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Chest Injury Mechanism in a Frontal Impact

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Paper was presented at the 22nd Annual Workshop on Human Subjects for Biomechanical Research. This paper has not been screened for accuracy nor refereed by any body of scientific peers and should not be referenced in the open literature.

BACKGROUND

The human thorax is one of the most frequently injured regions in frontal impact. Biomechanical evaluation should be based not only on epidemiological studies, but also on controlled laboratory investigations (4, 13, 14). While epidemiological studies reveal the type of trauma and may disclose injury mechanism, it fails to characterize the dynamic Biomechanical response of the human body during impact. One of the ways to conduct a laboratory investigation is to use an unembalmed human cadaver and subject the specimen to deceleration forces using a sled. Under this environment it is possible to use realistic restraint combinations such as air bag, knee bolster, lap and/or three-point belts. Although the human cadaver is not an exact replica of the living human, because of the similarity in anatomy and Biomechanical parameters, the results from these studies will help to understand the biodynamic response of the living human. This data can be used in the delineation of human tolerance, identification of injuries to hard and soft tissues, advancement of mathematical models, development of anthropomorphic test devices with improved biofidelity, and to evaluate the injury mitigating characteristics of the vehicle interiors.

Although significant research have been conducted in the past to delineate the Biomechanical response of the human thorax using cadavers and/or animal models, little information is available that describes the behavior of the thorax under realistic restraint systems. For example, the majority of the previous research focused on the response of the human thorax to blunt impact loading conditions. In principle, these data are applicable to an unrestrained occupant but do not simulate the effect of restraint loading, such as air bag or seatbelts, in a frontal impact situation (13, 14). One of the earlier experimental air bag and lap belt studies using living animals was conducted at the Holoman Air Force Base (9). These studies indicated that the baboon tolerance to frontal impacts at 48 to 64 kph exceeds 57 G. Due to lack of appropriate instrumentation, it is not possible to use the data from previous human cadaver data from car-to-car as well as sled tests to derive the thoracic deformation contours and correlate the trauma with biomechanics. Therefore, this study was developed to investigate the biodynamics of the human thorax under simulated frontal impact using air bag - knee bolster, air bag - lap belt, and air bag - three-point belt systems. The study was designed to determine the differences between the thoracic trauma quantified using autopsy and radiography. The mechanisms of skeletal damage under these restraint combinations are discussed.

MATERIALS AND METHODS

Fourteen unembalmed human cadavers, ranging in age from 29 to 81 years, height from 150 to 182 cm, weight from 41 to 84 kg were used. The subjects selected were screened for Hepatitis A, B and C, as well as the human immunodeficiency virus. Further, specimens were selected based in an evaluation of medical records and x-rays to exclude specimens with severe degenerative disease, and/or metastatic disease. All studies were performed in a hospital environment and even though the specimens were negative for infections, precautions similar to those in an operating room were followed during the study. Following specimen procurement, they were prepared and anthropomorphic data such as seated height, chest

circumference and chest depth, were obtained in accordance with the National Highway Traffic Safety Administration (NHTSA) specifications. Specimens were pressurized to approximate the *in vivo* pulmonary and vascular characteristics. Two chest bands were mounted on each preparation, the first or the upper level chest band covered the midsternum region approximately at the anterior level of the fourth rib, and the second or the lower chest band covered the xiphoid process approximately at the level of the sixth rib anteriorly (4,7). The specimens were prepared with accelerometers fixed to the skull in the temporal region, and at the C7/T1 and T12 spinous processes. To document the kinematics of the specimen during impact, photo targets were placed at the head, first thoracic vertebral level, hip, knee and shoulder regions. Specimens were positioned in the driver's seat of the buck. Force transducers were placed to document the belt loads. The standard lap and shoulder belt combination was used for the three-point belt test, and an extruded polystyrene foam was used to simulate the knee bolster.

All tests were conducted using a horizontal deceleration sled. The test was finished at 1000 f/sec with a left side onboard camera. The specimen kinematics documented with the photo targets was transferred into a motion analyzer for data processing. A new restraint system and steering column were used for each test. Biomechanical data were recorded using an onboard data acquisition system according to the Society of Automotive Engineers SAE J211b specifications. Data processing of the chest band output signals included a transformation of the individual curvature signals to obtain the deformation histories. The thoracic deformation contours were compared using RBAND_PC software from NTHSA (7). The pattern, the peak deformation, and the time of occurrence of the peak chest deflections were extracted for the upper and lower chest bands.

