATBM) (Shen et al. 2012) and include models of the thorax, abdomen, head, eye, skin, arm and leg bones, and lower abdomen. These models account for the anatomy and geometry of the human body and the material property of tissues, simulate the interaction of human body with projectile and clothing during impact, and calculate propagation of motion and stress waves and the delivery of energy inside the tissue. For the thorax region, the following injuries are modeled: pulmonary contusion, rib fractures, cardiac injuries, pneumothorax, and lethality.

The geometry of the models was developed using CT images from the National Library of Medicine's Visible Man Project, and material properties for bone and tissue developed from the literature. The geometry was scaled to represent a 50^{th} percentile male. The solver is LS-Dyna, which also contains several relevant modules and materials for human modeling. At present, the ATBM models are integrated into the Human Effects Modeling Analysis Program (HEMAP), which includes models of the projectiles and post-processing of the ATBM outputs, including the assessment of significance. Limitations to HEMAP/ATBM identified by the Institute for Defense Analyses (IDA) indicate that the models do not include complications or secondary injuries, are not adequately validated, and do not take into account natural variation in body properties or posture (Kramer Macheret, and Teichman 2016).

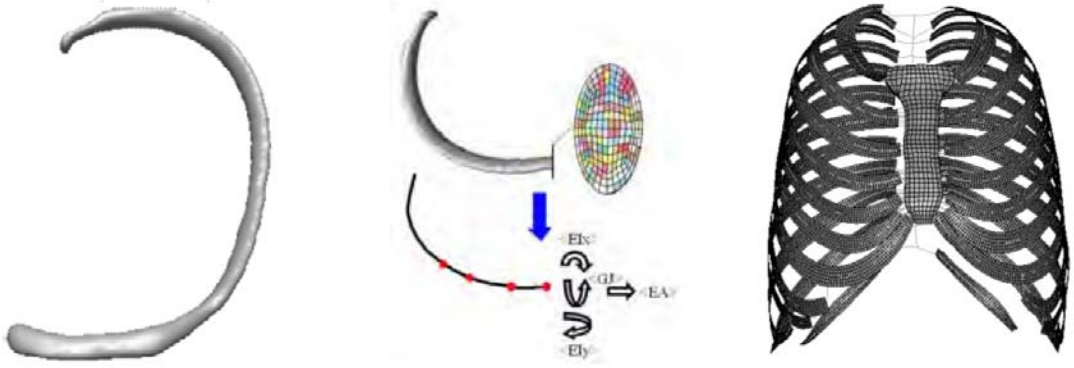
Despite the limitations and ongoing nature of the work, the alignment of RSI analyses with modeling capabilities (present and future) is essential to a full assessment of RSI. To that end, we provide detail on the thoracic injuries as modeled by ATBM to determine which of the attributes identified in our analysis can be directly modeled by ATBM and which of the attributes may require further development or experimental characterization.

A. Rib Model Development

Calculation of the deformation and stresses on ribs from blunt impact requires soft tissue models of the overlaying skin and muscle and of the underlying organs. The nine

types of tissue modeled in ATBM's torso module are lungs, heart, spleen, liver, abdomen, diaphragm, stomach, skin and muscle.

The model of the rib cage includes the ribs, cartilage, spine, and sternum (Shen et al. 2008), using the geometry from the Visible Man Project (see Figure 4-1). Each rib was modeled using non-homogeneous isotropic beams attached to a band of shell elements.



Source: Shen et al. (2008, 021022-3).

Note for Figure 4-1: FE modeling treated the rib as inhomogeneous composite beam/shell structure with bone material properties directly calculated from the CT number.

Figure 4-1. Finite Element (FE) Modeling of the Rib Cage

The ribs were assumed to behave as linearly elastic isotropic material, despite the fact that bones are orthotropic,[22] meaning that their elastic properties change when measured from different directions. Ribs are made up of cortical (hard) and trabecular (soft) bones and can be modeled using the Goldstein equations for the elastic modulus:

$$E = \begin{cases} 1352\rho^{1.48}\ (MPa) & 0 \le \rho < 1.4\ (\frac{g}{cm^3}) \\ 34623\rho - 46246\ (MPa) & 1.4 \le \rho < 2.0\ \left(\frac{g}{cm^3}\right), \end{cases}$$

where the effective density was measured from the CT images.

Density and elastic modulus were calculated individually for up to 150 beam elements per rib. Shell elements use the same material properties and introduce additional rigidity

[22] A comparison of orthotropic and isotropic simulations was performed by the ATBM developers, who concluded that "It is clear that isotropic or orthotropic material assumptions lead to only marginal difference in flexion stiffness. The tension and torsion stiffness are more sensitive to the material assumptions. During high-speed impact against ribs, bending along the short and long axis inside the cross-section are the main loading modes, therefore, the flexion stiffness is the most important quantity" (Shen et al. 2012).

and inertia. Modifications were made to the mass and stiffness of the beam elements to account for the effects of the shell.

The following measurements result from the simulation:

- Maximum chest wall deformation (mm),
- Impact Duration (ms),
- Delivered Energy (J),
- Maximum Lung Pressure (kPa),
- Maximum Rib Bending Moment (N-m), and
- Maximum Rib Stress (MPa).

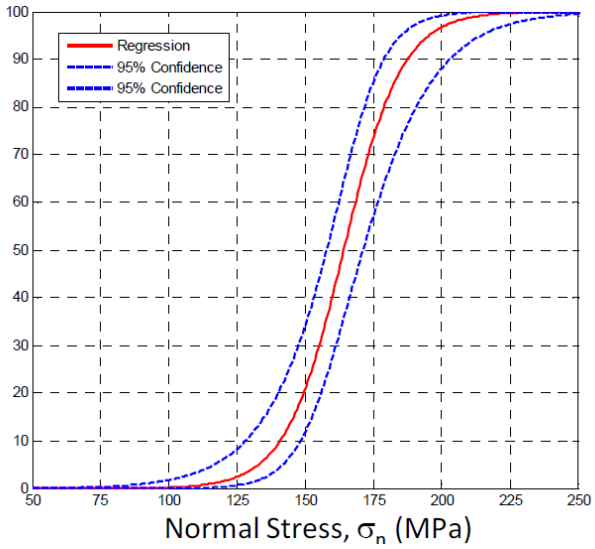
B. Injury Prediction

For rib fracture, the injury criteria were developed using 30 high-speed impact tests on swine, and 16 low-speed impact tests from the literature on humans. Subject-specific finite element models (FEMs) were developed for the swine using CT images. The scaled ATBM torso model was used for the humans. Impactors for the swine testing were 53 or 76 g and impacts ranged from 32 to 52 m/s, while impactors for the human testing were 1,750 or 23,340 g, and ranged from 4.42 to 12.83 m/s.

Using these data, the peak values of displacement, velocity, bending moment, normal stress, moment rate, and stress rate were used to predict fracture. The normal stress metric was found to have the highest correlation with rib fracture (percent of correct predictions = 80%). There were limitations to the correlations when multiple ribs were fractured because the simulation did not actually implement fracture and the subsequent redistribution of stresses around the rib cage. Therefore, data involving multiple fractures were removed to develop the correlation, which resulted in a percent of correct predictions of 95%. The resulting logistic regression equation and curve is shown in Figure 4-2. For completeness, we include in Table 4-1 all the injuries modeled in the thorax and abdomen their associated response variables and regression equations as determined by the ATBM developers.

We note that normal stress of the rib was selected as the response variable for pneumothorax, just as for rib fracture, even though it did not produce the best fit according to the regression statistics. The developers note that it was selected “because the rib stress has been the most thoroughly verified and the limited data sample available [four cases of pneumothorax were observed in the data set] may bias the regression statistics” Shen et al. (2012). The relationship between rib fracture and pneumothorax must continue to be investigated.

$$\ln\left(\frac{1-P}{P}\right) = 15.4490 - 0.0941\,\sigma_N \qquad (162.2\ MPa \text{ for } 50\%)$$



Source: Shen et al. (2012, 80).

Figure 4-2. Regression Curves for Rib Fracture in ATBM Torso Model

Finally, we note that multiple rib fractures are modeled in ATBM; however, the regression equation is exactly the same as for single rib fracture. It remains unclear how the simulation continues after the first fracture (if it does at all). The load across unfractured ribs is theoretically increased following a single fracture, but the details of that fracture will significantly affect the redistribution of stress. Alternatively, it is possible that the model does not incorporate fracture but rather applies the threshold independently to multiple ribs, which, logically, would be an underestimate of multiple fracture probability.

C. Application of Significance Results in ATBM

The accuracy of the simulated measurement and the logistic regression are subject to question as detailed in Kramer, Macheret, and Teichman (2016), and the model likely requires further development, validation, and statistical error quantification. Nonetheless, the existing model demonstrates a capability to predict rib fracture and provides promise as a potential model for multiple rib fractures.

Based on the attributes associated with rib fracture, as described in this document, we conclude that with minimal further development, an FEM such as the ATBM torso model will be sufficient to model two of the four identified rib fracture types:

- Three or more simultaneously fractured ribs, and
- Bilateral rib fracture.

