Characterization of Crash-Induced Thoracic Loading Resulting in Pulmonary Contusion

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Background: Pulmonary contusion (PC) is commonly sustained in motor vehicle crash. This study utilizes the Crash Injury Research and Engineering Network (CIREN) database and vehicle crash tests to characterize the occupants and loading characteristics associated with PC. A technique to match CIREN cases to vehicle crash tests is applied to quantify the thoracic loading associated with this injury.

Methods: The CIREN database and crash test data from the National Highway Traffic Safety Administration were used in this study. An analysis of CIREN data were conducted between three study cohorts: patients that sustained PC and any other chest injury (PC+ and chest+), patients with chest injury and an absence of PC (PC− and chest+), and a control group without chest injury and an absence of PC (PC− and chest−). Forty-one lateral impact crash tests were analyzed and thoracic loading data from onboard crash tests dummies were collected.

Results: The incidence of PC in CIREN data were 21.7%. Crashes resulting in PC demonstrated significantly greater mortality (23.9%) and Injury Severity Score (33.1 ± 15.7) than the control group. The portion of lateral impacts increased from 27% to 48% between the control group and PC+ and chest+ cohort, prompting the use of lateral impact crash tests for the case-matching portion of the study. Crash tests were analyzed in two configurations; vehicle-to-vehicle tests and vehicle-to-pole tests. The average maximum chest compression and deflection velocity from the dummy occupants were found to be 25.3% ± 2.6% and 4.6 m/s ± 0.42 m/s for the vehicle-to-vehicle tests and 23.0% ± 4.8% and 3.9 m/s ± 1.1 m/s for the vehicle-to-pole tests. Chest deflection versus time followed a roughly symmetric and sinusoidal profile. Sixteen CIREN cases were identified that matched the vehicle crash tests. Of the 16 matched cases, 12 (75%) sustained chest injuries, with half of these patients presenting with PC.

Conclusions: Quantified loading at the chest wall indicative of PC and chest injury in motor vehicle crash is valuable boundary condition data for bench-top studies or computer simulations focused on this injury. In addition, because PC often exhibits a delayed onset, knowing the population and crash modes highly associated with this injury may promote earlier detection and improved management of this injury.

Key Words: Pulmonary contusion, Thorax, Motor vehicle crash, Biomechanics, CIREN, Compression, Experiment.

These studies introduced animal models for the study of PC or described components of the host inflammatory response. The studies acknowledge MVC as a common cause of PC, yet little discussion is devoted to similarities between the loading applied to the model and that experienced by a vehicle occupant.

The purpose of this work is therefore to quantify the loading conditions resulting in PC and its sequelae after MVC-induced blunt chest trauma. The study proceeds in three parts. The first is to use the CIREN database to investigate the occupants, vehicle types, and crash modes most commonly associated with PC. The strength of the CIREN database is that it contains detailed information on: 1. the crash that caused Abbreviated Injury Scale (AIS) score of 3 or greater in the enrolled patient and 2. the individual’s hospital course. CIREN data are collected through an in-depth case review process conducted by participating physicians, radiologists, engineers, and crash investigators.

After the CIREN database study, data from lateral impact vehicle crash tests were analyzed to quantify crash parameters of interest including the mean vehicle crush, mean crash-induced change in vehicle velocity (Delta-V), and occupant loading data from the chest of an anthropometric test device hereafter referred to as a dummy. For reasons based on the outcome of the CIREN analysis, this analysis was restricted to passenger vehicles in lateral impact tests.

The final aspect of this study was to query the CIREN database for cases whose crash characteristics matched the analyzed vehicle crash tests. Matching was conducted through analysis of the Collision Deformation Classification (CDC) code from the CIREN case reconstruction and by matching exterior crush and Delta-V within one SD of the values determined through analysis of the crash tests. The CDC code is a comprehensive crash classification standard established by the Society of Automotive Engineers (standard SAE-J224), including the direction of force, general area of vehicle damage, and specific horizontal location of damage along the struck side of the vehicle.

