ASSESSMENT OF THORACIC INJURY CRITERIA FOR SIDE IMPACT

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ABSTRACT

A series of 34 side impact tests conducted at the Medical College of Wisconsin and at Ohio State University using post-mortem human subjects in a Heidelberg type sled, were examined for the purpose of developing and assessing thoracic injury criteria for side impact. The effects of three test conditions were investigated: test speed (24 or 32 kph), impact surface (padded or rigid), and pelvic offset (present or absent). The post-mortem human subjects were instrumented with accelerometers on the ribs and spine and chest bands around the thorax and abdomen to characterize their mechanical response during the impact. Load cells at the walls measured the impact force at the level of the thorax, abdomen, pelvis, and lower extremity. The resulting injuries were determined through radiography and detailed autopsy and their severity was coded according to the AIS 90 Scale. Rib fractures were the most common injury type with injury severity ranging from AIS=0 to AIS=5. Chest deflections were derived by using the chest band data to compute the chest contours at every millisecond during the event.

The test data were analyzed using statistical techniques such as ANOVA, linear regression, logistic regression, and categorical analysis. Several existing candidates for side impact injury criteria were evaluated such as Thoracic Trauma Index (TTI), Average Spinal Acceleration (ASA), chest deflection, chest velocity, chest VC, peak and average contact force, stored energy criteria (SEC) and energy storing rate criteria (ESRC) for their injury prediction ability. The age of the subject was found to influence injury severity while gender and mass were found to have little or no influence on injury response. Accelerations filtered with SAE Class 180 filters were better predictors of injury than accelerations filtered with SAE class 600, 60 or FIR100 filters. Maximum normalized chest deflection (dmaxn) was a better predictor of rib fractures (R^2=0.54, p-value=0.0001) and injury severity based on AIS (score p-value=0.0001, Gamma=0.71) than any other existing injury criteria with TTI being the next best predictor of injury severity based on AIS (score p-value=0.0012, Gamma=0.64). Maximum normalized resultant upper spine acceleration (rspu180n) was the best individual predictors of injury severity based on rib fractures and maximum AIS levels with a p-value=0.0001. A model using a linear combination of age, dmaxn, and rspu180n was a significantly better predictor of rib fractures and injury based on AIS (p-value=0.0001, Gamma=0.86). Similarly, a model using a linear combination of age and the product of dmaxn and rspu180n was also a good predictor of injury severity (p-value=0.0001, Gamma=0.85).

KEYWORDS: side impact, injury criteria, thorax

DESPITE THE IMPLEMENTATION of a federal standard for side impact in 1990, the biomechanics community has not accepted a universal injury criterion for the thorax. The EU injury criteria utilizes the chest deflection and VC as the side impact injury criteria while the US standards use TTI for side impact regulation. The Thoracic Trauma Index (TTI) is a chest acceleration based measurement which was developed using data from 84 cadaver sled tests (Eppinger, 1984, Morgan et al., 1986).

Stalnaker et al. (1979) and Terriere et al. (1979) analyzed force deflection data of the struck side half thorax in a series of cadaver lateral drop tests onto an unpadded or padded force plate. They found chest compression to correlate better with thoracic injury than thoracic accelerations. Using the results from these studies, EU applies a threshold on maximum chest deflection (42 mm) and maximum VC (1.0) in their regulation.

Lau and Viano (1986) analyzed data from 123 frontal impacts to anesthetized rabbits from which they proposed the Viscous Criterion, an injury criterion based on the product of peak chest deformation velocity and peak normalized chest deflection to predict thoracic soft tissue injury. Viano (1989) analyzed the data from a number of cadaver impactor tests in side impact and found that the peak viscous response VCmax and peak chest compression were better predictors of thoracic injury than acceleration based criteria.

Wang (1989) performed an analytical study of the mathematical and physical properties of the viscous criterion and proposed energy concepts such as Stored Energy Criterion (SEC) and Energy storing Rate Criterion (ESRC), Dissipated Energy Criterion (DEC), and Energy Dissipating Rate Criterion (EDRC) as candidates for thoracic injury assessment. Through mathematical manipulation, the SEC was found to be proportional to the square of chest compression while the ESRC is proportional to the square of chest viscous criterion.

Cavanaugh et al. (1993) reported the results of seventeen sled tests using the Heidelberg type sled setup with unembalmed cadavers and found that chest compression, Viscous Criterion (VC), and Average Spine Acceleration (ASA) were more predictive of thoracic injury than acceleration and force based criteria. According to Cavanaugh, ASA is a measure of rate of change of momentum transfer and is effective in predicting the injury reducing abilities of soft padding.