Table 4-1. Injury Correlations for the Thorax and Abdomen as Implemented in ATBM

Effects/Injury Model	Response Variable	Regression Equations
Thorax		
Minor Lung Contusion	$\%V_{lung}$	$\ln(p/1-p) = -10.6914 + 4.6384 \ln(\%V_{lung})$
Moderate Lung Contusion	$\%V_{lung}$	$\ln(p/1-p) = -18.3434 + 6.1216 \ln(\%V_{lung})$
Severe Lung Contusion	$\%V_{lung}$	$\ln(p/1-p) = -41.2662 + 12.1327 \ln(\%V_{lung})$
Single Rib Fracture	σ_{rib}	$\ln(p/1-p) = -15.449 + 0.0941\sigma_{rib}$
Multiple Rib Fracture	σ_{rib}	$\ln(p/1-p) = -15.449 + 0.0941\sigma_{rib}$
Pneumothorax	σ_{rib}	$\ln(p/1-p) = -10.9084 + 0.0460\sigma_{rib}$
Ventricular Fibrillation	VC_{max}^{thorax}	10.7
AIS > 4	VC_{max}^{thorax}	$\ln(p/1-p) = -1.49 + 3.19 \ln(VC_{max}^{thorax})$
Heart Lesions	VC_{max}^{thorax}	$\ln(p/1-p) = -1.94 + 3.79 \ln(VC_{max}^{thorax})$
Heart Rupture	VC_{max}^{thorax}	$\ln(p/1-p) = -2.65 + 4.40 \ln(VC_{max}^{thorax})$
Abdomen		
Mild Liver Laceration	$\%V_{liver}$	$\ln(p/1-p) = -11.9278 + 6.127 \ln(\%V_{liver})$
Moderate Liver Laceration	$\%V_{liver}$	$\ln(p/1-p) = -9.4336 + 3.728 \ln(\%V_{liver})$
Severe Liver Laceration	$\%V_{liver}$	$\ln(p/1-p) = -31.6093 + 9.120 \ln(\%V_{liver})$
Single Rib Fracture	σ_{rib}	$\ln(p/1-p) = -15.449 + 0.0941\sigma_{rib}$
Multiple Rib Fracture	σ_{rib}	$\ln(p/1-p) = -15.449 + 0.0941\sigma_{rib}$

Source: Shen et al. (2012, 11).

At present, we conclude that existing models have no capability to model the remaining rib fracture types:

- Two or more fractures in a single rib, and
- Open rib fracture.

Due to the ongoing need for experimental validation of the existing models, we propose that experiments going forward are optimized to collect rib fracture prediction data and characterization of the fracture. Existing data (if x-rays were maintained) could also potentially be used for this purpose. It is essential to determine whether and under what conditions multiple fractures in a single rib or in open rib fractures can be produced. Following that (already necessary) experimentation (with slightly modified data collection procedures), one can weigh the value of the additional complexity of efforts to model these types of rib fractures.

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5. Findings and Recommendations

We conclude this document with a summary of our findings and recommendations.

A. Findings

Our findings are as follows:

- When estimating the significance of rib fractures, applying the reported data to our statistical framework proved challenging. Certain assumptions must be made regarding the available data before assessing rib fracture significance.
  - Most blunt-impact trauma data, including rib fracture data, are from motor vehicle accidents, falls, assaults, and industrial accidents (Sirmali et al. 2003, 135) and the mechanism of injury differs from blunt-impact NLWs (i.e., low mass/high velocity vs. high mass/low velocity). For our analysis, we treated all data the same, regardless of mechanism of injury.
  - Certain populations are more vulnerable to rib fractures than others, particularly the elderly ($\geq$ 65 years of age) as a result of decreased bone density (Pressley et al. 2012, 911). Older patients with even a single fracture or those patients with cardiac and/or pulmonary conditions have greater susceptibility to complications than younger adults (Middleton et al. 2003, 30). For our analysis, we assume that every person is equally vulnerable to rib fractures, regardless of age and/or pre-existing cardiac and/or pulmonary conditions.
  - Children display greater vulnerability than adults to intrathoracic injuries via blunt trauma. Their chest walls are more pliant, which protects their ribs from fracture but allows for greater energy transfer to the intrathoracic organs and greater incidence of complications (hemothorax, pneumothorax, and lung contusion) (Sirmali et al. 2003, 136; Kessel et al. 2014, 834). Again, we assume that every person is equally vulnerable to rib fractures, regardless of age and/or pre-existing cardiac and/or pulmonary conditions.
  - The medical literature does not study rib fractures in isolation. When rib fractures are reported, clinicians and medical researchers rarely capture data on rib fractures in isolation, and the data that do exist rarely indicate the characteristic of the fracture (e.g., transverse, oblique, overriding, and so forth), how many fractures within one rib, location within the rib, or which rib. For our analysis, we break down the terms in our statistical framework

to explicitly consider the likelihood and consequence of each potential injury or complication, given that a particular rib fracture type occurs.

  - The human thoracic region is composed of a large number of different soft and hard tissues, each with its own properties. The complexities required the analysis of a broad set of injuries and potential complications.

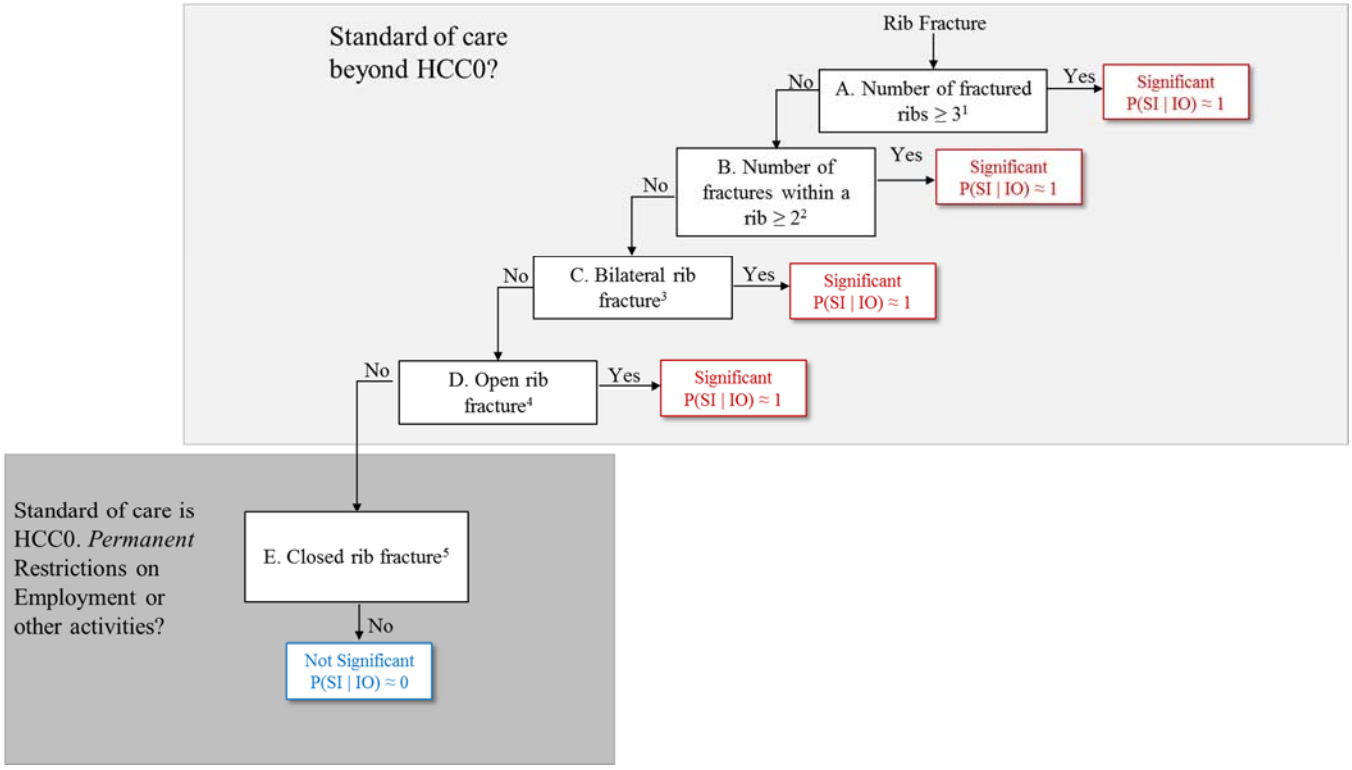
- Little is known about a rib fractures' contribution to chronic pain and long term disability (Gordy et al. 2014). Nor does the literature provide consistent association between fractures and chronic disability/pain.
- A study by Mayberry et al. concluded that patients with two or fewer fractures and no additional injuries and/or complications were able to return to work or usual activity sooner than patients with additional injuries and/or complications (Kerr-Valentic et al. 2003).