The hypothesis behind this unifying aspect of the study is that injury data from matching CIREN cases coupled with thoracic loading data from the dummy situated in the vehicle crash test will provide two important results: realistic loading data for future mechanistic studies of PC and associated thoracic injuries, and insight into injury mechanisms associated with MVC-induced PC and thoracic injury.

**MATERIALS AND METHODS**

**Databases**

The CIREN network was established by the National Highway Traffic Safety Administration (NHTSA) in 1998. The CIREN database includes roughly 3,500 MVCs, generally with maximum AIS of 3 or greater. CIREN’s mission is to bring together engineering and medical knowledge during a case review at which time the crash mechanics, biomechanics, and clinical aspects of injury are assessed. CIREN is one of the most detailed databases of injuries sustained in car crash-induced trauma and contains operative notes, radiographic images, and photographs of crash victims.

NHTSA’s Vehicle Crash Test Database is a comprehensive source of engineering data generated through vehicle crash testing. It includes acceleration, force, and deflection traces from the vehicle; location and type of crash test dummies in the test vehicle; and additional media describing the tests such as crash test video and reports. This data are available online in a searchable archive maintained by NHTSA.¹⁷

**CIREN Data Collection**

The CIREN database is continually updated as additional case studies are completed from the eight centers throughout the United States. The CIREN database was downloaded containing all case information from 1996 through 2006. At the time of acquisition, the database contained 3,567 total cases. Case occupants less than 15 years of age were not considered in the analysis, eliminating 963 cases.

The CIREN data were imported into SAS statistical analysis software, (version 9.1e, Cary, NC). The cases were sorted into one of three groups: occupants who had sustained a PC and any other chest injury (PC+ and chest+), occupants who did not present with PC but experienced some form of chest trauma (PC− and chest+), and a control group who did not present with chest injury whatsoever (PC− and chest−). The first group is by definition positive for chest injury because PC is a chest region injury. Individuals in this group may have sustained additional chest injuries but were placed in this category based on the presence of PC alone. Cases were categorized after analysis of the patient’s AIS for each injury. Injury codes are derived directly from the diagnosis provided by the patient’s attending physicians and radiologists.

Patient demographics (age, gender, height, weight), injury characteristics (Maximum Value on the Abbreviated Injury Scale [MAIS], Injury Severity Score [ISS], mortality), and vehicle demographics were compared between cohorts. Based on the wheelbase length, vehicles were classified into three groups: with small or compact vehicles having a wheelbase less than 265 cm, intermediate or full size vehicles having a wheelbase between 265 cm and 291 cm, and large vehicles having wheelbases exceeding 291 cm. Crash characteristics including the Principal Direction of Force of the crash, Delta-V, and the complete CDC code allowed for thorough description of the crash characteristics of all cases in CIREN.

Statistical comparisons between groups were conducted via analysis of variance, with Tukey’s post hoc test for pairwise comparisons between groups. χ² tests were used for comparisons between categorical data. A significance level of 0.05 was used in all statistical tests.
Crash Test Data Collection

Vehicle Crash test data were downloaded from NHTSA’s research and development website.\textsuperscript{17} This database contains a summary of nearly 6,000 tests from model year 1965 to the present containing data on the crash configuration, vehicle model, and type of dummy used in the test.

All data used in case comparisons originated from lateral impact crash tests. Tests from four distinct lateral impact crash test configurations were analyzed to broaden the range of crashes investigated. Two of these, the Lateral Impact New Car Assessment Program (LINCAP) tests and the Federal Motor Vehicle Safety Standard 214 (FMVSS) tests, replicate vehicle-to-vehicle lateral impacts. The remaining two test configurations, FMVSS 201 pole and FMVSS 214 pole, replicate vehicle-to-pole type lateral impacts. The crash test configurations, parameters for each test, and unique test numbers used in this study are provided in Table 1. A complete description of these lateral impact tests can be found in the literature.\textsuperscript{18} The tests used in this study were commissioned by NHTSA for research purposes rather than specifically for regulatory purposes.