Pintar et al. (1997) analyzed the data from a series of twenty-six human cadaver sled tests using the Heidelberg type sled system with thorax, abdomen, and pelvic wall to better understand side impact injury tolerance. The cadavers were instrumented with accelerometers and chest bands from which thoracic deflections were computed. The resulting injuries were mainly rib fractures with injury severity ranging from AIS=0 to AIS=5. Assessment of existing injury criteria using logistic regression suggested TTI to be a better predictor of injury than ASA or maximum normalized chest deflection (C). A new injury criteria TTI*C, a product of maximum normalized chest deflection and TTI yielded the best statistical outcome compared to any of the existing criteria examined. This study had a large enough sample size, however there was not a detailed analysis of all existing injury criteria.

Chung et al. analyzed the data from limited stroke high energy impacts to six cadaveric subjects at the level of the sixth rib. This study suggested that chest deflection and the energy generated in a lateral velocity pulse impact correlated with the number of rib fractures better than acceleration or the viscous response of the struck side rib cage. Injury criteria based on acceleration (TTI, R^2=0.033) or the viscous response (VCmax, R^2=0.007) did not correlate with the number of rib fractures. Chest deflection or stored energy criteria correlated well to the number of rib fractures. However, this was a very small sample size (6 tests) and all the cadaveric subjects had serious or severe injuries.

The current study is an extension of the Pintar (1997) study. Thirty four side impact sled test data using post-mortem human subjects conducted at the Medical College of Wisconsin and Ohio State University were analyzed using various statistical analysis procedures. Existing thoracic and abdominal injury criteria such as TTI, ASA, chest deflection, VC, Stored Energy Criteria (SEC), and Energy Storing Rate Criteria (ESRC) were computed for each test and the injury predictive ability of these existing criteria were evaluated for the available data. Further, using regression methods, new injury functions were developed and their injury predictive ability was assessed.

TEST METHODOLOGY

A series of 34 human cadaver tests with chest band instrumentation was conducted to assess impact injury tolerance under side impact loading conditions (Appendix). Testing was conducted at the Medical College of Wisconsin (MCW) and at Ohio State University (OSU). A Heidelberg type side impact sled test apparatus configured for left sided impacts was utilized at both test centers. The human subjects at MCW were unembalmed fresh and frozen human cadavers while those at OSU were all fresh cadavers. The cardiovascular system of the cadavers was pressurized to approximately in-vivo conditions. The pulmonary system was pressurized prior to impact and then left open to atmospheric pressure (Pintar, 1996).

Instrumentation of the cadaver included the following: triaxial accelerometers fixed to T1 or T2 vertebra, T12 vertebra, and sacrum, uniaxial accelerometer fixed to the left lateral portion of rib 4 and rib 8 to measure medial-lateral acceleration and accelerometer fixed to sternum to measure anterior-posterior acceleration. The load wall was instrumented to measure impact forces at the levels of mid thorax, abdomen, and pelvis. Both the test centers instrumented the surrogate with two 40 channel chest bands at the level of rib 4 and the 7^{th} rib. Side impact tests were conducted under a variety of different configurations: two different velocities, 24 kph and 32 kph; flat rigid wall; flat wall with 10 cm of Ethafoam LC200 padding; and rigid or padded wall with pelvic load plate offset by 12 cm to represent an armrest.

Following the tests, the human subjects were radiographed and necropsied to delineate any trauma to the hard and soft tissues that occurred during the impact event. The injury severity was coded according to the AIS 90 manual (Abbreviated Injury Scale, 1990). AIS was assigned to rib fractures as follows: 1 rib fracture: AIS 1; 2-3 rib fractures: AIS 2; >3 rib fractures on only one side of chest: AIS 3, >3 rib fractures on both sides AIS 4. In each case, the presence of haemo/pneumo thorax or flail chest increased the AIS level by 1. A haemo/pneumo thorax was assumed when there were pleural tears caused by the fractured ribs. A flail chest was considered to be an unstable chest wall which was determined by the individual pathologist at each test center.

Details of the test apparatus, cadaver preparation, and instrumentation are provided in Pintar et al. (1996, 1997).

DATA ANALYSIS

Transducer data were processed using various filter classes and the appropriate filter classes were applied for computing existing injury criteria. The rib and spinal acceleration signals were filtered with SAE Channel Class 600, 180, and 60 filters, and FIR100 filters. Resultant upper and lower spinal accelerations were computed. The thoracic, abdominal, and pelvic force signals were filtered with SAE Class 600 and 180 filters. The accelerations and forces were normalized using the equal velocity-equal stress scaling procedure outlined by Eppinger et al. (1984) as shown in Equation 1.

$$\text{acceleration}_{norm} = \text{acceleration} * \left(\frac{\text{mass}}{75\text{ kg}}\right)^{033}$$

$$\text{force}_{norm} = \text{force} * \left(\frac{75\text{ kg}}{\text{mass}}\right)^{0.66} \qquad (1)$$

where mass = mass of subject in kg. standard mass = 75 kg

The FIR100 filtered peak rib 4, rib 8, and T12 lateral accelerations (rlu100, rll100, spl100) and the age and mass of the subject were used to compute the Thoracic Trauma Index (Eppinger, 1984) given by Equation 2.