B. Recommendations

Based on our findings, our recommendations for NLW developers are as follows:

- Define the significance of rib fracture types, as illustrated in Figure 5-1.
- Classify the following rib fracture types as significant because the medical treatment for the injuries or the complications have HCC1+ standards of care:
  - Three or more simultaneously fractured ribs, or
  - Two or more simultaneous fractures within one rib, or
  - Bilateral rib fracture, or
  - Open rib fracture.
- Classify the following rib fractures as not significant because the literature suggests HCC0 standard of care, with low likelihood of permanent disability.
  - Closed rib fracture with one or two simultaneously fractured ribs, and
  - Each rib only fractured once, and
  - Not a bilateral fracture and not an open fracture.
- For future study of permanent injury, promote investigation of metrics which evaluate blunt force impact effects on long term pain, mobility, and lung capacity. This includes the Mayberry group's effort to determine rib fracture attributes which predict long term disability (see Appendices A and B to this document).

- Investigate whether existing models, such as Advanced Total Body Model (ATBM) may predict two of the rib fracture classes we identify as significant, which include:
  - Three or more simultaneously fractured ribs and
  - Bilateral rib fracture.



Legend for Figure 5-1

[1] Lee et al. (1990, 689); Sirmali et al. (2003, 135); Karmy-Jones and Jurkovich (2004, 248); Sharma et al. (2008, 313); Shields et al. (2010, e117).

[2] U.S. Army Medical Department Center and School (n.d., 1-4).

[3] Easter (2001); Pressley et al. (2012); Chapman et al. (2016).

[4] Lafferty et al. (2011, 102); Aetna (2016).

[5] Kerr-Valentic et al. (2003); Easter (2001); Middleton et al. (2003); Mayberry et al. (2009); Kouritas et al. 2013; Lube (2013); Fathi (2012)

Figure 5-1. Decision Flow Diagram:
Classifying Rib Fractures as Significant Based on Rib Fracture Type

At present, we conclude that existing models have no capability to model the remaining *significant* rib fracture types:

- Two or more fractures in a single rib, and
- Open rib fracture.

Due to the ongoing need for experimental validation of the existing models, we recommend an optimization of future experiments to collect rib fracture prediction data and characterization of the fracture. Existing data (if x-rays were maintained) may support this purpose. This effort must predict the conditions under which multiple fractures in a single rib or in open rib fractures result. Given that experimentation to develop and validate the model is already necessary, additions to the testing should be made to gain understanding of the conditions that might cause the rib fracture attributes found to be significant in this report. In the event that multiple, bilateral, or open fractures are found to occur under expected weapon use conditions, a modeling capability with increased fidelity on fracture type must be pursued.

Appendix A.
Chronic Pain from Rib Fracture

Rib Fracture Disability: Chronic Pain Studies

Chronic pain is now recognized as a major public health challenge (Institute of Medicine (IOM) 2011). Chronic pain is pain that continues when it should not, as in pain that lasts beyond the usual course of an acute injury and adversely affects the individual's well-being (American Chronic Pain Association 2016). Still, little is known about the specific contribution of rib fractures to chronic pain and disability (Gordy et al. 2014), Recent studies confirm a high incidence of chronic pain after *traumatic* rib injury, contrary to the traditional view that most rib fracture pain resolves within 6 to 8 weeks (Shelat et al. 2012; Fabricant et al. 2013).

Dr. John Mayberry from the Oregon Health & Science University led a series of studies to understand the baseline disability associated with rib fractures. One of the group's early exploratory studies followed 40 rib fracture patients, dividing them into groups according to number of fractures (two or fewer, three or more) and the presence/absence of associated injuries (Kerr-Valentic et al. 2003). Pain was self-assessed by patients at days 1, 5, 30, and 120 post-injury using the Wong-Baker FACES® Pain Rating Scale (Wong-Baker FACES Foundation 2016). Patients also reported the number of days missed from work and the ability to perform usual daily activities. There was no statistical difference between the levels of pain reported by each patient group at 120 days. Finally, the study concluded that patients with two or fewer fractures and no additional injuries and/or complications were able to return to work or usual activity sooner than patients with additional injuries and/or complications.

A later study followed 203 patients with rib fractures for six months (Gordy et al. 2014). For each patient, they recorded the total number of rib fractures, the bilaterality of rib fractures, the chest wall region where fractures were located, the presence of flail chest, the need for mechanical ventilation, and the use of pain control. During the study, patients were given the McGill Pain Questionnaire (MPQ) and the RAND-36 Health Survey. The MPQ is a validated tool designed to provide quantitative measurements of subjective pain using unique pain descriptors. (Hawker et al. 2011). The RAND SF-36 Health Survey is an extensively validated 36-item questionnaire that evaluates physical and mental variables. (Rand Corporation. 2016).

Gordy et al. (2014) had difficulty finding significant predictors of chronic pain or disability among the injury characteristics of rib fractures. Factors such as the number of fractured ribs or the presence of any complications were not predictive of chronic pain. The

severity of pain within the first 2 weeks was predictive of chronic pain. For the subset of patients with isolated rib fractures (89 patients), the prevalence of chronic pain was 28%, and the prevalence of chronic disability was 40%. Within this subset, bilaterality of rib fractures predicted chronic disability. We already proposed that bilateral fractures are a significant injury. These results are similar to the earlier retrospective study conducted by another group from Singapore (Shelat et al. 2012), where they surveyed 102 patients a year after injury and concluded that chronic pain was not related to age, number of ribs fractured, flail chest, hemothorax and/or pneumothorax, chest tube insertion, or Injury Severity Score (an anatomical scoring system that provides an overall score for patients with multiple injuries (see Trauma.org., n.d.)

Directly measuring pain is difficult, and experimental efforts such as using functional magnetic resonance imaging (fMRI) (Wagner et al. 2013) are most often subjective. No unified or industry-standard pain scale is in use, and over 20 different scales (e.g., the Wong-Baker FACES Pain Rating Scale or the MPQ) are used in different jurisdictions and contexts (Dvorsky 2013). Pain scales often heavily rely on patient self-reporting and are commonly 0–10 scales, such as the example shown in Table A-1. From this description, we see that a person is considered disabled and unable to function independently and likely unable to maintain a job at a pain level of 7/10.

Closed Rib Fracture not often associated with severe chronic pain

Although studies conclude that prolonged pain and the disability as a result of that pain are common, these studies only followed patients on the order of a few months to 1 year. Shelat et al.'s (2012) study interviewed patients after 1 year and found that 22.5% were still suffering from pain. However, it is unlikely that many of these patients were suffering a debilitating level of pain (i.e., close to 7/10). Kerr-Valentic et al. (2003) found a mean pain score of 1/10 at 120 days among the 40 patients in their study. Shelat et al. (2012) studied more than twice as many patients and found a median score of 3/10 at 1 year. Although the incidence of pain is high, we suggest that the level of pain that the patient might suffer throughout the rest of his or her life has sufficiently low probability of rating 7/10.

Table A-1. Example of Typical Descriptive 0–10 Pain Scale

Comparative Pain Scale		
	0	No pain. Feeling perfectly normal.
Minor Does not interfere with most activities. Able to adapt to pain psychologically and with medication or devices such as cushions.	**1** **Very Mild**	Very light barely noticeable pain, like a mosquito bite or a poison ivy itch. Most of the time you never think about the pain.
	2 **Discomforting**	Minor pain, like lightly pinching the fold of skin between the thumb and first finger with the other hand, using the fingernails. Note that people react differently to this self-test.
	3 **Tolerable**	Very noticeable pain, like an accidental cut, a blow to the nose causing a bloody nose, or a doctor giving you an injection. The pain is not so strong that you cannot get used to it. Eventually, most of the time you don't notice the pain. You have *adapted* to it.
Moderate Interferes with many activities. Requires lifestyle changes but patient remains independent. Unable to adapt to pain.	**4** **Distressing**	Strong, deep pain, like an average toothache, the initial pain from a bee sting, or minor trauma to part of the body, such as stubbing your toe real hard. So strong you notice the pain all the time and *cannot completely adapt*. This pain level can be simulated by pinching the fold of skin between the thumb and first finger with the other hand, using the fingernails, and squeezing real hard. Note how the simulated pain is initially piercing but becomes dull after that.
	5 **Very Distressing**	Strong, deep, piercing pain, such as a sprained ankle when you stand on it wrong or mild back pain. Not only do you notice the pain all the time, you are now so preoccupied with managing it that you normal lifestyle is curtailed. Temporary personality disorders are frequent.
	6 **Intense**	Strong, deep, piercing pain so strong it seems to partially dominate your senses, causing you to think somewhat unclearly. At this point you begin to have trouble holding a job or maintaining normal social relationships. Comparable to a bad non-migraine headache combined with several bee stings, or a bad back pain.
Severe Unable to engage in normal activities. Patient is disabled and unable to function independently.	**7** **Very Intense**	Same as 6 except the pain completely dominates your senses, causing you to think unclearly about half the time. At this point you are effectively disabled and frequently cannot live alone. Comparable to an average migraine headache.
	8 **Utterly Horrible**	Pain so intense you can no longer think clearly at all, and have often undergone severe personality change if the pain has been present for a long time. Suicide is frequently contemplated and sometimes tried. Comparable to childbirth or a real bad migraine headache.
	9 **Excruciating Unbearable**	Pain so intense you cannot tolerate it and demand pain killers or surgery, no matter what the side effects or risk. If this doesn't work, suicide is frequent since there is no more joy in life whatsoever. Comparable to throat cancer.
	10 **Unimaginable Unspeakable**	Pain so intense you will go unconscious shortly. Most people have never experienced this level of pain. Those who have suffered a severe accident, such as a crushed hand, and lost consciousness as a result of the pain and not blood loss, have experienced level 10.

