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Investigation of pulmonary contusion extent and its correlation to crash, occupant, and injury characteristics in motor vehicle crashes

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ABSTRACT

Background: Pulmonary contusion (PC) is a leading injury in blunt chest trauma and is most commonly caused by motor vehicle crashes (MVC). To improve understanding of the relationship between insult and outcome, this study relates PC severity to crash, occupant, and injury parameters in MVCs.
Methods: Twenty-nine subjects with PC were selected from the Crash Injury Research and Engineering Network (CIREN) database, which contains detailed crash and medical information on MVC occupants. Computed tomography scans of these subjects were segmented using a semi-automated protocol to quantify the volumetric percentage of injured tissue in each lung. Techniques were used to quantify the geometry and location of PC, as well as the location of rib fractures. Injury extent including percent PC volume and the number of rib fractures was analyzed and its relation to crash and occupant characteristics was explored.
Results: Frontal and near-side crashes composed 72% of the dataset and the near-side door was the component most often associated with PC causation. The number of rib fractures increased with age and fracture patterns varied with crash type. In near-side crashes, occupant weight and BMI were positively correlated with percent PC volume and the number of rib fractures, and the impact severity was positively correlated with percent PC volume in the lung nearest the impact.
Conclusions: This study quantified PC morphology in 29 MVC occupants and examined the relationship between injury severity and crash and occupant parameters to better characterize the mechanism of injury. The results of this study may contribute to the prevention, mitigation, and treatment of PC.

1. Introduction

Clinically, pulmonary contusion (PC) is recognized as an indicator of severe chest injury and is associated with significant morbidity and mortality (Stellin, 1991; Cohn, 1997). Patients may be asymptomatic or symptoms can range from simple dyspnea to profound respiratory failure requiring mechanical ventilation ultimately leading to death (Cohn, 1997). The onset of symptoms is typically delayed and requires up to 24 h for full manifestation (Clark et al., 1988). Hypoxia is due to ventilation/perfusion mismatching from direct lung injury; however, it has been established that PC has a significant inflammatory component that contributes to the morbidity and mortality resultant from the injury (Hoth et al., 2009a,b). A systemic inflammatory response occurs with an immediate effect on mortality and longer lasting effects that alter the patient's ability to respond to subsequent infectious challenges (Hoth et al., 2009a). PC has been shown to be an independent predictor of required ventilation support and the development of serious complications such as acute respiratory distress syndrome (ARDS) and pneumonia (Allen and Coates, 1996; Miller et al., 2001; Hamrick et al., 2009). One study correlating the volume of PC with the risk of developing ARDS showed that the risk of ARDS is 82% for a patient whose lungs have more than 20% contusion volume versus 22% for a patient whose lungs have less than 20% contusion volume (Miller et al., 2001).

PC is a leading injury in blunt chest trauma (Allen and Coates, 1996). Motor vehicle crashes (MVCs) are associated with approximately 60–70% of all blunt chest trauma and are the most common cause of PC (Galan et al., 1992; Allen and Coates, 1996; Cohn, 1997). An analysis of the leading thoracic injuries by Abbreviated Injury Scale (AIS) code in the 2000–2008 National Automotive Sampling System Crashworthiness Data System (NASS CDS) revealed PC to be the leading AIS 2+ and AIS 3+ injury coded. PC accounts for 38% of serious (AIS 3+) thoracic injuries in NASS CDS (Stitzel et al., 2010).

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Although PC is a commonly encountered injury in blunt thoracic trauma, the relationship between insult and outcome is not fully understood. PC volume is difficult to assess from experiments with postmortem human subjects because the lung tissue response is significantly different in nonliving subjects. The inflammatory response that accompanies PC has been studied in animal models and matched finite element models have developed PC injury metrics (Raghavendran et al., 2005; Stitzel et al., 2005; Hoth et al., 2006; Gayzik et al., 2007a,b, 2008a, 2011). Anthropomorphic Test Devices (ATDs) are used to measure chest acceleration and deflection and predict thoracic injury following impact, but these devices do not provide specific information on lung loading. Recently, a lung surrogate prototype was developed to provide pressure data specific to the five lung lobes in an effort to expand the injury assessment capabilities during experimental testing to include a PC risk measure (Danelson et al., 2011b). In living human subjects, controlled, mechanical impacts to the lungs are not possible due to risk of injury to the test subject. However, PC in MVC occupants can be studied using radiological scans, medical data, and crash characteristics to better understand how these injuries occur. The Crash Injury Research and Engineering Network (CIREN) is a valuable database that collects detailed information on MVC occupants. MVC occupants admitted to a level 1 trauma center at an enrolling CIREN center are eligible for enrollment in the database if they meet certain inclusion criteria. Case occupants 13 years of age and older must sustain an AIS 3 or higher injury, with limited exceptions for AIS 2 injuries in multiple body regions or injuries of special interest to the National Highway Traffic Safety Administration (NHTSA). The model year of the vehicle of the case occupant must also be within six years of the time of enrollment unless NHTSA approves enrollment of an older vehicle. Cases of catastrophic impacts and occupant ejection are also excluded (NHTSA, 2006). Through the CIREN program, detailed vehicle, crash, and medical information is collected for each patient and presented at a multidisciplinary case review. The goal of each case review is to bring together engineering and medical knowledge to assess the crash mechanics, biomechanics, and clinical aspects of an injury.