$$\text{TTI} = 1.4 * \text{age} + \frac{1}{2}(\text{rib100} + \text{spl100}) * \frac{\text{mass}}{75\text{ kg}} \qquad (2)$$

where rib100 is the maximum of (1.3 * rlu100 − 2.02) and rll100

The SAE Class 180 filtered T12 lateral acceleration (spl180) was used to compute Average Spinal Acceleration ASA10, ASA15, and ASA20 as defined by Cavanaugh (1993). The average spinal accelerations were normalized for age and mass using Equation 3.

$$\text{ASA} = \text{ASA} * \frac{\text{age}}{45} * \frac{\text{mass}}{75\text{ kg}} \qquad (3)$$

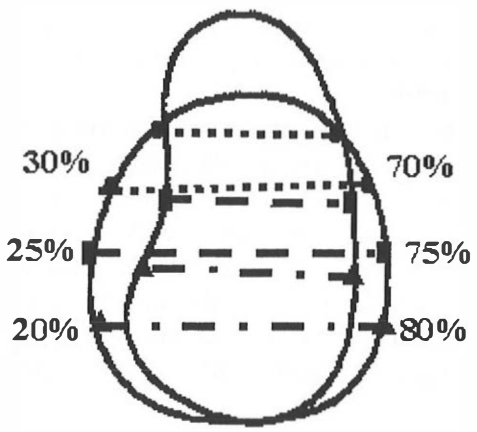

Figure 1: Location of chest deflection computation along the chest band .

Using the curvature data from each chest band, chest band contours were computed at every millisecond during the impact phase of the event. The origin of each contour was chosen at the point at which the band crossed the spine. Proceeding clockwise from the origin around the band, and considering the entire circumferential distance as 100%, distances were computed between 20% and 80% points, 25% and 75% points, and 30% and 70% points along the band (Figure 1) for every millisecond during the impact event. Chest deformation time histories between the pairs of points were calculated as the difference in the distance between the two points before impact and at every millisecond during the impact event. Therefore, 6 deflections, 3 from the top band and 3 from the bottom band, were computed. The chest deflections were filtered with SAE Class 600 filters and differentiated to obtain rate of deformations and VC using the method recommended by SAE (J1733). The deflections were normalized using the original chest width before the impact event at the location of deflection computation (Equation 4).

$$\text{Deflection}_{norm} = \frac{\text{deflection}}{\text{chest width at time 0}} \quad (4)$$

TEST RESULTS

Among the 34 sled tests, 13 were conducted at the Ohio State University (OSU) and 21 were conducted at the Medical College of Wisconsin (MCW). Figure 2 presents the number of tests in each test condition. Only 5 tests were conducted with the presence of pelvic offset (pelvic load wall offset by 12 cm to represent an armrest).

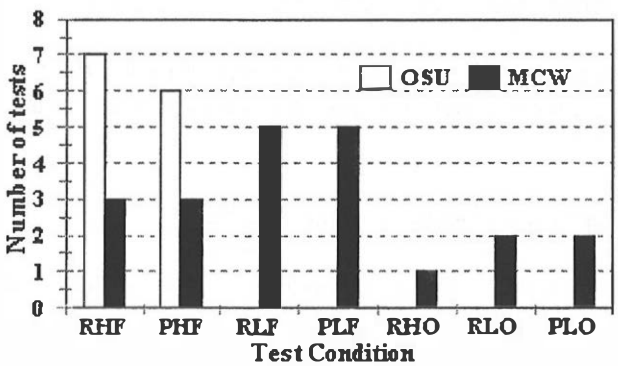

Figure 2: Number of tests conducted at different test centers and different test conditions. R=rigid wall, P= padded wall, H=high impact velocity (32 kph), L=low impact velocity (24 kph), F=flat wall, O=pelvic offset.

The maximum AIS injury (MAIS) for all subjects was due to the number of rib fractures and associated soft tissue injury (hemo/pneumo thorax). The mean age of the subjects in this data set was 68.5± 12.5 years. The mean age of subjects who sustained MAIS≥3 severity injury is 72±9 years while those sustaining less than MAIS=3 severity injury had an average age of 56.5±16 years (Figure 3). The average mass of the subject was 73±21 kg. There were 6 female subjects in the high speed tests and 2 in the low speed tests.

Among the six computed chest deflections for each subject, the location of the maximum normalized deflection for the 34 tests was evenly distributed at the level of top and bottom band. However, the maximum normalized deflection was better correlated to the maximum normalized deflection computed at the top band (R^2=0.9) than to the maximum normalized deflection computed at the bottom band (R^2=0.7).