RESULTS

Primary results of the thoracic deformation contours and the overall kinematics of the specimens using the photo targets have been presented at the 37th Stapp Conference (14). Briefly, the kinematics of the specimen varied among the three restraint combinations. In the air bag - knee bolster restraint system experiments, the specimen kinematics indicated the contact of the knee with the knee bolster to occur approximately at the time of full deployment of the air bag (40 ms). With the knees further loading the knee bolster, the lower torso initially contacted the air bag in the region of the lower rim of the steering wheel. The upper torso loaded the air bag and the lower regions of the thorax continued to load the air bag and the lower wheel rim. In the air bag - lap belt experiments, the pelvis was restrained by the lap belt during the period of full deployment of the air bag (40 ms). The upper torso pivoted around the restraint and contacted the air bag following its full deployment. In the air bag - three-point belt restraint system, the belt loaded the specimen prior to air bag contact. The shoulder belt reached its peak forces during the time the specimen was in contact with the air bag. In the air bag - lap belt and the air bag - knee bolster tests, permanent deformations of the steering wheel occurred. In contrast, little or no residual steering wheel and column deformations occurred in the air bag - three-point belt restraint tests.

Normalized peak chest deflections at the upper thoracic levels for the air bag - lap belt and the

air bag - three-point belt systems were greater compared to the normalized chest deflections at the lower thoracic level. In contrast, the air bag - knee bolster combination indicated higher levels of normalized chest deflections in the lower level compared to the upper thoracic level. While no differences were observed in the time of occurrence of the upper and lower peak chest deflections between air bag - knee bolster and air bag - lap belt combinations, the introduction of the tree-point belt system produced early peaks ($p < 0.01$), both at the lower and upper levels of the thorax. The thoracic deformation contours indicated a uniform compression of the thorax in the anterior region for the air bag - knee bolster and the air bag - lap belt system and a region of localized loading of the thorax by the shoulder harness for the air bag - three-point belt system.

The injury patterns for the air bag - three-point belt combinations demonstrated rib fractures to occur in the region where the shoulder belt loaded the chest or, on the lateral-most aspect of the rib cage on the right side. Routinely, ribs two to eight showed skeletal damage. In contrast, in the air bag - knee bolster tests, bilateral rib fractures occurred primarily in the lower portion of the rib cage secondary to the contact of the chest with the lower medial portion of the steering wheel and rim. In this case, ribs four to seven demonstrated skeletal trauma with no fractures in the lateral aspect of the cage compared to the shoulder harness - air bag combination. The lowest number or fractures occurred in the air bag - lap belt system. There were more right sided rib fractures in the other two restraints compared to the air bag - lap belt system.

A total of 59 rib fractures were identified at autopsy. In contrast, only eleven rib fractures were identified from the clinical radiographs. It should however, be emphasized that all the rib fractures identified at autopsy were such that no laceration of the costal pleura occurred. In addition, no internal vital organ trauma occurred under any of the restraint combinations.

DISCUSSION

Rib fractures were identified in all specimens (except one) during autopsy. The costal pleura was not torn. Clinical radiography however, did nor identify all these fractures. In fact, only one out of five fractures were apparent on x-rays. Rib fractures alone do not constitute a life threatening injury except in severe cases such as flail chest which may occur secondary to multiple bilateral rib trauma (1-2,11). It should be noted that the physical findings of a rib fracture are often non specific and the routine clinical impression of the likelihood of rib fracture is not always reliable due to the functional characteristics of the thorax. Clinically, a negative chest film does not rule out rib fracture.

The majority of previous Biomechanical studies have used autopsy data, particularly the rib fractures, to quantify the thoracic trauma based on the Abbreviated Injury Scale (AIS). One of the principal reasons for adopting this methodology is that it obviates the need to have radiographic equipment and more trauma can be visualized during a detailed autopsy. While this approach is logical, it should be emphasized that the AIS is developed for the living human where clinical findings are used to assess the severity of the injury (10). Human cadavers do not permit similar *in vivo* evaluations. It may be appropriate to develop a scaling

factor if the AIS rating is based on autopsy in human cadaver tests.

While the present study identified skeletal trauma in all specimens, no internal organ injuries occurred in any case. This result is in good agreement with literature (5,8,12). Clinically, thoracic trauma is principally governed by the status of the intrathoracic components and often assessed as hemo or pneumothorax, major vascular trauma and pulmonary contusion. These types of trauma cannot be easily assessed in an unembalmed cadaver. Differences in the intrathoracic pressure dynamics between the living human and the cadaver, and the absence of respiration in a cadaver are among the contributing factors. The type of trauma observed in the present study may also be due to the severity of impact. All tests were conducted at 32 or 48 kph. At higher changes in velocity (e.g., 56 kph) it is reasonable to hypothesize that the significant increase in kinetic energy may induce more severe rib cage trauma and instability thus resulting in penetrating the costal pleura and/or soft tissue trauma to the human thorax.