Prior research has utilized the CIREN database to study PC in MVC occupants (Gayzik et al., 2009; O'connor et al., 2009). O'connor et al. (2009) found that an increasing vehicle delta-v, near-side lateral deformation, and fixed object frontal collisions were significantly associated with PC. In frontal collisions, frontal intrusion increased the chance of sustaining PC by 50%. In near-side lateral impacts, there was a greatly increased risk of PC regardless of intrusion or the type of object struck. This suggests that occupant proximity to the near-side door in lateral impacts may be a driving factor in PC injuries. Gayzik et al. (2009) also noted that lateral impacts were more common among patients sustaining PC (48%) versus a control group with no chest injury (27%), and mortality and Injury Severity Score (ISS) were significantly greater for occupants sustaining PC. The aforementioned study also compared CIREN occupant chest injuries in real-world crashes with ATD measurements in near-side impact crash tests with similar loading configurations.

The injury mechanism for PC involves an initial mechanical insult to the chest followed by a secondary inflammatory response that further affects the extent of the injury (Windsor et al., 1993). As there is a delay in the onset of clinical symptoms and sustained alterations in immunity that predispose the patient to later infections, unlike many other traumatic injuries, there is an opportunity for therapeutic intervention in patients who sustain PC. Thus, from a clinical standpoint, early identification of these at risk patients is an important endeavor. In an effort to identify factors associated with higher PC severity, the purpose of the current study was to relate PC volume to crash and occupant parameters in real-world MVCs.

2. Materials and methods

2.1. Subject selection

The CIREN database was selected as the data source for this study because it contains extensive vehicle, crash, and medical data on injured MVC occupants. Subjects selected for this analysis sustained a PC injury and were enrolled at the Toyota – Wake Forest University School of Medicine CIREN center between January 2006 and June 2009. Subjects with scans taken more than 14 h after the crash were excluded due to the known increase in lesion size 24–48 h following insult (Cohn, 1997). Detailed vehicle, crash, occupant, and injury data was collected from the CIREN database for the 29 selected subjects. Vehicle and crash data collected included: the make, model and year of the vehicle; energy absorbed; maximum crush; object struck; occupant seating location; belted status; and airbag deployment. Crash type, delta-v, and barrier estimate speed (BES) were collected for the highest severity impact. Occupant and injury data collected included: height, weight, age, gender, ISS, and the involved physical component(s) in the vehicle attributed to causing the PC injury (Schneider et al., 2011). Data was collected on July 13, 2011 using the CIREN SQL interface and SQL developer (Oracle, Redwood Shores, CA). All cases selected have undergone a full case review with medical, engineering, and crash reconstruction specialists to determine injury causation. Quality control checks have been undertaken and the cases are designated as "complete" in the database.

2.2. Lung segmentation

For each of the 29 subjects, the first chest computed tomography (CT) scan taken following the crash was segmented in Mimics (v12.3, Materialise, Plymouth, MI). A semi-automated method of lung segmentation to quantify lung volumes developed by the Virginia Tech-Wake Forest University Center for Injury Biomechanics has been previously reported (Daly et al., 2008; Weaver et al., 2009). Using this method, attenuation-defined masks were created to represent the volumes of the total chest cavity (total chest cavity volume), trapped air (low attenuation volume), injured lung tissue (high attenuation volume, HA), healthy lung tissue (lung attenuation volume), and the total lung (total lung volume). Volumes were measured with respect to each individual lung to discern the extent of injured tissue in the left and right lungs. The low attenuation volume represents pneumothorax, while the HA volume includes PC, as well as other lung pathologies such as aspiration, atelectasis, pleural effusion, and hemothorax (Wagner et al., 1988; Allen and Coates, 1996; Daly et al., 2008). Voxels within the HA and lung attenuation volumes were included in the total lung volume and voxels within the low attenuation volume were excluded. The ratio of HA lung volume to total lung volume was used to calculated the percentage of HA tissue within the lung (termed 'percent HA lung volume'). Fig. 1 illustrates the medical images and resulting lung segmentation results for a PC subject.

The lung segmentation method uses attenuation thresholds, dilatation and erosion operations, and minimal manual editing. The attenuation thresholds used were reported by Danelson et al. and are consistent with HU thresholds reported for nonaerated, poorly aerated, and normally aerated lung tissue (Gattinoni et al., 2001; Danelson et al., 2011a). In the segmentation process, the total chest cavity was first isolated, followed by the volumes of low attenuation, HA, lung attenuation, and total lung tissue. Detailed steps of the lung segmentation process are as follows:

1. A voxel within normal lung tissue was chosen and voxels within 200 Hounsfield Units (HU) of this chosen voxel were selected.