The analysis was limited to crash tests of passenger vehicles (excluding light trucks and vans). In addition, only tests using the EuroSID-2 (European Side Impact Dummy, 2nd generation) dummy, or an updated version of the same dummy, the EuroSID-2re, were used. Potentiometers embedded in the thorax of this model record the lateral thoracic displacement during the crash. Data from the selected tests were obtained through NHTSA’s Signal Browser software and the vehicle crash test report.\textsuperscript{17} Crash test data collected for this study included the vehicle Delta-V (calculated from onboard accelerometers),\textsuperscript{19} crush profile, and dummy rib deflection. Peak rib deflection was normalized by half the width of the dummy thorax module and is expressed in terms of a percent compression.\textsuperscript{20} The maximum deflection velocity was determined by differentiation of the deflection trace. Chest module loading data are presented for a subset of crash tests that were not equipped with side impact airbags, or in which the dummy did not contact the airbag.

Video and a written summary of each crash test were also downloaded through NHTSA’s research and development web site. The data were used to verify the crash mode, cross-check test data, and ensure that no malfunction of the dummy or instrumentation was noted in the test.

Matching CIREN Cases to Crash Test Cases

The pool of potential CIREN cases was restricted to passenger cars. This was performed to reduce variability because of the height of the occupant from the road and to more closely match the crash tests analyzed. Matched cases met three criteria. The case occupant was the front seat occupant on the near side lateral impact position. The CDC code, including direction of force, general area of damage, and other parameters describing the crash configuration, was

### Table 1 Summary of Lateral Impact Tests Used in Matching Protocol

<table>
<thead>
<tr>
<th>Test</th>
<th>Barrier</th>
<th>Impact-Speed</th>
<th>Impact Angle</th>
<th>Test Dummy</th>
</tr>
</thead>
<tbody>
<tr>
<td>FMVSS 214</td>
<td>Moving deformable barrier (1,387 kg)</td>
<td>54 km/h (33.5 mph)</td>
<td>27 degrees CW from lateral</td>
<td>EuroSID-2/EuroSID-2re</td>
</tr>
<tr>
<td>LINCAP</td>
<td>Moving deformable barrier (1,367 kg)</td>
<td>54 km/h (33.5 mph)</td>
<td>27 degrees CW from lateral</td>
<td>EuroSID-2/EuroSID-2re</td>
</tr>
<tr>
<td>FMVSS 201</td>
<td>Rigid pole (254 mm dia.)</td>
<td>29 km/h (18 mph)</td>
<td>Lateral impact, driver-side</td>
<td>EuroSID-2/EuroSID-2re</td>
</tr>
<tr>
<td>FMVSS 214</td>
<td>Rigid pole (254 mm dia.)</td>
<td>15 degrees CW from lateral</td>
<td>27 degrees CW</td>
<td>EuroSID-2/EuroSID-2re</td>
</tr>
</tbody>
</table>

Side impact comparisons are restricted to passenger cars. Tests shown in bold were included in the rib module loading study.
The specific coding used to match each test is provided in Table 2. To be consistent with the vehicle crash test data and to avoid a potentially confounding factor, matching CIREN cases in which the occupant was protected by a side airbag were excluded.

