

Improving Injury Causation Analysis and Coding in CIREN Using the BioTab Method

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Abstract - The NHTSA-sponsored Crash Injury Research and Engineering Network (CIREN) has collected and analyzed crash, vehicle damage, and detailed injury data from over 4000 case occupants who were patients admitted to Level-I trauma centers following involvement in motor vehicle crashes. Since 2005, CIREN has used a methodology known as “BioTab” to analyze and document the causes of injuries resulting from passenger vehicle crashes. BioTab was developed to provide a complete evidenced-based method to describe and document injury causation from in-depth crash investigations with confidence levels assigned to the causes of injury based on the available evidence. This paper describes how the BioTab method is being used in CIREN to leverage the data collected from in-depth crash investigations, and particularly the detailed injury data available in CIREN, to develop evidence-based assessments of injury causation. CIREN case examples are provided to demonstrate the ability of the BioTab method to improve real-world crash/injury data assessment.

INTRODUCTION

Traditional crash data collection

Investigations of motor vehicle crashes have provided a wealth of information regarding crash configurations, vehicle involvement, restraint system usage, and resulting injuries from a wide range of crash situations. The National Highway Traffic Safety Administration (NHTSA) maintains several databases of vehicle crashes with varying amounts of information and data elements. Census-based databases like the Fatal Accident Reporting System (FARS) derive their information from Police Accident Reports (PARs) that have limited information on injuries to occupants. The National Automotive Sampling System Crashworthiness Data System (NASS-CDS) (1) samples and investigates over 4500 tow-away crashes each year in the United States and collects a large variety of environment, vehicle, crash, and occupant, and injury data elements for each crash. These elements can include: roadway, traffic and weather descriptions, make/model/year of the vehicle, and associated characteristics regarding the external crush of the vehicle and internal intrusion of vehicle interior components, tire inflation status, occupant gender, age, height, weight, seat position, restraint conditions, descriptions of injuries sustained by vehicle occupants, the Abbreviated Injury Scale (AIS) code for injuries, and a “source of injury,” which is usually the single component or object contacted by the occupant that is believed to have caused a particular injury.

While these data-collection systems provide a rich description the crash environments and vehicle damage, they collect a limited amount of data on occupant injury outcomes and provide limited descriptions of injury causation. For example, the current model for collecting injury data and recording injury causation does not associate the causes of injury with the different crash events in multi-crash situations, it doesn’t record how intrusion of vehicle components may affect injury causation, and it does not consider how factors such as age, health status, and occupant stature, weight or other physical attributes may contribute to an occupant’s injuries. In most cases, injuries are linked to a single “source” of contact, which is often generically and incorrectly labeled the “mechanism” of the injury. Scarboro (2) recently highlighted these issues and described how there is a need to establish a method by which injury causation and injury mechanisms can be logically deduced through a consistent and thorough process based on the available evidence. The BioTab injury analysis method was developed by Schneider et al. (3) to fill this need and has been applied in the CIREN program. This paper describes the application of BioTab in CIREN and presents results from using BioTab to analyze and document injury causation and injury mechanisms in different types of crashes over the past five years.

The CIREN program

The NHTSA-sponsored CIREN program has been ongoing for over twelve years and has collected detailed crash, vehicle, occupant, and injury information on more than 4000 case occupants of late-model-year vehicles, most of whom sustained at least one serious or more severe injury (AIS => 3) or at least two moderate (AIS = 2) injuries. Other selection criteria are involved, but the crashes are primarily selected based upon injury severity of the occupant – that is, CIREN is an outcome-based crash/injury database. A complete list of CIREN inclusion criteria is provided in the United States Federal Register (4). Briefly, CIREN selects on the basis of a severe injury (at least one AIS 3+ or two AIS 2+ in two different body regions) to the occupant of a crashed vehicle. The vehicle must be within 6 years of the current model year and there must be documented evidence that the occupant was restrained by a seatbelt and/or that an airbag deployed. In-depth investigations of the case occupant's vehicle and the crash scene are performed using a modified version of the NASS-CDS protocol. Data from these investigations are linked to detailed medical records of the case occupant's injuries. This includes radiological images and reports, clinical progress, notes during treatment, operating room reports, photographs of external injuries such as contusions and abrasions, occupant interviews, discharge reports, and a one-year follow-up assessment of the occupant's quality of life. A thorough multidisciplinary review of each case is conducted to derive a biomechanical basis for the case occupant's injuries based on physical evidence and knowledge of injury biomechanics in the peer-reviewed literature. A review team at each CIREN center consists of an experienced NASS-trained crash investigator, a board-certified trauma physician, a biomechanical engineer with experience in injury biomechanics research, a data coordinator, and emergency response personnel. Other physicians (pediatric surgeons and radiologist) and engineering personnel may be consulted as needed for individual cases. These reviews confirm the crash and injury assessments (including AIS coding) and involve applying the BioTab method to injury causation assessment for all AIS 3+ injuries sustained by the case occupant.

The BioTab method

The BioTab method for analyzing and documenting injury causation in motor vehicle crashes is described in detail by Schneider et al. (3) and is therefore only summarized briefly in this paper. The flowchart in Appendix B provides an overview of the BioTab method and an expanded version of this flowchart is provided in Schneider et al.

The BioTab approach to analyzing the causes of injuries focuses on identifying and documenting injury causation scenarios (ICSs), which systematically define all factors that are believed to have been necessary for, or contributed to, the occurrence and/or severity of an injury. It also documents the particular body region and organ/component mechanisms by which the injury occurred, thereby making a clear distinction between the "scenarios" by which injuries occur and the specific mechanical, chemical, or thermal actions within, or on, the occupant's body that caused the tissue damage constituting the injury.

ICSs fall into one of two categories. The first involves an injury that is caused by another injury. For example, a lung laceration that was caused by a nearby rib fracture, or a bladder laceration that was caused by an adjacent displaced pubic ramus fracture. In these cases, all that is documented in the ICS is the injury being coded and the "causal injury." However, in most cases, an injury is not caused by another injury and an ICS is documented with the elements or factors described below. Confidence levels are associated with each ICS based on available evidence, and up to two ICSs can be documented for each injury as long as neither ICS has a confidence level of "certain."

When completing an ICS for an injury that is not "caused by another injury," the following factors must be identified and recorded:

- the source of energy causing the injury (SOE),
- involved physical components (IPCs)
- body regions contacted by IPCs and internal paths from the injured body region to the body regions contacted,

- critical intrusions,
- contributing factors, and
- a brief descriptive name for the ICS.