Source: (Rich 2008).

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Appendix B.
Rib Fracture Disability and Surrogates for Chronic Pain

The literature lacks reliable methods to objectively quantify an individual's experience of pain (Younger, McCue, and Mackey 2009). Clinicians are taught that rib fracture pain and disability resolves in 6 to 8 weeks. However, recent studies conclude that prolonged pain is common and that the contribution of rib fractures to disability is greater than previously expected (Fabricant et al. 2013).

At present, few standards exist for grading disability or quality of life after rib injury. Our framework in Chapter 3 evaluates risks associated with long-term pain, providing clinical data to support the case that severe long term chronic pain from rib fractures where HCC0 treatment is the standard of care presents a low risk. However, conversations with the Joint Non-Lethal Weapons Directorate (JNLWD) note that modeling, predicting, and evaluating pain experienced by a human subject presents challenges. In this appendix, we discuss how existing disability rating systems may accommodate evaluation of rib fracture disability and propose surrogates for chronic pain disability that may, in the future, provide more objective measures of pain—namely, moving and breathing.

U.S. Military

DoDI 6130.03 (DoD 2010) establishes medical standards for new recruits in the military Services. This instruction does not provide information on rib injuries other than that current symptomatic cervical ribs are a disqualifying condition. Fractures are a disqualifying condition in cases where a malunion or nonunion of a fracture or current retained hardware (including plates, pins, rods, wires, or screws) used for fixation is symptomatic or interferes with the proper wearing of equipment or a military uniform. Nonunion is "failure of normal healing of a fractured bone" (Stedman 2012, 1167). Malunion is "faulty union of the ends of a broken bone resulting in a deformity" (Stedman 2012, 1011). Additional disqualifying conditions include a bone contusion or history of bone contusions of more than a minor nature that interferes with the performance of duty and that occurred in the preceding 6 months and has not recovered. Several complications of rib fractures are also considered disqualifying conditions, including the following:

- Non-specific abnormal findings on radiological and other examinations of body structure, such as the lungs or other thoracic or abdominal organs;

- Current or history of recurrent acute pneumonia;
- Current or history of pneumothorax occurring in the year preceding an examination if due to trauma; and
- Unexplained ongoing or recurring cardiopulmonary symptoms that impair a physically active lifestyle.

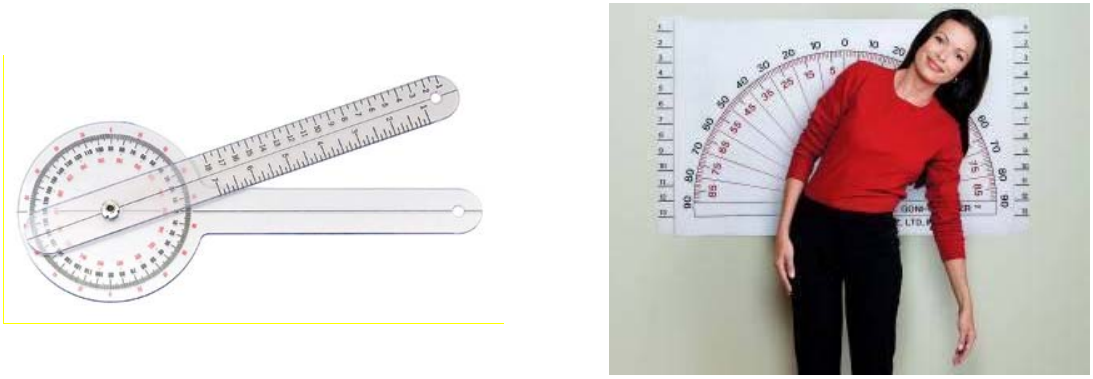
U.S. Department of Veterans Affairs (DVA)

The VASRD details requirements for assigning a rating between 0% and 100% to a veteran's conditions (DVA 1992). This assignment of a rating is done to reflect the degree to which a condition impairs a veteran's ability to work (CBO 2014). Ratings are given for rib conditions only if the ribs or part of them have been removed (DVA 2015). We consider the removal of ribs to constitute a significant injury since this requires a greater than HCC1 level of care (i.e., surgery).

For all other rib bone injuries or conditions, the condition is rated analogously with a condition that is found in the VASRD (Military Disability Made Easy 2013a). That is, the rib condition is rated as another condition that most closely describes the main symptoms or that has the same treatments as the rib condition. The most common symptom of rib fracture is mild to severe pain that typically worsens when moving (e.g., bending, twisting, or reaching) or when breathing (Mayo Clinic 2016). Below, we consider how VASRD ratings might evaluate long term pain or disability associated with rib fractures, by considering range of motion and lung function.

A rib fracture would likely limit how much a person can move his or her torso without intense pain. An analogous VASRD rating for this type of motion could be the ratings for limited ROM of the thoracolumbar (thoracic + lumbar) spine.

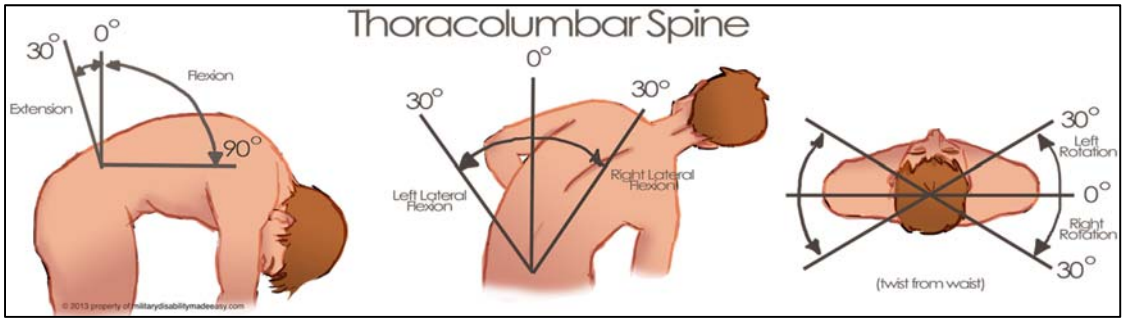
Ratings of ROM in the thoracolumbar spine are based on goniometer measurements. A goniometer is essentially a protractor, such as the type shown in Figure B-1. Six different measurements—left rotation, right rotation, flexion, extension, right lateral flexion, and left lateral flexion—are required to rate ROM in the thoracolumbar spine areas, as shown in Figure B-2. To get the combined ROM for rating purposes, all six measurements are added together. The normal combined measurements for the thoracolumbar spine is 240°. All measurements are rounded to the nearest 5°.



(a) **(b)**

Source: (a) Manchester-Bedford Myoskeletal (2016); (b) United Health Supply (2016).
Note for Figure B-1: (a) Goniometer; (b) Measurement of lateral flexion.

Figure B-1. ROM in the Thoracolumbar Spine



Source: Military Disability Made Easy (2013c).

Figure B-2. ROM Measurements for Thoracolumbar (Thoracic + Lumbar) Spine

Table B-1 displays the VASRD rating the thoracolumbar spine (Military Disability Made Easy. 2013c). For any condition that is rated primarily on limited motion, if pain is present with motion, the patient will get at least the lowest compensable rating regardless of the goniometer measurement. For example, if a person's flexion measures more than 90° but the motion is painful, this person would receive a 10% rating instead of the 0% shown in Table B-1.

Table B-1. VASRD for Thoracolumbar Spine

Rating	ROM Thoracolumbar Spine
50%	Entire thoracolumbar spine frozen in an unfavorable position
40%	Flexion measures 30° or less OR Entire thoracolumbar spine frozen in an unfavorable position
20%	Flexion measures more than 30° but not more than 60° OR Combined ROM is 120° or less
10%	Flexion measures more than 60° but less than 90° OR Combined ROM is between 125° and 240°
0%	Flexion measures 90° or more OR Combined ROM measures 240° or more

Source: Military Disability Made Easy. 2013c.

To rate how well a person can breathe, the VASRD relies on a set of tests called spirometry, which measures the functioning of the lungs, including how well the lungs take in air and exhale the left over gases (DVA 2006; Military Disability Made Easy 2013b). The spirometry measurements include forced vital capacity (FVC), which is the maximum volume of air that a person can exhale after taking a full breath; forced expiratory volume in 1 second (FEV-1), which is the maximum volume of air that a person can exhale in 1 second; and the ratio of FEV-1 to FVC. The FVC and FEV-1 measurements are noted as a volume and as a percentage of the predicted values for an average healthy person of the same age, height, ethnicity, and sex. Predicted values for FVC and FEV-1 are can be found in reference tables, such as those found on the Centers for Disease Control (CDC) website for African-American, Caucasian, and Mexican-American men and women (The National Institute for Occupational Safety and Health 2015). An excerpt from the reference table for predicted values of FEV-1 for Caucasian males is shown in Table B-2. In this table, we see, for example, that for a 25 year old Caucasian male 170 cm tall, FEV-1 is predicted to be 4.19 L (see red box in Table B-2).