Table 2: Collision Deformation Classification (CDC) Code and Crush Calculations Used for Matching Crash Injury Research and Engineering Network (CIREN) Cases to Selected Lateral Vehicle Crash Tests

<table>
<thead>
<tr>
<th>Vehicle to Vehicle Type</th>
<th>Vehicle to Pole Type</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>FMVSS 214</strong></td>
<td><strong>UNICAP</strong></td>
</tr>
<tr>
<td><strong>Principal direction of force</strong></td>
<td>Lateral ± 20 degrees</td>
</tr>
<tr>
<td><strong>General area of deformation</strong></td>
<td>Left or right (L or R)*</td>
</tr>
<tr>
<td><strong>Specific horizontal location</strong></td>
<td>Side center (P, Y, or Z)</td>
</tr>
<tr>
<td><strong>Specific vertical location</strong></td>
<td>All, everything below beltline, or top of frame to top of vehicle (A, H, E)</td>
</tr>
<tr>
<td><strong>Type of damage</strong></td>
<td>Wide</td>
</tr>
<tr>
<td><strong>Weighted average crush calculation (cm)</strong></td>
<td>10% \cdot C_1 + 20% \cdot C_2 + 20% \cdot C_3 + 20% \cdot C_4 + 20% \cdot C_5 + 10% \cdot C_6</td>
</tr>
<tr>
<td><strong>Weighted crush range (cm)</strong></td>
<td>12.2–20.0</td>
</tr>
<tr>
<td><strong>Delta-V range (km/h)</strong></td>
<td>24.1–27.7</td>
</tr>
</tbody>
</table>

* Depending on case occupant’s seating position.

The purpose of the weighted average was to accurately reflect the specific type of crush. Depending on the CDC code classification (i.e., vehicle-to-vehicle or vehicle-to-pole type crash), the appropriate weighted crush was applied to the matching algorithm.

RESULTS

CIREN Data

Group populations, patient demographics, injury characteristics, and vehicle characteristics from the CIREN database are shown in Table 3. The incidence of PC in the total CIREN population was 21.7% (566 of 2,604). Study cohorts were primarily examined relative to the control group (PC− and chest−). The PC− and chest+ group were significantly older, and demonstrated a lower male-to-female ratio than the control group. In terms of the injury data, the MAIS, ISS, and mortality were significantly elevated relative to the control group.

MAIS, ISS, and mortality were highest in the PC+ and chest+ group. This group exhibited significantly greater injury data than the control group and PC− and chest+ group. The male-to-female ratio was also majority male in the PC+ population.
and chest+ group. No differences in height and weight were noted among population groups.

The incidence of PC was also investigated with respect to vehicle parameters. Significant differences were noted in the mean vehicle model year for the PC- and chest+ group, but the difference was 1 year. The mean wheelbase of all vehicles was in the intermediate size range, but a significant reduction in wheelbase size was noted for the PC+ group. This is reflected in Figure 1, which shows the incidence of PC by vehicle class. The incidence of PC remains steady across the small and intermediate class and drops substantially in larger wheelbase vehicles.

Crash characteristics from the CIREN database are found in Figure 2, which shows the crash classification based on the general area of damage (a part of the CDC code) for all cohorts. The most common crash mode for all groups was frontal, but the proportion of lateral crashes steadily increases across study cohorts. In the PC+ and chest+ cohort, nearly half (48%) of crashes were lateral impacts.

Analyzing only those patients with PC in side impact reveals a strong influence between the impacted side of the vehicle and the location of the contused lung. Figure 3 shows the breakdown of contusion classification based on struck side of the vehicle. Contused lung is strongly dependent on struck side for both right and left impacts. Bilateral lung contusions constitute substantial portions of both right and left side impact.

The results of the CIREN portion of the study were used to focus the search criteria for the vehicle crash test database. The results of this study demonstrated a sharp increase in the proportion of lateral impacts associated with PC. Although the crash modes for the PC+ and chest+ cohort were essentially equally split between frontal and side impact, it is important to consider relative frequency of these crash modes. It is well documented that frontal impacts occur with more than twice the frequency of side impact crashes, yet side impact crashes represented nearly half of all PC cases in CIREN (Fig. 2). This disproportionate increase justified the study of thoracic loading in side impact.