The source of energy (SOE) is the event that resulted in the energy transfer to the occupant that caused the injury being coded and can be the crash event, a deploying airbag, or activation of a seatbelt pretensioner. Involved physical components, or IPCs, are objects that contacted and loaded the occupant in a manner that is considered essential for the injury being coded to have occurred. IPCs typically include vehicle interior and restraint-system components, but can also be objects external to the vehicle, other occupants, loose objects or cargo within the vehicle, or even regions of the injured occupant's body (e.g., an occupant's forearm contacting their head). For injury causation scenarios where an injury resulted from contact of two different body regions with *two different IPCs*, both of these IPCs are documented as part of a single injury causation scenario.

Each injury causation scenario and each involved physical component must be supported by evidence, for which guidelines are provided in Schneider et al. (3). Evidence for an IPC includes marks on, and damage or deformation to, the IPC, consistency between the IPC location, the initial occupant position/posture and occupant kinematics that are expected based on the crash dynamics and occupant restraints, and consistency between the patterns of minor injuries and the type of loading that is expected from contact with the IPC. Data from an event data recorder (EDR) that indicate belt use or lack of belt use, pre-impact braking, seat-track fore/aft position, and airbag deployment timing, may also be evidence for an IPC.

For each IPC, the body region (or regions) contacted by the IPC are identified and documented. When an IPC contacts a body region other than the body region where the injury being coded exists, an internal (to the injured occupant) path is defined between the body region contacted by the IPC and the injured body region. Documenting an internal path objectively describes how force generated by contact with an IPC is transmitted from the IPC to the body region where the injury occurred, or how contact with an IPC sets up inertial loading conditions that result in an injury (e.g., shoulder-belt forces applied to the thorax and shoulders cause the head mass to pull on the cervical spine in a frontal crash).

Critical intrusions are intrusions without which the injury being coded would not have occurred. Contributing factors increase the likelihood and/or severity of an injury but are not essential for the injury to have occurred. Common examples of contributing factors are occupant age, gender, bone condition, obesity, pre-existing medical conditions, driver braking/bracing, and an occupant not being in a "normal" seated posture at the time of a crash (e.g., occupant sleeping with seatback fully reclined). Intrusions of vehicle components are more often considered to be contributing factors than they are considered to be critical.

For each ICS, a brief descriptive name is assigned to simplify reference to the ICS and provide a clear indication of how the injury occurred. For example, if a hip fracture occurred from knee loading by the knee bolster, an appropriate descriptive name would be "knee loaded by knee bolster."

As previously indicated, the BioTab method distinguishes between the scenario by which an injury occurred and the "mechanisms" by which the tissues constituting the injury were damaged. These mechanisms are body-region specific. A list of body region-level and organ/component-level injury mechanisms for each of the twenty body regions used in BioTab is provided in Schneider et al. (3). Injury mechanisms are commonly defined by the elements of an ICS, but may be defined independently of an ICS using findings from the biomechanical literature that associate a particular injury pattern with a particular type of loading or mechanical response.

METHODS

The flowchart of Appendix B shows the key steps involved in conducting and reviewing a CIREN case and particularly in using the BioTab method to analyze injury causation in CIREN. This approach to analyzing and documenting injury causation has been applied to clinically significant injuries (generally AIS 3+) for all CIREN case occupants in crashes that have been investigated by CIREN centers over the past five years. This currently includes over 1200 case occupants with more than 3000 injuries. The results of using BioTab on these injuries, occupants, and crashes have been tabulated to provide overall summaries of the types of injuries and body regions injured, and the elements of injury causation scenarios such as the involved physical components as a function of crash type. Confidence levels assigned to ICSs and IPCs have also been compiled, as have the body region and organ/component-level injury mechanisms. The results that follow show tabulations of some of this information. In addition to these tabulations of BioTab data, three case examples are presented to highlight the strengths of the BioTab method and to show how BioTab improves the completeness of injury causation analysis and documentation.

RESULTS FROM APPLYING THE BIOTAB METHOD IN CIREN

CIREN Biotab Analysis/Status

Figure 1 shows the percentages of all injuries for different ranges of injury severity by body region for the 1200 CIREN occupants whose AIS 3+ injuries were coded using BioTab. The largest percentages of injuries occur to the head/face, thorax, and pelvis. With injury causation coding for over 600 serious (AIS 3+) thoracic injuries, the BioTab data in CIREN, combined with NASS-CDS data (Elliott et al. (5)) are a powerful resource to understand how these injuries occur and perhaps how they can be prevented.

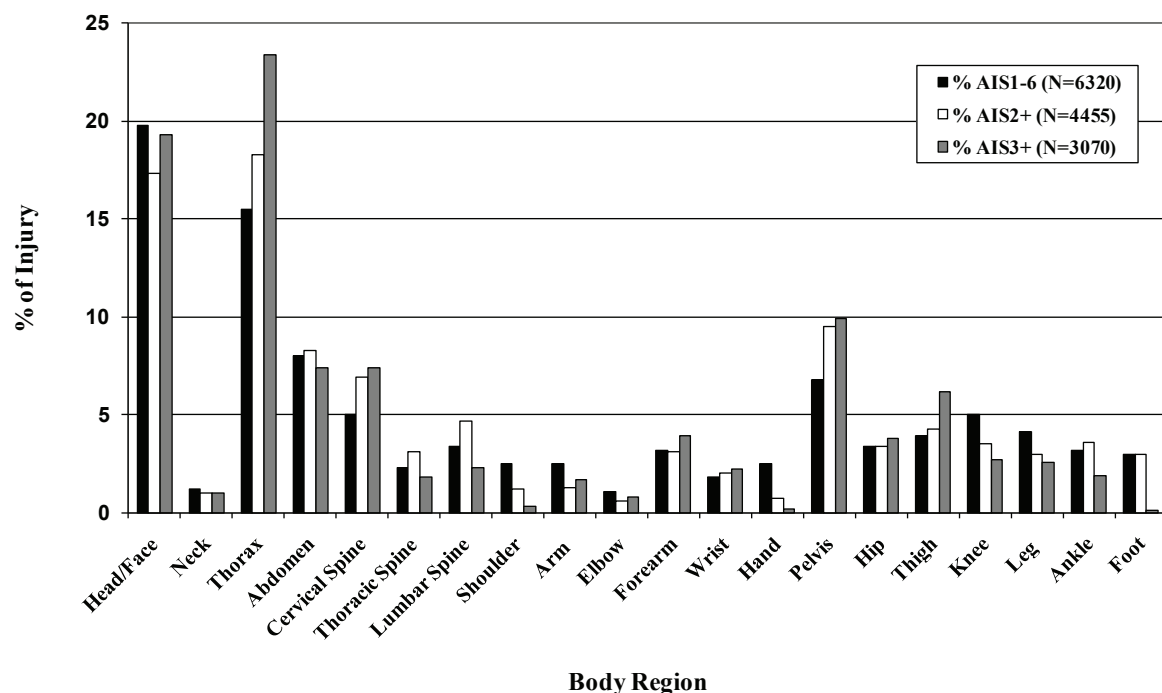


Figure 1. Percent of injuries for different ranges of injury severity sustained by CIREN occupants in different body regions

Of the 1200 cases for which injuries have been coded using BioTab, 57% involve an occupant who was involved in a frontal crash and 35% involve an occupant in a side impact. The remaining cases are associated with occupants involved in rollovers and other crash modes. This distribution of crash types is not intended to be representative of real-world crashes but is a function of CIREN sampling criteria and priorities which, as previously noted, are documented in the Federal Register (4).