Table B-2. FEV-1 Predicted Values in Liters for Male Caucasian

	Age (Years)												
Height (cm)	20	21	22	23	24	25	26	27	28	29	30	31	32
147	3.27	3.25	3.23	3.21	3.19	3.17	3.14	3.12	3.10	3.08	3.05	3.03	3.01
148	3.31	3.29	3.27	3.25	3.23	3.21	3.19	3.16	3.14	3.12	3.10	3.07	3.05
149	3.35	3.33	3.31	3.29	3.27	3.25	3.23	3.21	3.18	3.16	3.14	3.11	3.09
150	3.40	3.38	3.36	3.33	3.31	3.29	3.27	3.25	3.23	3.20	3.18	3.16	3.13
151	3.44	3.42	3.40	3.38	3.36	3.33	3.31	3.29	3.27	3.25	3.22	3.20	3.17
152	3.48	3.46	3.44	3.42	3.40	3.38	3.36	3.33	3.31	3.29	3.27	3.24	3.22
153	3.52	3.50	3.48	3.46	3.44	3.42	3.40	3.38	3.35	3.33	3.31	3.28	3.26
154	3.57	3.55	3.53	3.51	3.49	3.46	3.44	3.42	3.40	3.37	3.35	3.33	3.30
155	3.61	3.59	3.57	3.55	3.53	3.51	3.49	3.46	3.44	3.42	3.39	3.37	3.35
156	3.66	3.64	3.61	3.59	3.57	3.55	3.53	3.51	3.48	3.46	3.44	3.42	3.39
157	3.70	3.68	3.66	3.64	3.62	3.60	3.57	3.55	3.53	3.51	3.48	3.46	3.44
158	3.74	3.72	3.70	3.68	3.66	3.64	3.62	3.60	3.57	3.55	3.53	3.50	3.48
159	3.79	3.77	3.75	3.73	3.71	3.68	3.66	3.64	3.62	3.60	3.57	3.55	3.52
160	3.83	3.81	3.79	3.77	3.75	3.73	3.71	3.69	3.66	3.64	3.62	3.59	3.57
161	3.88	3.86	3.84	3.82	3.80	3.77	3.75	3.73	3.71	3.69	3.66	3.64	3.61
162	3.92	3.90	3.88	3.86	3.84	3.82	3.80	3.78	3.75	3.73	3.71	3.68	3.66
163	3.97	3.95	3.93	3.91	3.89	3.87	3.84	3.82	3.80	3.78	3.75	3.73	3.71
164	4.02	4.00	3.98	3.95	3.93	3.91	3.89	3.87	3.85	3.82	3.80	3.78	3.75
165	4.06	4.04	4.02	4.00	3.98	3.96	3.94	3.91	3.89	3.87	3.85	3.82	3.80
166	4.11	4.09	4.07	4.05	4.03	4.01	3.98	3.96	3.94	3.92	3.89	3.87	3.85
167	4.16	4.14	4.12	4.09	4.07	4.05	4.03	4.01	3.99	3.96	3.94	3.92	3.89
168	4.20	4.18	4.16	4.14	4.12	4.10	4.08	4.06	4.03	4.01	3.99	3.96	3.94
169	4.25	4.23	4.21	4.19	4.17	4.15	4.13	4.10	4.08	4.06	4.03	4.01	3.99
170	4.30	4.28	4.26	4.24	4.22	4.19	4.17	4.15	4.13	4.11	4.08	4.06	4.03
171	4.35	4.33	4.31	4.29	4.26	4.24	4.22	4.20	4.18	4.15	4.13	4.11	4.08
172	4.39	4.37	4.35	4.33	4.31	4.29	4.27	4.25	4.22	4.20	4.18	4.16	4.13
173	4.44	4.42	4.40	4.38	4.36	4.34	4.32	4.30	4.27	4.25	4.23	4.20	4.18
174	4.49	4.47	4.45	4.43	4.41	4.39	4.37	4.34	4.32	4.30	4.28	4.25	4.23
175	4.54	4.52	4.50	4.48	4.46	4.44	4.42	4.39	4.37	4.35	4.33	4.30	4.28
176	4.59	4.57	4.55	4.53	4.51	4.49	4.47	4.44	4.42	4.40	4.37	4.35	4.33

Source: Taken from Centers for Disease Control, "FEV_1 Predicted Values: Male Caucacsian," (n.d., 1 of 2).

Table B-3 shows the VASRD ratings for lung function. If our example 25-year-old, 170-cm tall Caucasian male's spirometry measurement resulted in a measurement of, say, FEV-1 = 2.51 L, then 2.51 L ÷ 4.19 L = 0.60, meaning that the FEV-1 measurement for this 25-year-old male is 60% of the predicted value. This male's disability rating would be 30% according to Table B-3.

Table B-3. VASRD for Lung Function

Measurement	Result	Rating
FEV-1	Less than 40%	100%
FEV-1	40%–55%	60%
FEV-1	56%–70%	30%
FEV-1	71%–80%	10%
FEV-1/FVC	Less than 40%	100%
FEV-1/FVC	40%–55%	60%
FEV-1/FVC	56%–70%	30%
FEV-1/FVC	71%–80%	10%

Source: Military Disability Made Easy. 2013b.

Surrogates for Evaluating Pain

ROM as a Predictive Attribute of Significant Injury

Instead of attempting to measure pain directly, one may quantify the disability resulting from that pain by measuring how much the pain restricts a person's ROM. We discussed the VASRD ratings for ROM of thoracolumbar spine—essentially motion of the trunk—earlier in this appendix (see subsection "U.S. Department of Veterans Affairs (DVA)"), but the ratings do not give us a direct idea of how much person's ability to perform work or other necessary life functions might be limited at any particular disability rating. For this information, we looked at studies reported in the medical literature that attempt to correlate ROM with functional ability. Although this relationship is not well defined, these studies conclude that most individuals use only a relatively small percentage of their full active ROM of the spine when performing activities (Bible et al. 2010).

Note that the goniometer measurements, such as those pictured in Figure B-2, do not isolate movements of the thoracic spine from the lumbar spine; rather, they evaluate the ROM of the entire region. Measurements of the neck area or the cervical spine generally are evaluated in isolation from the rest of the spine and are rated separately in the VASRD. However, we assume that pain from rib fracture would more critically affect the trunk (thoracolumbar) than the neck (cervical). Unfortunately though, compared to both the cervical and the lumbar areas, far less information exists about the thoracic spine since comparatively fewer spinal disorders are isolated to this region. (Fujimori et al. 2014; Lake et al., n.d.). Furthermore, when considering motion of the thoracolumbar spine area (see Figure B-2), the thoracic spine contributes much less to this motion than the lumbar spine. In the studies measuring functional ROM we found that since subjects performed activities as they normally would, they were not forced to move the lumbar spine in isolation. We

assume here, then, that we can make at least a loose comparison between the results of these studies and the VASRD measurements for rating the thoracolumbar spine.

Cobian et al. (2013) recorded spine motions while 10 healthy young adults performed 16 common activities of daily living (ADLs). They observed that the maximum active ROM required to complete most of the ADLs was only 40 to 60% of the available lumbar ROM The ADLs studied and the average ROM required to perform each ADL are reproduced in Table B-4. Subjects generally used less than 30% of the available ROM to complete most of the ADLs listed. Only four activities required lumbar movement greater than 40% of the available ROM: putting on pants, putting on a jacket, picking up an object from the floor, and twisting with an object. From the VASRD ratings from Table B-1, a person with lumbar spine ROM limited to only 40% of maximum (which would be 96° combined ROM) would be considered 20% disabled but would still be able to perform most of the ADLs listed in Table B-4.

Table B-4. Average ROM During Each ADL
Expressed as a Percentage of the Maximum Available ROM

Activity	Lumbar Flexion-Extension (%)	Lumbar Lateral Bending (%)	Axial Rotation (%)
Sit to stand	**37**	13	13
Pick up from floor	**73**	28	24
Twisting with an object	12	20	**72**
Walk	14	21	18
Putting on pants	**47**	26	23
Tying shoes	**38**	21	19
Shower	**34**	**32**	23
Putting on jacket	19	**30**	**46**
Clearing table	**37**	19	19
Backing up car	15	17	**31**
Reaching to shelf	17	24	27
Writing	14	13	14
Looking for traffic	18	21	20
Phone	14	23	14
Taking a drink	12	…	11
Brushing teeth	…	…	…

When evaluating chronic pain associated with rib fractures, future studies should consider evaluating the point upon which range of motion is retarded by 30% or more.

Breathing as a Predictive Attribute of Significant Injury

The VASRD ratings for lung function do not give an idea about how limited lung function might restrict a person's life. For this information, we look to severity ratings for

those conditions for which spirometry is used to rate the patient's quality of life, including chronic obstructive pulmonary disease (CPOD) and asthma. COPD is a general term that describes airflow obstruction due to chronic bronchitis and/or emphysema. COPD and asthma are ranked as mild, moderate, or severe based on forced expiratory volume in 1 second (FEV-1) and FEV-1/FVC measurements.[23] The standard guidelines for ranking severity of both asthma and COPD are shown in Table B-5 and Table B-6.