Because the incidence of PC was highest in compact and intermediate vehicle types (Fig. 1), and as these vehicles are typically passenger cars, limiting the crash test analysis to passenger cars was deemed a justifiable approach. The mean height and weight of the three cohorts did not differ significantly and approximated the 50th percentile male values of 170 lbs (77.3 kg) and 69 inch (175.3 cm).21

**Vehicle Crash Test Data**

Forty-one lateral impact crash tests were examined for this study. Each test met all inclusion criteria for the study (passenger car, crash test configuration, and use of the specified dummy). Impact speed and impact angle were tightly
controlled per the test stipulations. All vehicles selected for analysis were common models. Figure 4 shows the average crush (nonweighted) and average Delta-V for lateral crashes in CIREN and for the analyzed crash tests. The mean non-weighted crush values from the crash tests were significantly below the same values from the CIREN database. The mean Delta-V aligned more closely, although it should be noted that the Delta-V for the crash tests was measured via onboard sensors whereas the Delta-V for the CIREN data were estimated from the vehicle crush profile.

All chest compression data were extracted from the left front seat occupant and therefore represent the near-side crash scenario. Figure 5 shows exemplar traces of the occupant loading at the chest wall for each crash test type analyzed. All traces show a roughly sinusoidal loading pattern. The mean and SD of the maximum medial-lateral compression and maximum deflection velocity are provided in Table 4. Crash test cases used for analysis of the rib module loading are shown in bold in Table 1. Statistical tests (t test, \( \alpha = 0.05 \)) for maximum compression and for maximum deflection velocity were conducted within each test type (i.e. within the vehicle-to-vehicle and vehicle-to-pole type tests). These tests indicated that maximum rib velocity was significantly different within tests but the compression was not.

**Matched CIREN and Vehicle Crash Tests**

Matching was performed independently for each crash test type (Table 2). The inclusive ranges for matched Delta-V and weighted average crush for all test types are shown in Table 2. The average weighted crush between the two vehicle-to-vehicle tests and the two vehicle-to-pole tests were not significantly different, so a common range was used for this parameter.

A total of 16 matching CIREN cases were identified. Thirteen cases matched the vehicle-to-vehicle type crash tests. The breakdown of specific matching cases is shown in Figure 6. No cases were found to match all vehicle-to-pole test criteria because many pole-type cases in CIREN lacked a calculated Delta-V. When only the Delta-V criterion was dropped, three cases were found to match the pole tests. No differentiation among the two vehicle-to-pole tests were made because the weighted crush was not found to be significantly different (Table 2).

In terms of injury data, 4 of the 16 cases did not sustain chest injury, but all of these patients sustained pelvic fractures. All of the remaining 12 cases sustained a chest injury, and half of these cases presented with PC. Figure 6, B shows the mean age by cohort. The mean age for the PC+ and chest injury+ group, 33.4 ± 13.0 years, was found to be significantly less than the PC− and chest+ and PC− and chest− cohorts (53.3 ± 23.9 years and 60.6 ± 32.3 years, respectively) through t test between cohorts (\( \alpha = 0.05 \)). The control group was significantly shorter than the remaining cohorts (\( p = 0.006 \), analysis of variance, \( \alpha = 0.05 \)). No other demographic, injury, or vehicle data differed significantly by cohort. There was one fatality in the matched case group, which matched the Lateral Impact New Car
Assessment Program-type test loading belonging to the PC/H11002 and chest/H11001 cohort. The case occupant was an 89-year-old male, right front seat passenger who was restrained. Most of the patients in the matched cases were restrained by a 3-point belt (14 of 16). There was no indication from the case vehicle reports that unrestrained occupants were out of position. All PC/H11001 patients were restrained.