Figure 2 shows the percentages of AIS3+ injuries by injured body region for frontal, side, and rollover crashes in the CIREN BioTab database. For brevity, only percentages of AIS 3+ injuries from the most frequently injured body regions are shown. Note that the thorax injuries are dominant for occupants involved in frontal and side crashes while cervical spine injuries are most common for occupants involved in rollover crashes.

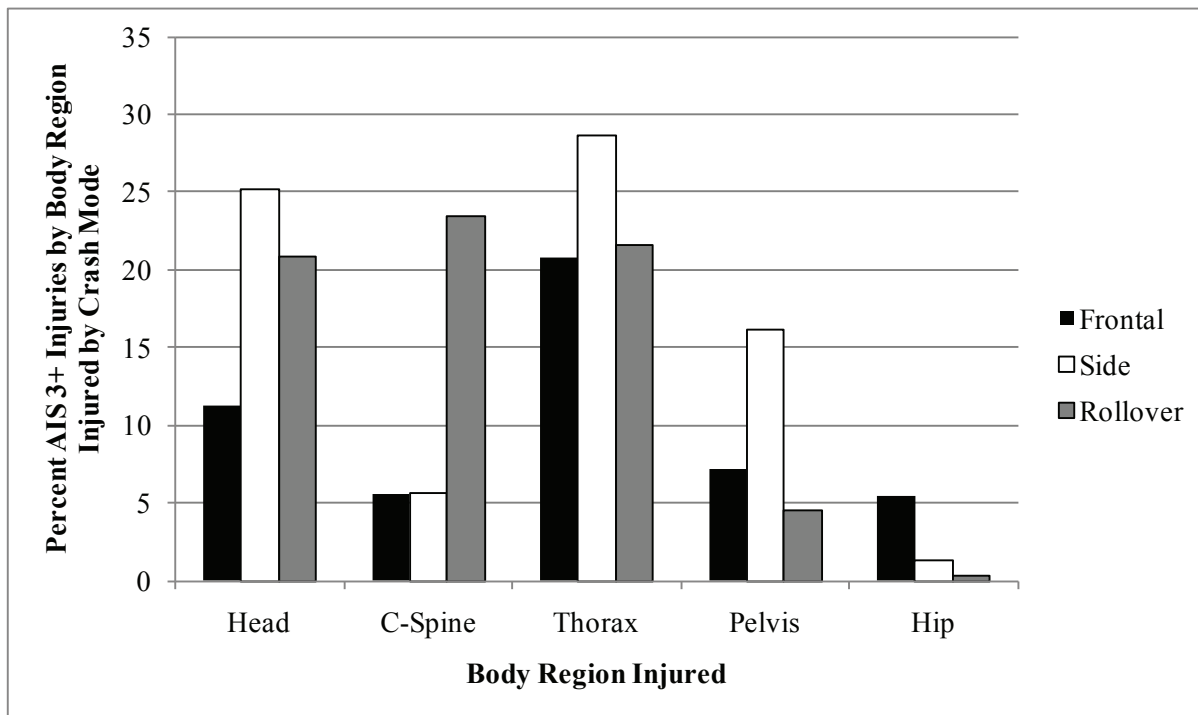


Figure 2. Percentage of AIS 3+ injuries by injured body region for which BioTab analysis was performed on the most frequently injured body regions by crash type

Figures 3, 4, and 5 show the three most common types of head, C-Spine, and thorax injuries as percentages of the total number of injuries to these respective body regions for frontal crashes side impacts, and rollover crashes. Subarachnoid hemorrhage is the most common head injury for frontal and side crashes, while the most common head/brain injury in rollovers is basilar skull fracture. For side impacts, the three most frequent head injuries involve a brain injury or bleed. Figure 4 shows that different crash modes are associated with injury to different structures in the cervical spine and vertebral bodies. Interestingly, the majority of the most common C-spine injuries involve injury to the posterior column of the cervical spine, suggesting a compression-extension mechanism or compression of the c-spine in an extended posture. Figure 5 indicates that, while lung contusions are very frequent thoracic injuries in all crash modes, frontal crashes have higher frequencies of rib fractures, and especially multiple fractures involving hemo- or pneumo-thorax.

The three most frequently Involved Physical Components (IPC) coded for head, cervical spine, and thorax injuries by crash mode are shown in Figures A1, A2 and A3 of Appendix A. In frontal crashes, the steering wheel, seat belt, and airbag are commonly coded as the IPC for thoracic injuries. This is expected since a CIREN occupant must be restrained by the seat belt and/or airbag to be included in the database.