Table B-5. Classifying Asthma Severity in Adults and Youths More Than 12 Years of Age

		Persistent		
Severity	**Intermittent**	**Mild**	**Moderate**	**Severe**
Lung function	FEV-1 > 80% FEV-1/FVC ≥ 80%	FEV-1 > 80% FEV-1/FVC ≥ 80%	60% < FEV-1 < 80% FEV-1/FVC reduced 5%	FEV-1 < 60% FEV-1/FVC reduced >5%
Interference with normal activity	None	Minor limitation	Some limitation	Extremely limited

Source: National Heart, Lung, and Blood Institute (2007).

Table B-6. Classification of Airflow Limitation Severity in COPD

Severity	**I: Mild**	**II: Moderate**	**III: Severe**	**IV: Very Severe**
Lung function	FEV-1 ≥ 80% FEV-1/FVC < 70%	50% ≤ FEV-1 < 80% FEV-1/FVC < 70%	30% ≤ FEV-1 < 50% FEV-1/FVC < 70%	FEV-1 < 30% OR FEV-1 < 50% + chronic respiratory failure FEV-1/FVC < 70%
Interference with normal activity	May not have symptoms	Symptoms such as shortness of breath are more severe and most seek treatment	Shortness of breath is evident, may notice a decrease in activity tolerance and fatigue more quickly than usual	Life-threatening; quality of life is greatly impaired

Source: Global Initiative for Chronic Obstructive Lung Disease™ (2017).

If a rib fracture permanently affects an individual's ability to breathe, we can determine the significance of that rib fracture based on guidelines from Table B-5 and Table B-6, combined with the VASRD ratings from lung function in Table B-3. For given FEV-1 measurements, Table B-7 compares VASRD to severity of asthma and limitation of airflow from COPD.

[23] FVC = forced vital capacity. The latest guidance takes other factors into account when assessing COPD, such as exacerbation history and symptoms displayed; however, we are concerned only with ranking severity of lung function.

Table B-7. Determining the Significance of Rib Fracture Based on Lung Function Limitation

FEV-1	VASRD	Asthma Severity	COPD Airflow Limitation Severity	Suggested Significance of Rib Fracture for Given Lung Function Limitation
>80%	0%	Mild	Mild	Not significant
71%–80%	10%	Moderate	Moderate	
60%–70%	30%	Moderate	Moderate	
56%–59%	30%	Severe	Moderate	
50%–55%	60%	Severe	Moderate	Significant
40%–49%	60%	Severe	Severe	

Note for Table B-7: The red line signifies our suggestion for determining significance of rib fracture based on permanent limitation to lung function.

We first propose that any closed rib fracture that results in chronic pain limiting lung function to FEV-1 < 56% and FEV-1/FVC < 70% should be considered significant.

When evaluating chronic pain associated with rib fractures, future studies should consider evaluating the point upon which FEV-1 and FEV-1/FVC approach these thresholds as a surrogate for evaluating pain.

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Appendix C.
Additional Rib Fracture Research

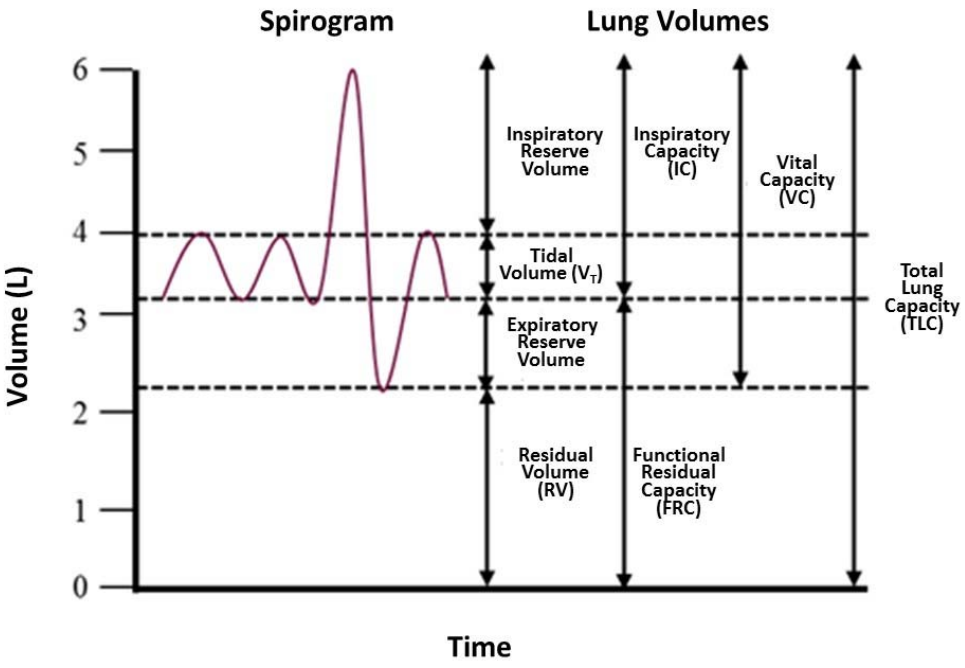
Rib Fractures: Attributes Evaluated for Significance, but Not Included in the Decision Flow Diagram

We now address rib fracture attributes evaluated for significance but omitted from the decision flow diagram for lack of substantive data, the attribute was too difficult to model, and/or the co-injuries or complications were assessed as non-causal.

Vital Capacity (VC)

A number of methodologies are available to determine pulmonary function (Culver 2012). The major method to determine lung capacity is to measure lung volume by spirometry. Spirometry measures the rate and volume of respired gases by an individual and is used to determine whether a patient has airway blockages or other lung function abnormalities (Stedman 2012). The spirometer is a simple gasometer that measures volumes through the production of a spirogram. A patient blows with maximal effort[1] into the spirometer through a tube to measure a variety of lung volume variables that clinicians use to assess lung function (Culver 2012) (see Figure C-1).

[1] Called the forced expiratory volume (FEV) maneuver.



Source: Adapted from information in Culver (2012, 21).

Note for Figure C-1: The spirogram (left) shows two cycles of quiet respiration, followed by a forced expiratory volume maneuver. The spirogram then concludes with a single cycle of quiet respiration. It can be seen that the tidal volume (V_T) and VC (right) can be easily measured from this test.

Figure C-1. The Spirogram and the Lung Volumes of Interest to Clinicians

Under normal conditions (quiet respiration), the volume of air inspired or exhaled is a small fraction of the total air capacity of the lungs and is known as the tidal volume (see Figure C-1). Using a spirometer and the forced expiratory volume (FEV) maneuver, a measurement of a patient's maximum amount of air that can be inhaled or exhaled can be measured. That volume is called the VC (vital capacity). Other volumes such as the reserve inspiratory and expiratory air volumes can be determined from this method when the VC and the tidal volume are known. However, the total lung capacity (TLC) and the dead volume of air that cannot be expelled (called the residual volume (RV)) cannot be measured with this method. Spirometric procedures using inert gases (e.g., helium) are used to measure RV and TLC. Values of these volumes and the rates over certain time periods can be used to determine ventilatory impairment (Culver 2012). These pulmonary function values are also affected by characteristics of the individual patient (e.g., age or weight). Several of these values are therefore reported per weight of the individual.

Failure to stabilize the chest wall, as in the case of a traumatic injury, can be an indication that mechanical ventilation is needed. The clinician's decision to ventilate such a patient can be made based on spirometry measurement and is based upon the fact that many pulmonary abnormalities are determined from VC or calculated values based on VC (Culver 2012). A patient's VC of less than 10 ml/kg of body weight has been cited as an

indication of the need for mechanical ventilation (Goldsworthy and Graham 2014). Mechanical ventilation can also be warranted if gas exchange is compromised. Gas exchange is typically monitored by measuring the oxygen and carbon dioxide concentrations in peripheral blood by pulse oximetry.

In the earliest stages of this study, we thought that vital capacity would be a suitable attribute to assess rib fracture significance. If a rib fracture patient's VC is less than 10 ml/kg of body weight, the medical treatment is mechanical ventilation, which is an HCC index of 1 or higher (HCC1+) standard of care. However, this attribute is too difficult to model. It is also unclear whether rib fracture types that have a VC less than 10 ml/kg of body weight can be consistently binned into the same type.

Location of Fracture within Any One Rib

To our knowledge, no data in the medical literature indicate the significance of fracture location within any one rib. In addition, the International Classification of Disease Codes, 9th revision (ICD-9) and International Classification of Disease Codes, 10th revision (ICD-10) do not capture the characteristic of the break, including fracture location within any one rib.

The only paper that possibly alludes to significance of rib fracture location is Chapman et al. (2016), and it is in the context of multiple fractures within the same rib. Chapman et al.'s RibScore includes "one fracture in each of three anatomic areas (anterior, lateral, and posterior)"[2] as a risk factor to predict pulmonary complications and cites one journal article to support its inclusion[3] (Chapman et al. 2016, 97). Based on our decision flow diagram, fractures of this type would already be significant because they would be categorized as "two or more simultaneous fractures within any one rib."