DISCUSSION

The aims of this study were twofold: to characterize the occupants, injuries, and crash modes associated with PC and apply a case-matching algorithm to the CIREN database to quantify the associated thoracic loading conditions via comparisons with similar laboratory-conducted crash tests. The results of this study provide several valuable contributions to the trauma research community regarding these aims. First, because PC can be an insidious injury exhibiting a delayed onset, knowing the population and crash modes associated with this injury could lead to earlier detection and improved management of the injury. Second, well-quantified loading conditions at the chest wall indicative of traumatic PC (and more generally, chest injury) will be a useful tool for designing future bench-top mechanistic studies of PC as well as for computer simulations focused on studying thoracic trauma. Additionally, this data will be useful to the automotive safety community with respect to the goal of preventing or mitigating thoracic injuries.

Characterization of the CIREN population was achieved through analysis of mean demographic, injury, and vehicle data for three distinct cohorts (Table 3). These were a control group without chest injury, a group with some form of chest injury in the absence of PC (typically rib fractures), and a final group with PC. These three cohorts revealed several interesting trends. Although there was no significant difference in age between the control group and the PC/H11001 and chest/H11001 group, the PC/H11002 and chest/H11001 group was found to be significantly older than the controls (37.2 ± 17.4 years vs. 46.6 ± 19.1 years). Because Delta-V was fairly uniform across all crash tests, these results suggest that age plays a role in the likelihood of developing PC after blunt chest trauma. In addition, significant gender differences were noted between cohorts in the characterization study with a greater number of males presenting with PC. As a whole, CIREN patient data were nearly evenly split between sexes (male-to-female ratio: 0.99:1). Males represented a larger proportion of drivers (54.7%) and cases with male drivers were associated with a significantly greater Delta-V (43.3 ± 19.7 km/h) than female drivers (40.2 ± 17.2 km/h) (t test, α = 0.05). Based on the results of this study, it appears that the occupants’ physical size, the vehicle wheelbase, or the vehicle weight are not predictive factors for sustaining PC in a vehicle crash.

There were significant differences between cohort injury characteristics. Patients in the PC+ and chest+ group exhibited significantly greater MAIS, ISS, and mortality. Our results suggest that this difference is predominantly because of the crash mode and crash severity. Figure 4 shows that lateral

Table 4  Mean and Standard Deviation of Rib Module Compression and Velocity for Analyzed Cases

<table>
<thead>
<tr>
<th>Test Type</th>
<th>Vehicle-to-Vehicle Type</th>
<th>Vehicle-to-Pole Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FMVSS 214 (4)</td>
<td>LINCAP (4)</td>
</tr>
<tr>
<td>Maximum M-L compression (%)</td>
<td>19.6 ± 3.2</td>
<td>26.4 ± 3.4</td>
</tr>
<tr>
<td>Maximum deflection velocity (m/s)</td>
<td>2.9 ± 0.3*</td>
<td>4.9 ± 0.4*</td>
</tr>
</tbody>
</table>

Sample size for each test is given. Tests included in this analysis are shown in bold in Table 1.

* Statistically significant differences within test types (t test, α = 0.05).

Fig. 6. Matched case summary. (A) Breakdown of cohort population for cases in the Crash Injury Research and Engineering Network (CIREN) database that matched vehicle crash tests. Matching test configuration for each cohort is also shown. (B) Mean and SD of patient age by study cohorts for matched case subpopulation.
Delta-V and average crush increase from the control group and are greatest for the PC+ and chest+ group. Lateral impact crash proportions are greatest for the PC+ and chest+ cohort. In lateral impact scenarios, the occupant is situated close to the point of momentum transfer of the impacting object. This leads to severe loading of the near side of the occupant (typically the chest, pelvis, or head). As a result of the detailed injury analysis in the CIREN database, correlation of internal injuries to external loading was possible. The influence of the occupant’s position within the vehicle on the resulting contusion is clear in Figure 3, through the high correlation between the aspect of the contusion and the crash mode.

The chest loads associated with the crashes were calculated through analysis of the vehicle crash tests. The loading of the dummy chest module was quantified using two variables: maximum medial-lateral compression and the maximum deflection velocity. Table 4 provides the averages of these values by test type. The data from the dummy chest module during the crash test in conjunction with the outcome data from matched CIREN cases provide a good estimate of the loading that caused these patients’ chest injuries.