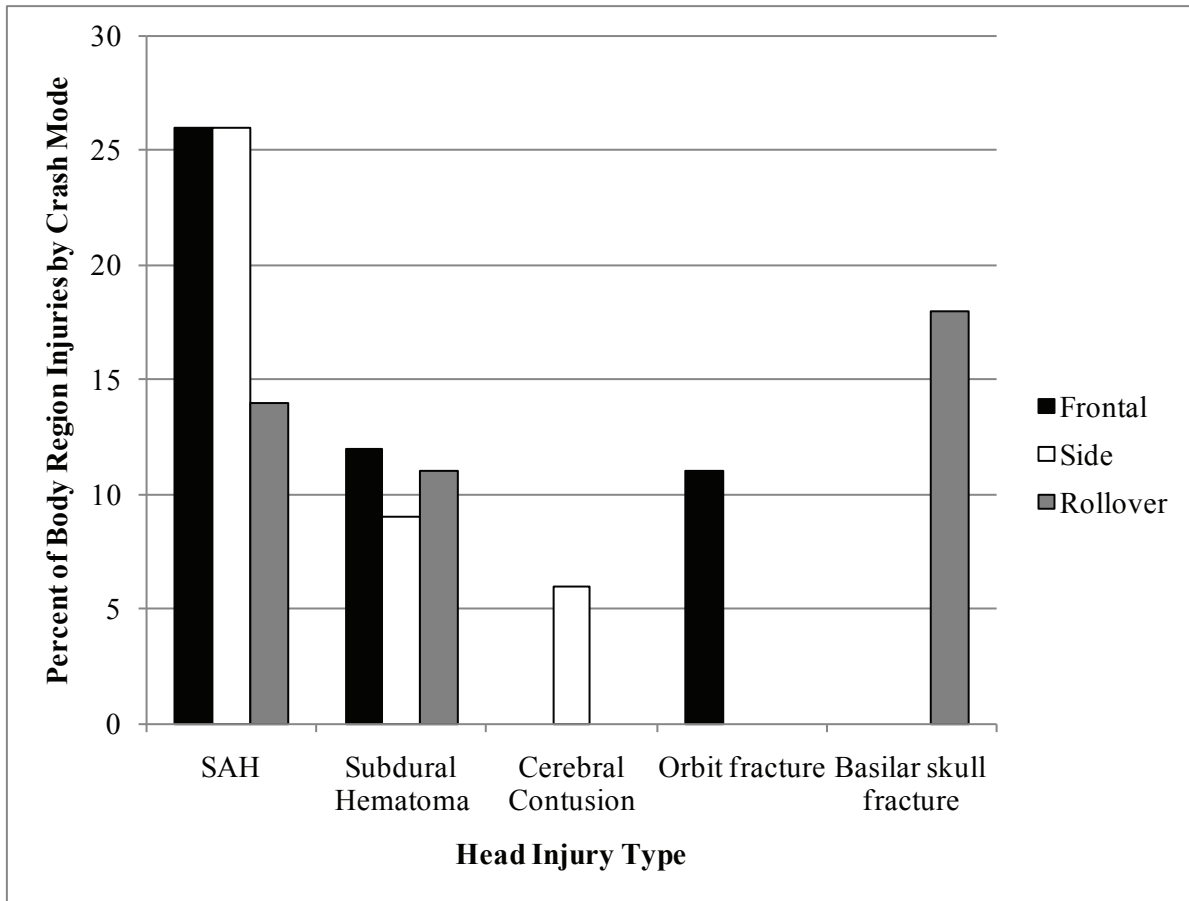


Figure 3. Three most common AIS 3+ head/brain injuries as percentages of the total number head/brain injuries by crash mode (SAH = subarachnoid hemorrhage).

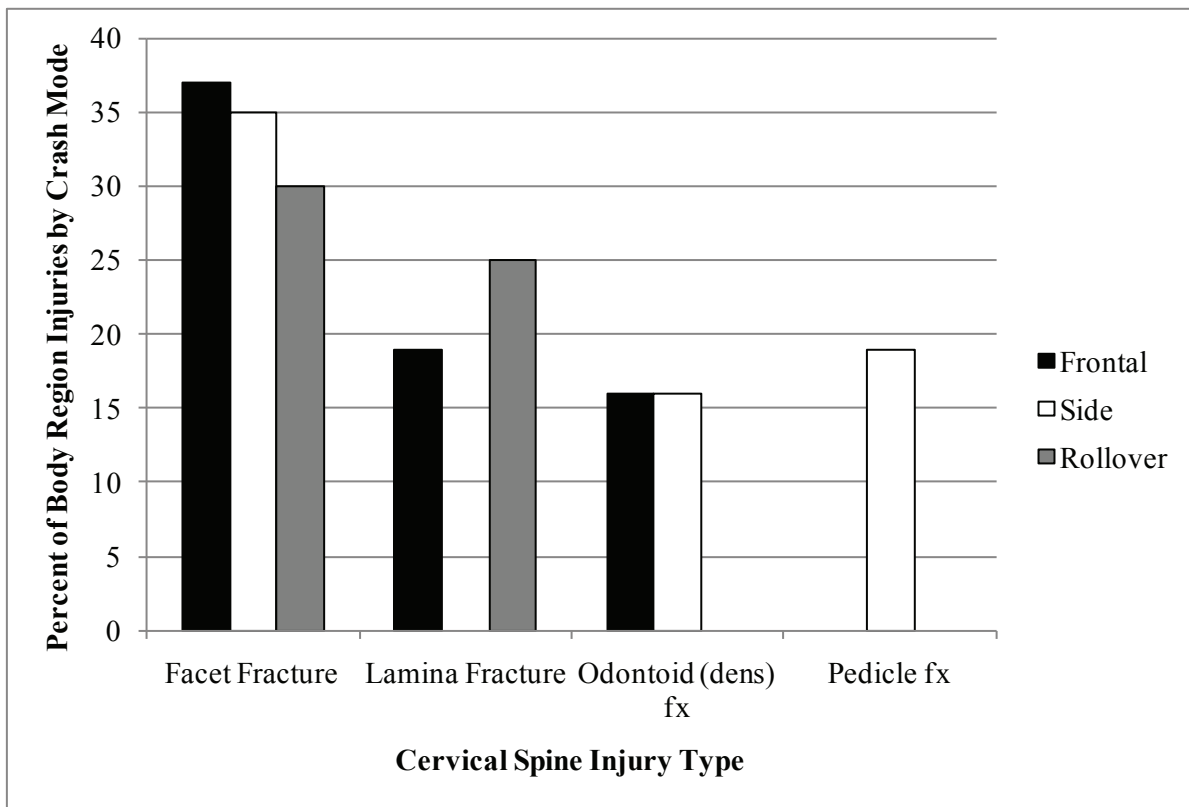


Figure 4. Three most common AIS 3+ C-Spine injuries as percentages of the total number of C-Spine injuries by crash mode.