Based on the pattern and location of the rib fractures identified at autopsy, as well as the kinematics during impact, mechanisms of rib injury can be derived. In the air bag - three-point belt restraint system, injuries were concentrated typically along the right edge of the shoulder harness and along the lateral-most region of the rib cage on the right side. Fractures along the belt are initiated by the focal compressive forces in the anteroposterior direction. This compressive load increases the radius of curvature at the lateral edge of the rib, thereby initiating fractures due to a bending reaction. Depending on the local yield and failure characteristics, fracture may occur at one or both of these regions in the rib cage. A similar pattern of trauma was observed in our previous sled studies with three-point belt restraint (13). These findings suggest that the air bag - three-point belt restraint loading is similar to the three-point belt restraint (in the absence of the air bag) loading on the human thorax to result in the chest injuries. In other words, it is likely that the skeletal trauma is induced by the harness belt prior to air bag loading the thorax. Consequently, it may be appropriate to study the stiffness, elongation, and loading characteristics of the belt if these injuries are to be mitigated.

For the air bag - knee bolster tests, bilateral injuries to the anterior region of the rib cage occurred with no injuries to the lateral areas. The mechanism of injury is secondary to the direct contact of the lower torso with the lower portion of the steering wheel rim resulting in fractures at this region without concomitant propagated skeletal trauma at the lateral site. A similar mechanism of injury could explain the rib fractures sustained in the air bag - lap belt experiments. The pivoting action of the harness around the hip and the likely lesser area of contact of the torso with the air bag may explain the fewer fractures.

ACKNOWLEDGMENT: This research was supported in part by the DOT NHTSA Grant DTNH22-93-Y-17028, and the Department of Veterans Affairs Medical Research Service. All findings and views reported here are based on the opinions of the authors and do not necessarily represent the consensus or view of the funding organizations. We also wish to acknowledge the assistance of Karl Pintar, M.D., Chief Pathologist (Ritired) in the conduct of the pathological evaluations.

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DISCUSSION

PAPER: **Chest Injury Mechanism in Frontal Impact**

PRESENTER: Narayan Yoganandan, Medical College of Wisconsin

QUESTION: Robert Levine, Wayne State University

Just a few comments. One, x-rays are not our only method of diagnosing fractures and treating patients. We take x-rays after we have seen a patient, evaluate the patient and decide that there may or may not be an injury there. No, we do miss real fractures. I believe we said this twenty years ago at Wayne State University; we were looking at three-point belts. We said we saw more fractures in autopsy than we saw in x-rays. We treat patients and not x-rays. We can pick up fractures other ways if we have to, but, again, it's more important what we think, rather than the x-rays.

ANSWER: I'm sorry if I've given you the impression that x-rays are the only means of looking at a patient and evaluating the trauma. The reason for me to use clinical x-rays is to recognize and identify rib fractures. Then looking at the biomechanical community, which has traditionally looked at the autopsy data, to primarily look at x-rays as one of the means to use the AIS rating which is not just a duplicate of autopsy data. As I understand it, the AIS is not set up for just autopsy data. So in other words, there is probably an overrating, or you need some kind of a scaling, when you go from an AIS rating usage for an autopsy to an AIS rating usage for a clinical patient.

Q: Guy Nusholtz, Chrysler Corporation

In a live individual, you have other factors which influence the bone which can make some of the x-rays materialize a little bit better. In fact, we have calcification and migration of calcium towards the fracture site which can make an x-ray in a live subject then have more indications of fractures as opposed to a post mortem subject. One of the questions I had is, why choose that particular three-point bending test as opposed to a four-point bending test or something which has the larger area under the center pull to prevent local fractures, and did you try to get a modulus out of your testing procedure?

A: No. I did not try to get a modulus out. Maybe we can look for the data. It is not a big deal to get a modulus out, whatever the applicability may be. The reason for selecting a three-point bending test was that it has been done before; we just wanted to compare. That was the only thing. We could have done a four-point bending test where you have a region of constant moment and you would be testing for failure due to pure bending.

Q: You can get a lot of scatter just by the fact that you get local crushing and so you've got somewhat of a negative response there, and maybe it's just, if you get a slightly different bending procedure, you might be able to get a better correlation.