The approach taken here provides valuable information with regard to loading boundary conditions for blunt chest trauma models. The percent compression, deflection velocity, and general shape of these loading curves are ideal input parameters for future experiments. In addition, as computer simulations of the human body for predicting injury become more prevalent, this type of data will be useful for recreating the appropriate injurious event.

The average peak chest compression and rib deflection velocity (25.3% ± 2.6% and 4.6 m/s ± 0.42 m/s) was slightly greater in the pole tests than in vehicle-to-vehicle type tests (23% ± 4.8% and 3.9 m/s ± 1.1 m/s). The difference in deflection velocity between pole and vehicle configurations was significant (p = 0.05, t test, α = 0.05), and the difference in compression approached significance (p = 0.11). Whether the data were examined from a pole-type or vehicle-type test, the loading data were roughly sinusoidal in nature, with a symmetric loading and unloading phase. Peak velocity was achieved before peak compression. Given the lung’s relative compliance and coupling to the chest wall, these externally measured loading parameters should be interpreted as loading conditions at the surface of the lung. Previous research on thoracic loading in side impact has shown that the door velocity-time profile heavily influences the severity of the loading. Although it is door deformation and movement that causes chest loading, measuring deflection directly from displacement sensors embedded in the chest module of the dummy captures this induced loading in the most direct manner possible.

It is useful to compare these findings with recent mechanistic studies of PC using animal models. In four of these six studies, blast-rate loading was applied to the study subject, an insult characterized by extremely high deflection velocity (50 m/s) and low compression (<5%). Our results show that this type of loading is markedly different from that of MVC, which would be characterized by loading at a reduced deflection velocity with increased chest compression. Although blast rate loading is appropriate for ballistic studies, our results indicate that the insult does not replicate loading in MVC. Two of the aforementioned studies applied chest loads that approximate what was found in this work. The former used an electronically driven piston to directly strike the lung of the subject at 2.8 m/s to a depth of 6.3 mm (correlates to roughly 30% compression). The latter used a drop device to achieve loading speeds between 3.4 m/s and 4.2 m/s, but did not control chest compression. Methods of blast-type loading included the use of a captive-bolt handgun, nail driver, and blast wave generator. In the studies using blast-type loading, neither deflection velocity nor chest compression was reported.

Twelve of the 16 matching CIREN cases (75%) exhibited chest trauma and half of these cases presented with PC. Clearly, factors beyond chest wall loading alone influence the specific types of thoracic injuries that will be present after blunt chest trauma, but the results strongly indicate that the dummy chest loading data are indicative of PC. When considering all matched cases, regardless of which type of test each matched, statistical tests comparing the mean values of the subpopulations (categories in Table 3) showed that only two parameters, age and height, were significantly different between groups. Although hindered by the limited sample size of matched cases, these findings again suggest that age plays a role in determining thoracic injury outcome given a similar loading profile. This finding is consistent with studies focusing on the aging thorax, which shows that aging is associated with structural and morphologic changes that can increase susceptibility to disease and decrease the body’s ability to withstand traumatic insults.

In an effort to normalize the study results, only passenger cars were considered in the matched case analysis. This was a reasonable restriction because the incidence of PC was higher in smaller vehicles (Fig. 1), and these vehicles tend to be passenger cars. Furthermore, in the majority of CIREN cases (76%) the case vehicle was a passenger car. The study findings are also consistent with the observation that there are crash compatibility deficiencies between many passenger cars and light trucks and vans. In 56% (9 of 16) of matched cases, the striking vehicle was a light truck, van, or SUV. In all PC+ matched cases, the striking vehicle fell into this category or was a vehicle-to-pole type crash. These results suggest that loading was either uniform along the vertical extent of the vehicle or presented at the height of the occupant’s chest. The dummy data also support these findings because the pole type exhibited a slightly greater peak compression and deflection velocity than the vehicle-to-vehicle tests. This is not meant to dismiss the severity of the vehicle-to-vehicle test data presented in this study. In fact, the lone patient fatality among the matched CIREN case subset was involved in a vehicle-to-vehicle lateral impact.
Although CIREN data do not represent a broad, population-based sample, the database does have unique strengths (namely extensive injury and crash reconstruction data). These attributes make CIREN data especially well suited for this type of study where the injury in question and vehicle crash data are closely linked and equally important to the conclusions.