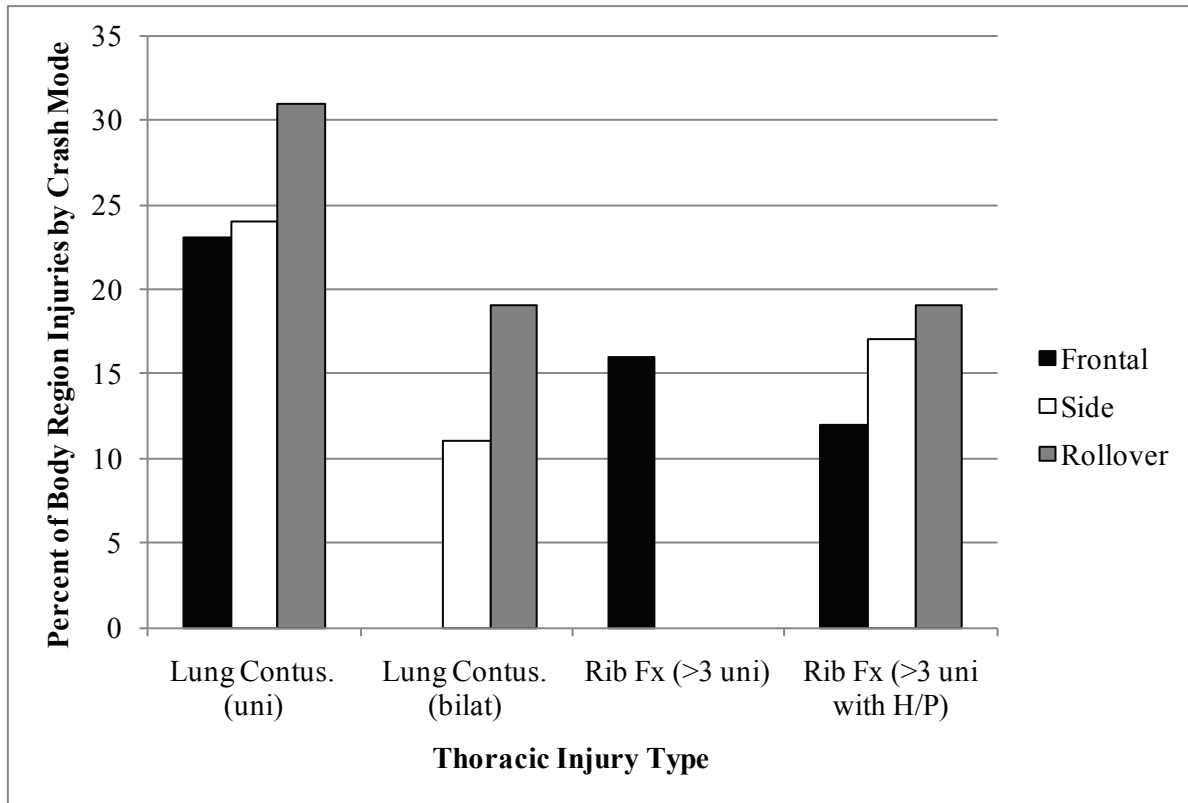


Figure 5. Three most common AIS 3+ thoracic injuries as percentages of the total number thoracic injuries by crash mode. (H/P = hemo- or pneumo-thorax)

As expected, in side crashes, the door interior is the most frequent IPC for thoracic injuries. For head injuries, the IPCs coded by crash mode are generally as expected, but surprisingly indicate that the roof siderail is the most frequently coded IPC in rollover crashes. This is expected for the cervical-spine injuries regardless of crash mode as the head loading the roof siderail becomes the load path to the cervical spine and the resulting injuries. Ridella and Eigen (6) showed the strong association of cervical-spine injuries to roof siderail contact in their analysis of occupants in CIREN rollover crashes.

Figure 6 shows the most frequent contributing factors in the BioTab analysis of injury causation. Intrusion, particularly in T-type side impacts, lack of seatbelt usage, and old age are the most frequent contributing factors. Matching these factors to crash modes and injured body regions allows for possible countermeasure development in terms of restraint and/or vehicle structural enhancements.

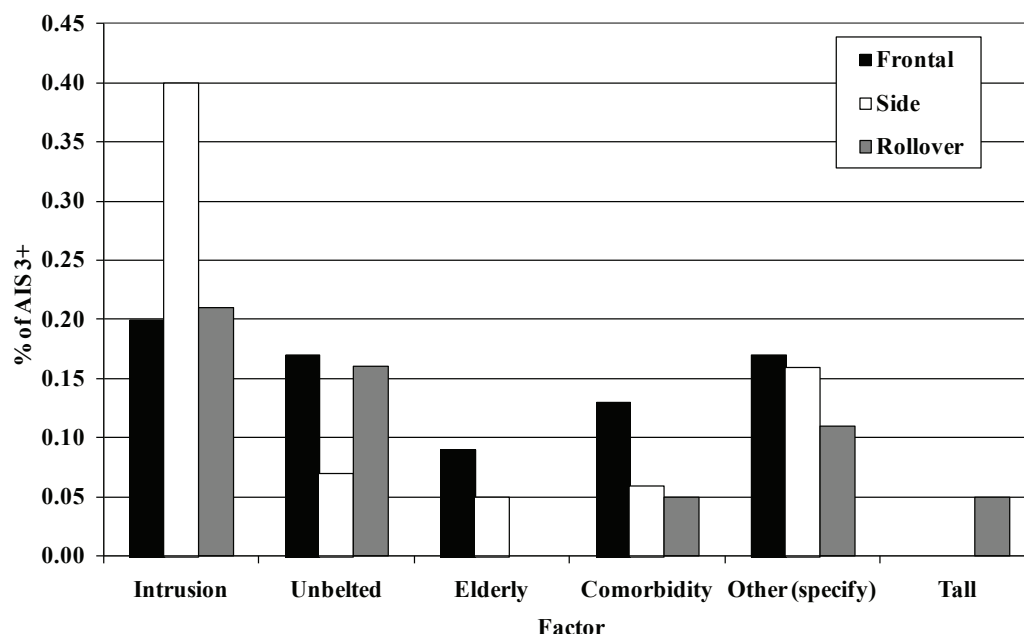


Figure 6. Top five contributing factors as percentages of all AIS 3+ injury in frontal, side, and rollover crash modes.

Examples of Injury Causation Analysis Using BioTab

Example 1: This case involves an 81-year-old belt-restrained male driver involved in a minor frontal single-vehicle crash. His late model compact vehicle was approaching a parking space at low speed when the driver inadvertently accelerated the vehicle through the parking space. The vehicle jumped a curb and struck a building perpendicular to the vehicle's path. The delta V calculated by WINSMASH for the impact with the building was 14 kph (8.7 mph). The vehicle damage (CDC code = 12UFDW01), which is shown in Figure 7, was to the front and minor, there was no intrusion of vehicle interior components into the driver space, and the steering-wheel airbag did not deploy.

As shown by the CT scan of Figure 8, the driver sustained fractures of the C4-C7 spinous processes and lamina fractures at C7 and T5. The C7 lamina fracture is classified as an AIS 3 injury. The Injury Causation Scenario for this injury includes the following:

Injury: C7 Lamina Fracture (AIS code = 6502243)

ICS Description: Head loading roof header (confidence = possible)

Source of Energy: Crash Event #1 (the undercarriage impact to curb, not the vehicle to building impact)

Involved Physical Component: Front roof header (confidence = possible)

Evidence: Vehicle acceleration (vertical), occupant kinematics, minor scalp contusion on right-front aspect of head observed in the CT scan.

Internal Path: Head to C-spine

Regional Mechanism: Compression/extension of the cervical spine

Contributing Factors: Occupant Age

Critical Intrusions: None

In narrative form, the undercarriage-to-curb impact caused both a longitudinal deceleration and a vertical acceleration of the vehicle that caused the driver to move forward and up relative to the vehicle interior. With no airbag deployment and relatively little space between the driver's head and the windshield header, the driver's forehead contacted the windshield header. Although there was no physical evidence of the head contact on the header, a head CT image indicated a contusion of the

upper-right region the scalp. This contact generated compression of cervical spine and, coupled with a resulting extension of the neck, caused the multiple spinous process and lamina fractures observed in the neck CT image.