Location: Fracture of the First and/or Second Rib

It has been a long-established belief that a fracture of rib 1 is an indicator of severe trauma (Richardson, McElvein, and Trinkle 1975, 251; Easter 2001, 321). Because rib 1 is protected by the clavicle, shoulder girdle, and musculature, it usually requires tremendous force to break. Because rib 1 is so well protected by these anatomical features, a fracture of rib 1 rarely occurs. When a fracture does occur, there may be injury to the "subclavian vein and artery, brachial plexus, apex of the lung, aortic arch, esophagus, and trachea." (Sclafani et al. 2014, 1027)

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[2] Chapman et al. obtained Denver Health Medical Center trauma registry data for rib fracture patients. These data also included computed tomography (CT) as part of the initial emergency department diagnostic evaluation. Including CT is how it was possible to determine anatomic area fractures (Chapman et al. 2016, 96).

[3] The paper is Livingston et al. (2008).

Blunt cardiac injury (BCI) is an infrequent but potentially fatal injury that can occur in thoracic trauma patients (Joseph et al. 2016). The prevailing clinical assessment is that rib injuries—in particular, rib 1 and rib 2 fractures—are markers for BCI and great vessel injuries. However, this idea remains controversial. Studies have shown that rib fractures are not good predictors of fatal BCI in thoracic trauma patients (Joseph et al. 2016). Thoracic vascular injuries have been found to be associated with rib fractures in thoracic trauma patients, but rib fractures are not particularly suitable markers for great vessel or other vascular injuries (Woodring et al. 1982; Sakellaridis et al. 2004). In many clinicians' opinions, the assessment of thoracic vascular injury is not indicated for patients with first and second rib fractures alone. Other supporting information is needed for an indication of vascular injury (Gupta, Jamshidi, and Rubin 1997).

The correlation of rib 1 and rib 2 fractures to lung, esophagus, and trachea damage has not been adequately established, and the correlation to BCI and great vessel injury remains controversial. The complications that could occur to an organ or major vessel would require surgical intervention (HCC1+), but, since it is questionable that the complications are causal, first and/or second rib fracture is not included as a rib fracture type in the decision flow diagram.

Location: Fifth through Twelfth Rib Fractures

Patients with fractures in the rib 5–12 region have an increased likelihood of abdominal solid organ injuries (ASOIs), but it is difficult to determine whether these injuries are caused by the fractured rib(s) or the blunt trauma. The liver, spleen, and kidneys are generally regarded as organs in the abdomen, but they are subject to injury with thoracic trauma, including fractured ribs (Sirmali et al. 2003; Sharma et al. 2008). These organs are positioned within the body cavity such that they are close to the lower ribs.

Rostas et al., in a recent systematic chart review study, suggest that rib fracture in both the middle (ribs 5–8) and lower (ribs 9–12) rib sections are a better overall predictor of ASOI (Rostas et al. 2016, 7). Earlier retrospective studies have shown that fractures of the lower ribs (9–12) correlate with ASOI in thoracic trauma patients (Al-Hassani et al. 2010). Existing Advanced Trauma Life Support (ATLS) guidelines also support the notion that ribs 9–12 are indicators of ASOI, but the incidence of fractures in this region are low (Rostas et al. 2016, 2). However, these studies do not correlate a specific fractured rib (i.e., rib number) to a specific abdominal organ, the characteristics of the breaks are unknown, and it is difficult to determine whether the ASOI is caused by the fractured rib or the blunt trauma.

The incidence of ASOI in patients who also have a fractured rib has been reported to be ~10%–16% (Rostas et al. 2016, 2), and ASOIs will require surgical intervention (HCC1+). However, in the absence of other quantitative data that links ASOI to the rib fracture region, we cannot say with any certainty that ASOIs are causal complications.

Assessing all fractures within the 5–12 rib region as significant would underestimate the non-significant, simple rib fractures that require an HCC0 standard of care and also fall within this location. Because we do not know the characteristic of the break, we are going to assume that any ASOI caused by a fractured rib in the rib 5–12 region is accounted for in previous "significant" rib fracture types of our RSI rib fracture framework (i.e., three or more simultaneously fractured ribs, two or more simultaneous fractures within any one rib, bilateral fracture, or open fracture). Therefore, since it is questionable that ASOI complications are causal, "rib(s) fractured within the rib 5–12 region" is not included as a rib fracture type in the decision flow diagram.

Closed Rib Fracture That Is Overriding

A closed rib fracture that is overriding is one in which one fragment of the fractured rib is positioned so that it overlaps with the other rib fragment, but both fragments do not break the skin (Hansen 2014, 92). To our knowledge, no studies address the medical treatment of closed, overriding rib fractures. Anatomy books do describe characteristics of a closed fracture, but the medical literature does not provide this level of detail. ICD-9 and ICD-10 codes specify number of fractured ribs, the location (right side or left side of thorax) and whether the fractured ribs are open or closed but do not capture characteristics of the fracture (ICD10Data.com 2017). A small percentage of fractured ribs fail to heal properly, resulting in nonunion or malunion (Lafferty et al. 2011, 98 and 102). Nonunion is "failure of normal healing of a fractured bone" (Stedman 2012, 1167). Malunion is "faulty union of the ends of a broken bone resulting in a deformity" (Stedman 2012, 1011). Logically, we believe that a fracture that includes a displacement (e.g., a closed rib fracture that is overriding) could lead to complications such as nonunion or malunion, but no studies support our assumption. Therefore, since we do not have data that support our conclusion that closed rib fracture that is overriding could lead to complications such as nonunion and malunion, "closed rib fracture, overriding" is not included as a separate rib fracture type in the decision flow diagram. However, it is included as a subtype of "closed rib fracture" discussed in Chapter 3.

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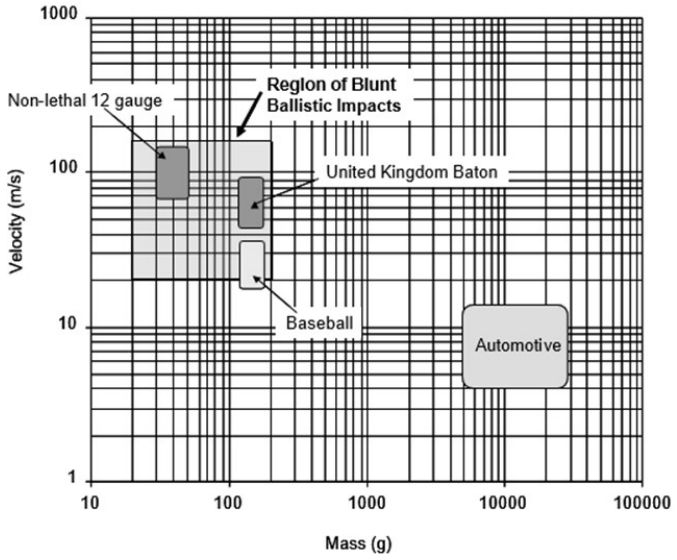
Appendix D.
Blunt-Impact NLW Background Information

Blunt-Impact NLWs: Mechanism of Injury and the Joint Non-Lethal Weapons Directorate's (JNLWD) Current and Developing Portfolio

The severity of injuries resulting from blunt force impact is dependent on the impulse delivered and the tissue to which the energy is transferred. The kinetic energy of a moving object is equal to one half the mass of that object multiplied by the velocity of the object squared (½ mv^2). In general, a lighter object traveling at high speed can potentially cause more damage than a heavier object traveling at a slower speed (Batalis 2016). Blunt force impact during motor vehicle accidents is the most common mechanism of injury for rib fractures in adults (Melendez 2016). The research and clinical data for blunt thoracic impacts in high-mass and low-impact speed scenarios is extensive. In contrast, the data for blunt thoracic impacts in low-mass and high-velocity impacts scenarios are limited. These conditions might occur in sports such as baseball or hockey and might also occur with a number of non-lethal kinetic weapons. Figure D-1 depicts the distinction between these two blunt impact scenarios.



Source: Bir (2000, 2 (Figure 1.1)).

Note for Figure D-1: Region of low-mass, high-velocity projectiles or blunt ballistic impacts involve impact velocities of 20–250 m/s and mass of 20–200 g.

Figure D-1. Blunt Impact as a Function of Velocity vs. Mass of the Projectile

Table D-1 summarizes JNLWD's portfolio of current and developing non-lethal kinetic weapon projectiles. Although the parameters on this list of projectiles vary, the mass and impact velocity of each projectile place the projectiles into the region of blunt ballistic impacts as displayed in Figure D-1. For existing weapons, projectile parameters such as mass, stiffness, aim angle, or impact velocity can be directly or statistically measured with high accuracy. Predicting the type and extent of injury once any of these projectiles impacts a target's thoracic region, however, is a challenge for several reasons. First, as discussed in Chapter 2, the human thoracic region is composed of a large number of different soft and hard tissues, each with its own properties. Understanding thoracic region tissue deformation and the mechanisms of energy transfer between tissue boundaries is exceedingly complicated. In addition, not only might body parameters such as overall body size or thickness of a fat layer vary from target to target, but characteristics such as posture or type of clothing worn might also vary. Finally, the location and likelihood of bone fracture under impact conditions are often dominated by the presence of defects in the bone, which have not been statistically quantified across the target population.