The presence of multiple injuries could be viewed as a potentially confounding factor between cohorts. As evidenced by the elevated ISS of the PC+ group, it is possible that shock induced release of proinflammatory mediators contributed to elevated diagnosis of PC in that cohort. CIREN cases are frequently severe crashes and in many cases patients have suffered multisystem trauma. Thus, although there is the possibility that a systemic inflammatory response could be misconstrued as PC, injury data are only entered in the database after detailed case review by the patient’s attending physicians and radiologists, ensuring that the diagnoses in CIREN are as accurate as possible.

All the thoracic loading data presented in this work are derived from a 50th percentile male dummy. Crash tests meeting the inclusion criteria that utilized female dummies were unavailable. We do not believe that this result had a large influence on the results, although 10 of the 16 matched CIREN case occupants were female. The mean height and weight of the matched case individuals were 168 cm ± 9.4 cm and 72.6 kg ± 15 kg, respectively, well within one SD of the standard height and weight of the 50th percentile male (175.3 cm and 77.3 kg). In addition, the dummy used in this work has demonstrated improved biofidelity over previous models and NHTSA has adopted its latest iteration (EuroSID2-re) for use in federally mandated vehicle side impact testing.

CONCLUSIONS

A study using the CIREN database was conducted to characterize the demographics, injury, and vehicle characteristics of patients presenting with PC. A procedure was developed to identify cases in the CIREN database that closely matched laboratory-conducted lateral vehicle crash tests. Compression and deflection velocity of the chest wall associated with these crashes were collected from the dummy occupants seated in analyzed crash tests. This data are intended for use as boundary condition data for future mechanistic studies of PC and for computer simulations focused on the study of PC and blunt thoracic trauma in MVCs.

The results showed that patients presenting with PC exhibit significantly greater MAIS, ISS, and mortality than all other cohorts. A separate cohort including only those individuals with a chest injury in the absence of PC were also found to exhibit increased MAIS and ISS values over controls (no chest injury). The mean age of individuals in this group (PC− and chest+) was significantly greater than the control group. CIREN cases presenting with PC were disproportionately involved in lateral impacts. A total of 16 CIREN cases were found to match the analyzed crash tests. Seventy-five percent of these cases exhibited an AIS score of 3 or greater chest injury. Half of the matched cases with chest injuries also presented with PC.

The average maximum chest compression and rib deflection velocity from the dummies was slightly greater in vehicle-to-pole type tests (25.3% ± 2.6% and 4.6 m/s ± 0.42 m/s) than in vehicle-to-vehicle type tests (23% ± 4.8% and 3.9 m/s ± 1.1 m/s). Loading was roughly sinusoidal and symmetric, with peak velocity achieved before peak compression. Pole type impacts exhibited significantly greater deflection velocity. Like the total CIREN population, age was found to be a significant factor between cohorts within the matched case subpopulation. The PC+ and chest+ cohort was significantly younger (33.4 ± 13.0 years) than the remaining cohorts (PC− and chest+) at 53.3 ± 23.9 years and PC− and chest− at 60.6 ± 32.3 years).

Through correlation with CIREN injury data, the results provide well-quantified chest loading data from MVC resulting in PC. This loading is markedly different from blast-type loading, which has been used in some mechanistic studies of this injury. We recommend using equipment that provides loading similar to that provided in this study for future benchtop studies of crash-induced PC. Computational studies of this injury can also use these findings to provide realistic boundary conditions for human body models.

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