Figure 7. Example-1 case vehicle damage



Figure 8. Sagittal CT scan of case occupant's cervical spine showing multiple posterior column fractures.

Example 2: This example involves a belt-restrained 8-year-old female seated on the left side of the second row of a late model compact sedan. The vehicle was entering an intersection when it was impacted in the middle of the left side by a two door sports car with a principal direction of force (PDOF) of 310 degrees.. The vehicle exterior damage (CDC code = 10LZAW03) is shown in Figure 9 and is confined primarily to the left-rear door with a maximum rightward intrusion of 9 cm. The calculated total delta V is 32 kph (20 mph of lateral delta V and longitudinal delta V). The case occupant's injuries include multiple brain lesions and diffuse brain bleeding and swelling. The BioTab analysis of the most serious brain injury is as follows:

Injury: Cerebrum Hematoma (AIS code = 1406524)

ICS Description: Head contact with striking vehicle (confidence = certain)

Source of Energy: Crash

Involved Physical Component: Hood of striking vehicle

Evidence: Crash direction and occupant kinematics as well as skin transfer on the hood and multiple facial fractures indicating direct contact. (confidence = certain)

Internal Path: None

Regional Mechanism: Linear acceleration (with likely resulting angular acceleration)

Critical Intrusions: Hood of striking vehicle

Contributing Factors: None



Figure 9. Exterior damage to vehicle in Example 2

Example 3: In this crash, a 30-year-old female driver lost control of her sport utility vehicle, and the vehicle departed the roadway and the left side struck a large tree (PDOF = 270 degrees). The vehicle damage (CDC code = 89LPAW04) shown in Figure 10 was severe and the lateral delta V was calculated at 45 kph (28 mph). The case occupant sustained bilateral hip (acetabular) fractures as shown in the MRI/CT image of Figure 11. The ICSs for these two hip fractures are described below. For the left hip, rightward intrusion of the driver door interior is a contributing factor and for the right hip interior-door intrusion is a critical factor in the ICS.

Injury: Left acetabulum fracture (outboard lower extremity) (AIS code = 8526043)

ICS Description: door loading of left hip (confidence = certain)

SOE: vehicle crash

IPC: door panel; IPC evidence: scuffmark (confidence = certain)

Internal Path: none

Critical intrusion: none

Contributing factors: intrusion of driver-door interior

ICS evidence: other injury (spleen laceration, pelvic ring fracture, right acetabulum fracture)

Regional mechanism: compression



Figure 10. Exterior vehicle damage for Example Case #3

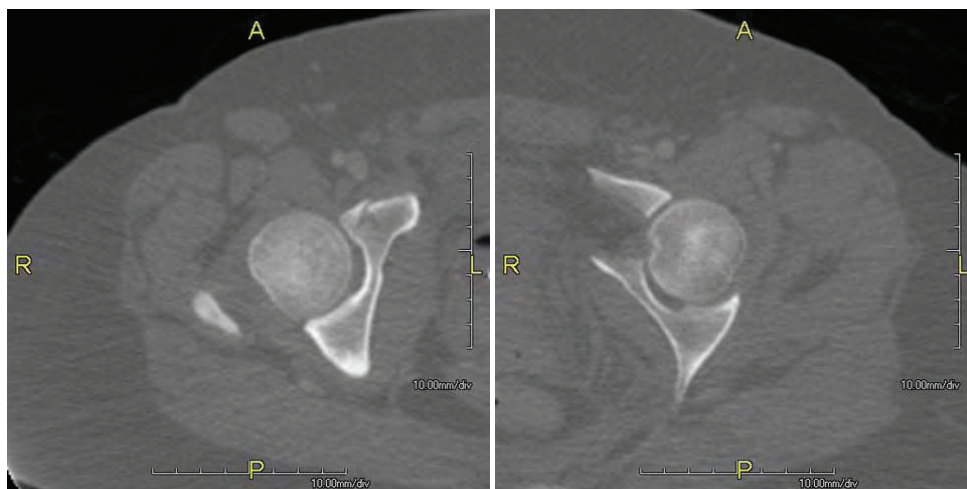


Figure 11. Image of case occupant showing bilateral acetabular fractures

Right acetabulum fracture (inboard lower extremity) (AIS code = 8526043)

ICS Description: Right hip loaded by center console with left hip loaded by door interior (nut-cracker scenario) (confidence = certain)

SOE: vehicle crash

IPCs: door panel AND center console/armrest; IPC evidence: component(s) deformed and/or scuffed (confidence = certain)

Internal Path: none

Critical intrusion: interior of driver door

Contributing factors: none

ICS evidence: other injury (left acetabulum fracture, pelvic ring fractures)

Regional mechanism: compression

DISCUSSION

A new approach to determining and documenting injury causation and injury mechanisms called BioTab has been used in the NHTSA's CIREN program. The BioTab method leverages the data collected from in-depth crash investigations and the detailed injury data available in CIREN to develop evidence-based assessments of injury causation and thereby improve the quality, accuracy, and completeness of the findings from in-depth crash investigations.

The three examples described in this paper highlight several strengths of the BioTab method relative to existing methods of recording injury causation and mechanisms. Example 1 demonstrates how the BioTab associates injuries with a particular crash event in a multiple event situation, uses minor injuries and medical imaging to establish injury causation, uses occupant kinematics and evidence from vehicle inspections to identify involved physical components, records injury mechanisms using biomechanically correct terms, and records relevant contributing factors. Example 1 also demonstrates how the BioTab leverages the medical imaging data and multidisciplinary expertise available in CIREN to determine injury causation. That is, in this case, there was no evidence of head contact in the vehicle or on the external surface of the occupant's scalp. Normally, a lack of this evidence would result in the C-Spine injuries being coded as being coded as a "non-contact" injury caused by inertial forces of the head pulling on the c-spine. However, with the medical imaging data available in CIREN, a sub-galeal hematoma was identified on the forehead, leading to this injury being coded to a head-contact scenario and a mechanism of c-spine compression-extension.

Example 2 demonstrates how Biotab identifies intrusions that are critical to the causation of injury. Example 3 further illustrates a case with one injury for which intrusion is critical and another injury for which it is a contributing factor. In Example 3, the left hip injury does not require door intrusion to occur even though the door intrusion can cause the injury to be more severe, and therefore the intrusion is considered to be a contributing factor. However, the injury to the right hip occurs from the hip loading the center console, which would not have occurred without the rightward intrusion of the door forcing the right hip into the center console. As a result, door intrusion is coded as critical for the right-hip injury. None of these factors are recorded or considered by other current methods used for determining and documenting injury causation from in-depth crash investigations. Further, no other methods of recording injury causation allow for coding multiple injury causation scenarios, associate multiple IPCs with a single injury, or require the evidence supporting the determination of injury causation be completely documented.