Table D-1. JNLWD's Portfolio of Current and Developing Non-Lethal Kinetic Weapon Projectiles

Round	Delivery	Payload	Projectile
12-gauge munitions	12-gauge shotgun	Stingball rounds, fin stabilized rounds, and sock rounds	
40mm munitions	M203 grenade launcher	Sponge rounds, foam rubber baton rounds, and crowd dispersal cartridges	
66mm Light Vehicle Obscurant Smoke System and Vehicle-Launched Non-Lethal Grenades	Same	Smoke, flash bang effects, riot-control agent munitions, and blunt trauma.	

Table D-1. JNLWD's Portfolio of Current and Developing Non-Lethal Kinetic Weapon Projectiles (Continued)

FN-303® Less Lethal Launching System	Same	Training/blunt impact, marking (washable-pink, permanent-yellow), and Oleoresin Capsicum liquid	
Modular crowd control munition (MCCM)	Same (pre-emplaced)	Six hundred 0.32 caliber rubber balls to suppress targets	
Stingball grenade	Hand thrown or fired out of a 12-gauge launch cup	One hundred 0.25 caliber rubber pellets propelled from grenade after explosion	
XM1116 12-Gauge Non-Lethal Extended Range Marking Munition	12-gauge shotgun	Under development	
Human Electro-Muscular Incapacitation (HEMI) projectile	M203 or M320 grenade launcher	HEMI device	

Source: DoD (n.d.).

For practical and ethical reasons, experiments to statistically determine the response of the thorax to blunt impact from a variety of projectiles would be extremely difficult to conduct. Thus, injury data are limited to incident reports after field-use and medical case studies. In support of Fiscal Year (FY) 2015 tasking by the Joint Non-Lethal Weapons Program (JNLWP), IDA surveyed the literature and found that definitive conclusions on the type and rate of expected injuries from non-lethal kinetic weapon projectiles could not be made (Kramer, Macheret, and Teichman 2016). However, the data can reveal types of injuries that actually do most commonly occur.

Kramer Macheret, and Teichman (2016) summarized field-use data from two studies to determine the types of injuries most likely to be reported after non-lethal blunt-impact weapon use. A 2013 study conducted by Penn State University and funded by the JNLWP analyzed records maintained by the Los Angeles Sheriff's Department (LASD) detailing 1,398 non-lethal bunt impact weapon uses, including the Stinger (37 mm round containing 0.32 caliber rubber balls), flash-bang, Sting-ball grenades, and 12-gauge beanbag (Kenny and Bovbjerg 2013). A 2004 study conducted by the National Institute of Justice (NIJ) (Hubbs and Klinger 2004) analyzed 373 cases that reported 979 blunt-impact munitions fired, including 37mm plastic batons, 12-gauge bean-bag, 12-gauge "super-sock", and 40mm "eXact iMpact™" rounds. The two studies reported over 600 injuries, with over one-third of those injuries in each study occurring in the chest/back region. The most common injuries, however, were those injuries likely to be insignificant (e.g., bruises and abrasions). Fractures, in general, were only a small percentage of the reported injuries—1.5% (Kenny and Bovbjerg 2013) and 3.9% (Hubbs and Klinger 2004)—with only ~1% of the injuries reported by Hubbs and Klinger being fractures in the chest area.

Field-use data report only those injuries that were most apparent at the time that the NLW was used. These data do not reveal serious complications that may develop in the days following trauma. For example, Misthos et al. (2004) and Plourde et al. (2014) reported that blunt thoracic trauma that included at least one rib fracture is a significant risk factor for delayed pneumothorax and hemothorax.[1] The medical case studies that we reviewed provided a more detailed picture of the injuries that occurred than the field-use reports did (see Section 2.B). Given that the patients in the case studies have sought or received some level of medical care, these studies are obviously biased toward reporting the more serious injuries.

Injuries from rubber and plastic bullets, one of the oldest non-lethal kinetic weapons, dominate the medical case studies. "Rubber bullet" is a generic term used to describe a large number of projectiles ranging from steel spheres or cylinders covered in a layer of rubber to small rubber pellets used in buckshot rounds. Direct-fire rubber bullets were first used in 1970 by British forces in Northern Ireland (Millar et al. 1975). Because of the severity of injuries caused by rubber bullets, they have largely been replaced by plastic rounds, which can be shot more accurately and have less potential for injury (Rocke 1983) Case studies reporting injuries from the more modern projectiles in JNLWD's portfolio are rare.

[1] The type and characteristic of the one fractured rib is unclear in Plourde et al. and Mithos et al.

Illustrations

Figures

Tables

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Abbreviations

ADL	activity of daily living
ARDS	acute respiratory distress syndrome
ASOI	abdominal solid organ injury
ATBM	Advanced Total Body Model
ATLS	Advanced Trauma Life Support
BCI	blunt cardiac injury
CDC	Centers for Disease Control
CPOD	chronic obstructive pulmonary disease
CT	computed tomography
CTS	Chest Trauma Score
CVICU	Cardiovascular Intensive Care Unit
DoD	Department of Defense
DoDD	Department of Defense Directive
DoDI	Department of Defense Instruction
DVA	U.S. Department of Veterans Affairs
FE	finite element
FEM	finite element model
FEV	forced expiratory volume
FEV-1	forced expiratory volume in 1 second
fMRI	functional magnetic resonance imaging
FVC	forced vital capacity
FY	Fiscal Year
g	gram
HCC	Health Care Capability
HCC0	HCC index of 0
HCC1	HCC index of 1
HCC2	HCC index of 2
HEMAP	Human Effects Modeling Analysis Program
HEMI	Human Electro-Muscular Incapacitation
IC	inspiratory capacity
ICD-10	International Classification of Disease Codes, 10th revision
ICD-9	International Classification of Disease Codes, 9th revision
ICOAP	Intermittent and Constant Osteoarthritis Pain
ICU	Intensive Care Unit
IDA	Institute for Defense Analyses
IOM	Institute of Medicine
IO	injury occurred
J	joule

JCIDS	Joint Capabilities Integration and Development System
JNLWD	Joint Non-Lethal Weapons Directorate
JNLWP	Joint Non-Lethal Weapons Program
kPA	kilopascal
KPP	key performance parameter
KSA	key system attribute
LASD	Los Angeles Sheriff's Department
ml/kg	milliliters per kilogram
m/s	meters per second
MCCM	modular crowd control munition
MECE	mutually exclusive and collectively exhaustive
mm	millimeter
mmHg	millimeter of mercury
MPa	megapascal
MPQ	McGill Pain Questionnaire
ms	millisecond
N-m	Newton-meters
NAMET	National Association of Emergency Medical Technicians
NDIA	National Defense Industrial Association
NIJ	National Institutes of Justice
NLW	non-lethal weapon
NRS	Numeric Rating Scale
NSAID	non-steroidal anti-inflammatory drug
NSWCDD	Naval Surface Warfare Center Dahlgren Division
NTDB	National Trauma Data Bank
OIS	Organ Injury Scale
OTC	over-the-counter
RFS	Rib Fracture Score
RICW	rest, ice, compression, elevation
ROM	range of motion
RSI	Risk of Significant Injury
RV	residual volume
SF-36 BPS	Short Form-36 Bodily Pain Scale
SF-MPQ	Short-Form McGill Pain Questionnaire
SI	significant injury
SOI	solid organ injury
TLC	total lung capacity
USD(AT&L)	Under Secretary of Defense for Acquisition, Technology, and Logistics
V_T	tidal volume
VASRD	Veteran Affairs Schedule for Rating Disabilities
VAS	Visual Analog Scale
VC	vital capacity

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Non-lethal weapons (NLWs) are systems designed and employed to immediately and reversibly incapacitate targeted personnel or materiel, while minimizing fatalities, permanent injuries to personnel, and undesired damage to property. This document considers effects from non-lethal blunt-impact munitions, such as rubber bullets and bean bags. Often employed in crowd dispersal, these munitions serve as a deterrent by inducing pain or muscle spasm at the site of impact of the affected individual. These weapons may also induce rib fractures—the focus of this document. The Joint Non-Lethal Weapons Directorate (JNLWD) serves as the Department of Defense's (DoD) NLW Program Executive Agent's day-to-day management office. As part of the DoD acquisition process, combat developers must compare the capabilities of NLW systems to requirements to assess the systems' technical maturity. One particularly important requirement stipulates the acceptable likelihood of injury. This requirement is often quantified as the Risk of Significant Injury (RSI). A NLW's RSI is a compound metric that estimates the likelihood that the NLW will cause an injury and the significance of that injury. Computational models could potentially estimate the first part of RSI, the likelihood that the blunt-impact produced by a NLW will cause rib fracture. This project focuses on the second part of RSI, the significance of these injuries, which could guide future JNLWD modeling efforts.

15. SUBJECT TERMS
blunt-impact NLW; Health Care Capability (HCC); non-lethal weapon (NLW); rib; rib fracture; Risk of Significant Injury (RSI); rubber bullet

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