A: But the disadvantage with the four-point bending test, when you are dealing with a rib, a particular isolated rib, is that you may not have enough span and because of the curvature and the shape of the geometrical orientation, it may not be easy to do a four-point bending

test as you look for simply supported beam with straight ends. So there are pluses and minuses for both the tests.

Q: OK. Thank you.

Q: Jeff Crandall, University of Virginia

Yoga, I was sort of interested in that you didn't find an improvement in the detection of fractures using obliques or laterals. Given that the belted occupants had a lot of fractures on the lateral sides, what we found in Virginia is that we got improved detection. In fact, we found the ultimate was CT but the expense simply wasn't worth it. I wonder if you want to comment on that.

A: Did you have the same three-point belt system? It also depends on the severity of the fracture. If you have a very severely displaced fracture, the costal pleura is torn. Maybe you will see that some of the fractures that we got were really minor fractures and if you had used the AIS, the rating would have really gone up. That is probably one reason why an additional oblique or film, for example, did not accentuate the identification of the rib fractures.

Q: But in theory these lateral fractures are in parallel with the AP view. So you would expect an improved detection by taking oblique or lateral.

A: Well, you remember one other thing also is you are making an assumption that in theory the AP is perpendicular to the lateral, Number One. And if you look at the complex anatomy of the rib cage and the way in which it criss-crosses and all, depending on the type of fracture and the severity of fracture, it may or may not show up.

Q: Oh, I agree. You may not still detect them all but you'll get an improved percentage of detection. I think we found in a workshop paper a couple of years ago that we did on this, that it was vastly improved, almost twice the number.

A couple of quick ones. The speed of the sled. Were they common for all tests, like thirty mile per hour?

A: Roughly, yes.

Q: And what's the percent of the elongation for the lap and shoulder belt?

A: It was a standard lap and shoulder belt. I believe it is six percent.

Q: Six percent on both of them?

A: Yes.

Q: OK. And now, did we get any assists from knee bolster on the three-point belt test?

A: I don't understand your question when you say "assists".

Q: Did we have any contact between the knee and the knee bolster on the three-point test. It's not part of your combination, but based on what I see of your results, it seems to me it would help if you have some assists from a knee bolster with a three-point belt; you can reduce some of the forces.

A: If you particularly have the knee bolster sitting very close to your knee, maybe you will have some assistance. But if the knee bolster is a good three or three and a half inches away, I suspect whether you will get any kind of an assist or changes in the kinematics because of the knee bolster, because primarily the torso belt prevents the occupant from going and hitting.

Q: Thank you.

A: You're welcome.

Q: Peter Orner, M.D. (California)

On the rib fracture, I think there is a problem in what you did with use of the x-rays. In the first place, you had cadavers, and in the second place, you listed the cause of death as pulmonary. The lungs in these cadavers are probably not normal. I think that is a fair statement. Probably a higher fluid content than in you or me right now.

You took what looked like to me to be ordinary chest films. These were not rib films to characterize rib fractures. The closest thing was when you gutted out the chest, that was a rib film. That is precisely what a rib film is in clinical practice. You over penetrate to have the x-rays go right through the viscera to show the ribs alone. So I don't think you parallel well, it doesn't appear you parallel well the clinical, (or) I should say the actual use of x-rays in dealing with live people.

The last thing is from a standpoint of data collection for biomechanics which you should have done, what you should look at, so far as the efficacy of chest x-rays in picking up fractures a month or two later on a living person after there is callous formation, then you can retrospectively say there was a rib fracture there, and that is a common way we pick up rib fractures anyway. The obvious rib fracture was picked up on a chest film as a displaced rib fracture. You didn't have very many and your examples you showed had no displacement.

A: We did not get any displaced rib fractures. You track in a clinical situation after six or eight weeks, you can kind of conjecture, there was a rib fracture before because of the physiologic changes that happens to the body. Regarding the chest films we took, the films which I showed you, a few of them were real rib films per se, but we did change them. We probably did about four to eight times the number of x-rays that is commonly done on a patient. In terms of it was not a regular chest x-ray; we did change the radiation exposure. We did do a number of iterations in terms of the radiation exposure because it was a cadaver, and who cares?

Q: Oh yes. The point about that is, though, you can't ask the cadaver to turn a little bit so you get a better view. Can you?

A: No, I give you that. That is correct. You cannot ask a cadaver and also there are differences in the lungs and the internal tissues and all. Yes, that we all have to live with because it is a cadaver. We don't have a choice as far as I know.

Q: OK.

A: Thank you.