Other studies have demonstrated the utility of the BioTab data and method. Ridella and Eigen (6) demonstrated the application of the BioTab process to specific injuries of occupants involved in vehicle rollover crashes. By determining the injury mechanisms to the head, the cervical spine, and the thorax, the primary body regions injured by belt-restrained occupants in rollover crashes, vehicle countermeasures can be designed to reduce the risks of these injuries. In addition, response requirements for crash dummies to assess countermeasure effectiveness can be derived from this injury analysis technique. Maltese et al. (7) also used BioTab data and the BioTab method to identify contacts associated with AIS 3+ injuries to children in side impacts and to characterize the factors that are associated with the causes of these injuries. These data were used to suggest design changes to vehicles that will improve occupant protection for children in side impacts and that provide motivation for the design of improved child ATDs.

The injury data collected and analyzed in CIREN to date can provide more information regarding the effects of occupant health, age, and other co-morbidities. Over 20% of BioTab injury cases are occupants over 65 years. Further analysis of these data will enable a greater understanding of the causes of injuries to elderly occupants that is still not fully understood.

CONCLUSIONS

A new method for documenting the causation of injuries in motor vehicle crashes has been developed. This method addresses the limitations of current methods of injury causation coding by establishing the concept of injury causation scenarios, which includes:

- identifying the source of energy that caused an injury,
- identifying the physical components contacted by the occupant during the crash that set up the conditions resulting in the injury,
- identifying the body regions contacted by physical components,
- defining the internal paths between the body regions contacted by involved physical components and the body region in which an injury occurred.
- allowing alternative and multiple physical components to be coded,
- providing for identifying and documenting occupant, crash, and restraint system factors that contributed to the occurrence and/or severity of an injury,
- requiring documentation of evidence for each injury causation scenario and each physical component contacted by the occupant, and
- assigning levels of confidence to injury causation scenarios and involved physical components based on available evidence.

In addition, BioTab distinguishes between the scenario or scenarios by which an injury occurred and the physical, chemical, or thermal mechanisms resulting from those scenarios that produced the tissue damage constituting the injury being coded.

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Appendix A

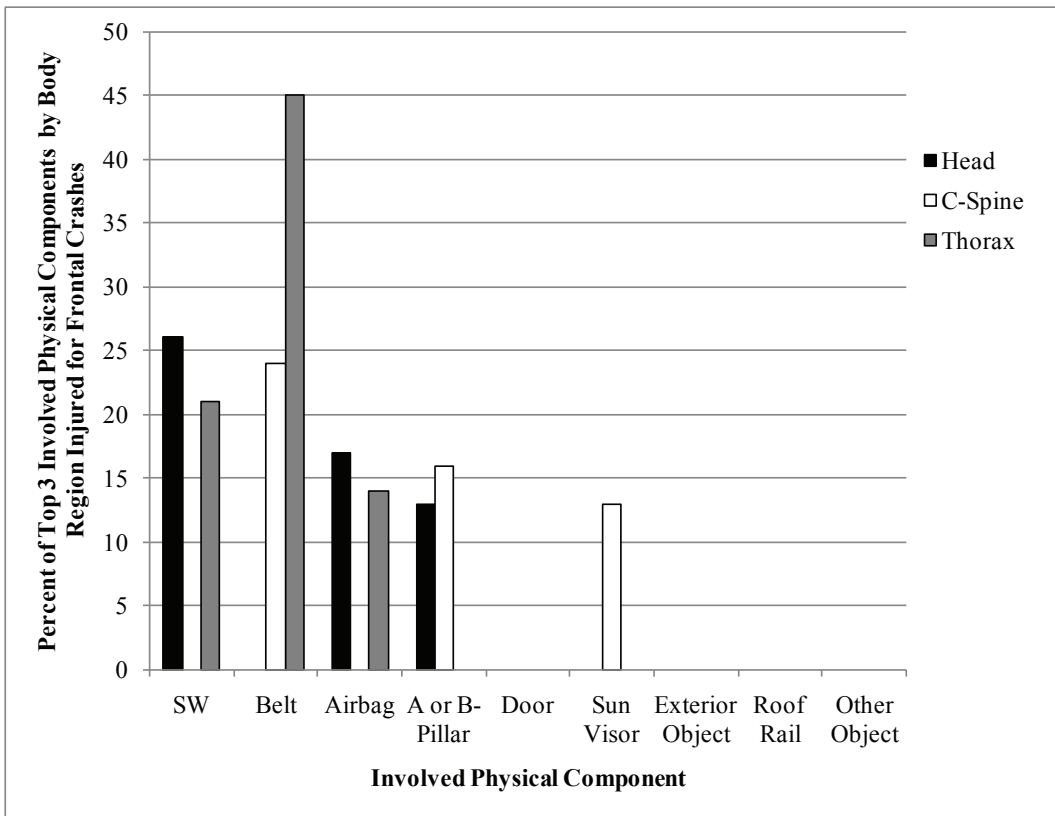


Figure A1. Percentages of the top 3 most frequent involved physical components for selected body regions in frontal crashes

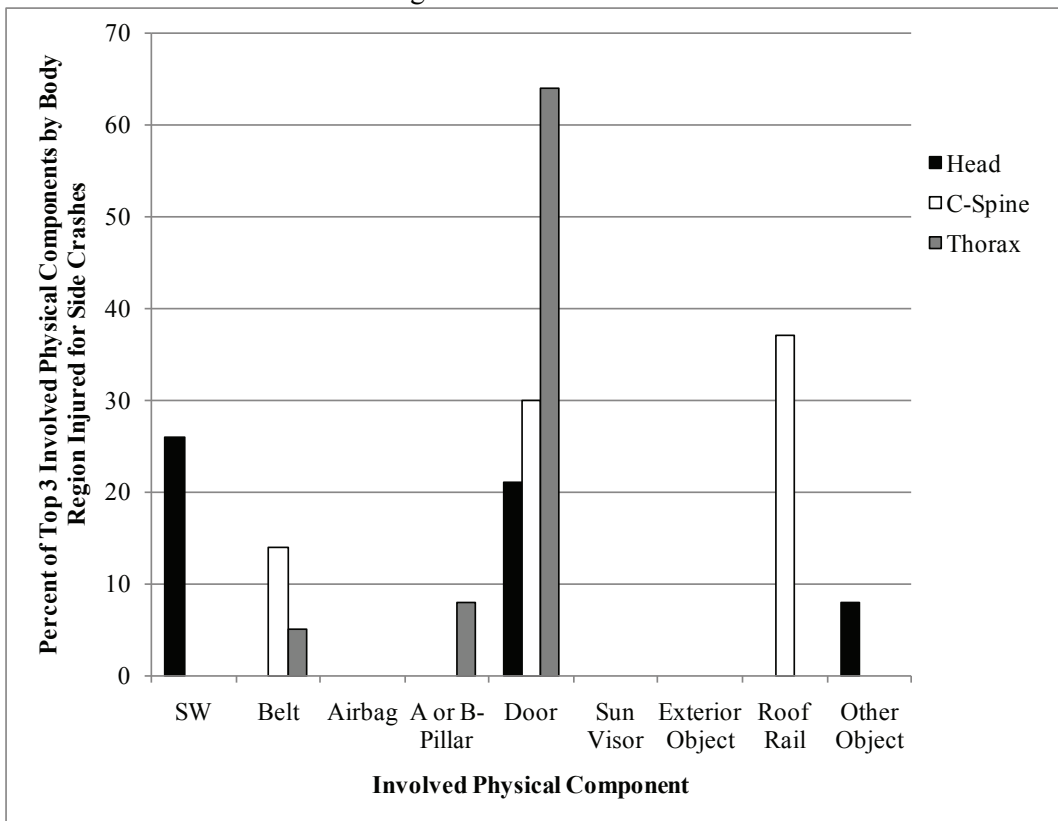


Figure A2. Percentages of the top-3 most frequent involved physical components for selected body regions for near-side occupant in side crashes

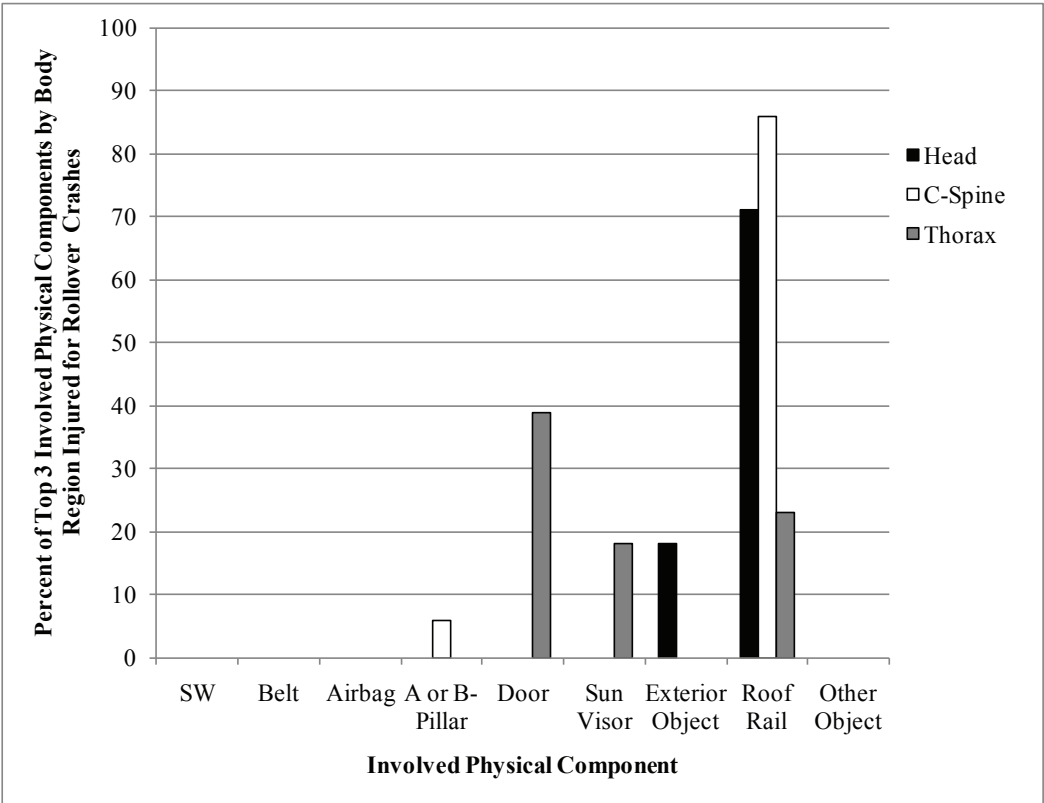


Figure A3. Percentages of the top 3 most frequent involved physical components for selected body regions in rollover crashes

Appendix B

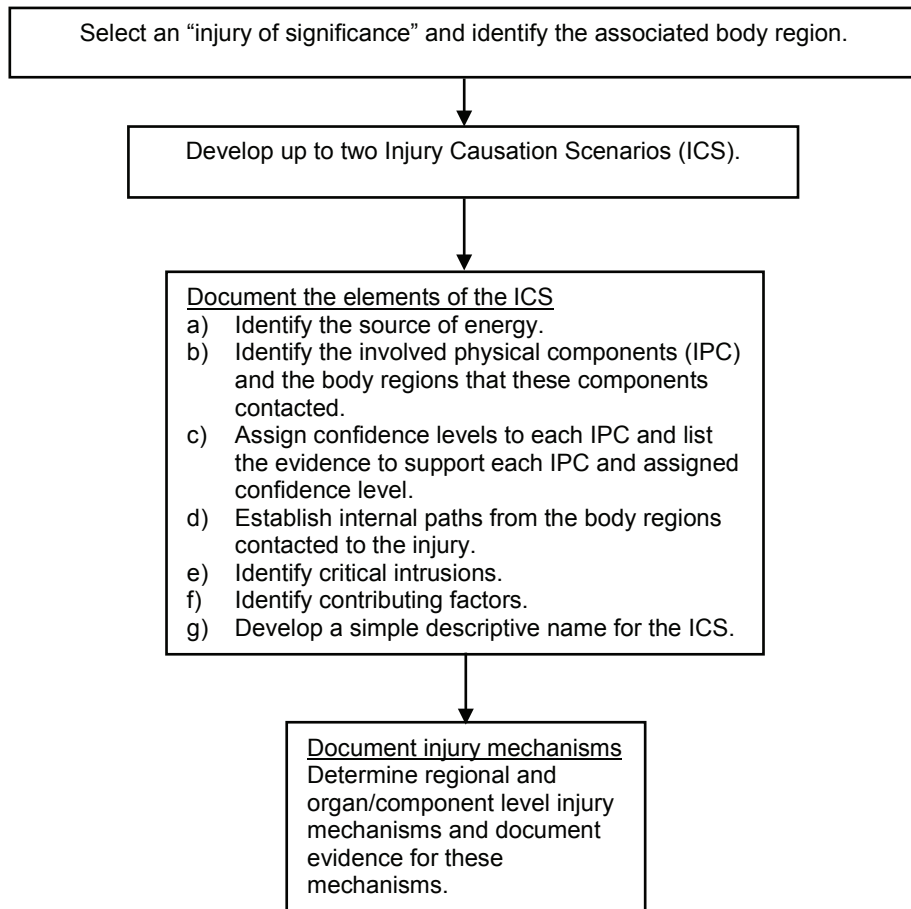


Figure B1. Flowchart summarizing the key steps used in applying the BioTab method to CIREN data.