The majority of the subjects (19) sustained maximum AIS level injury of MAIS≥4 (Figure 4). Eight of the 34 subjects sustained MAIS<3 injury severity and seven subjects sustained MAIS=3 injury severity. Figure 5 presents the mean number of rib fractures along with the corresponding standard deviation for each test condition. Some subjects experienced greater than 35 rib fractures. However, a number of these fractures were deemed minor and the subject was coded to sustain AIS=4 severity thoracic injury due to rib fractures. The average number of rib fractures sustained by the subjects tested at 32 kph is 19±11 while that for subjects tested at 24 kph is 6.5±6. There were 11 abdominal injuries of AIS=2 severity which all occurred in the high speed tests into a rigid or padded flat wall. In six of the high speed flat wall tests, the subject sustained AIS=2 shoulder injuries. There were 2 pelvic fractures (AIS=2) in the high speed-rigid flat wall tests and 2 pelvic fractures (AIS=2) in pelvic offset condition with rigid wall. The presence of padding had minimal influence on injury severity while the test speed significantly influenced injury severity (Figures 3 and 5). Details of the test results are presented in the Appendix.

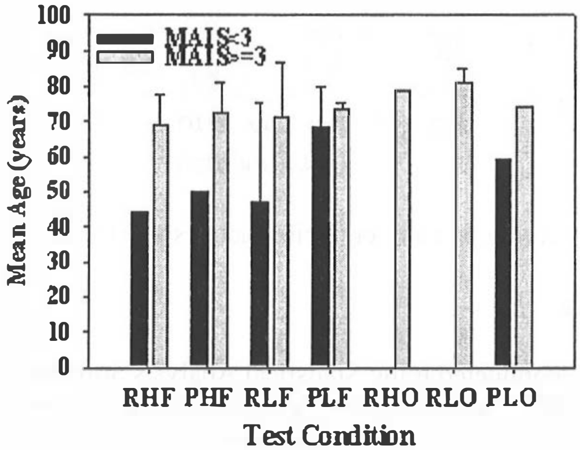

Figure 3: Mean age and standard deviation of subjects at time of death versus test condition and injury severity. R=rigid wall, P= padded wall, H=high impactvelocity (32 kph), L=low impact velocity (25 kph), F=flat wall, O=pelvic offset.

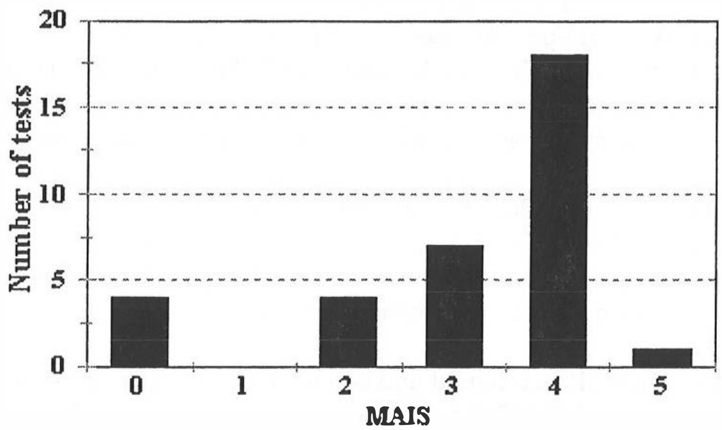

Figure 4: Number of tests versus maximum AIS injury (MAIS) sustained by the cadaveric subject.

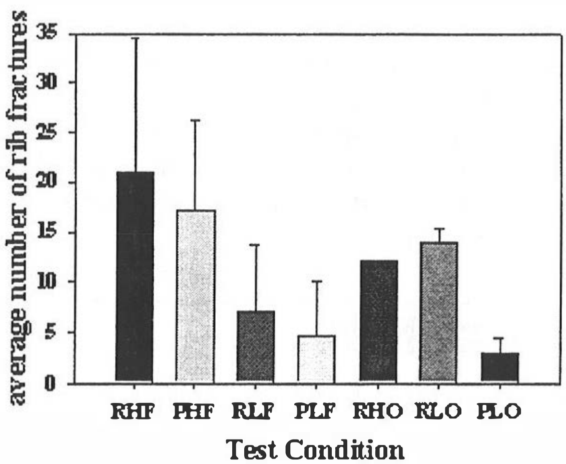

Figure 5: Average Number of rib fractures versus test condition.

ANALYSIS PROCEDURE

Statistical analyses were conducted using Statistical Analysis Software, SAS (SAS Institute, 1990) and JMP (SAS Institute, 1998). The response or dependent variable considered was the injury severity in the form of either (1) total number of rib fractures (rbfx) as a continuous variable, (2) Injury severity as a dichotomous nominal variable (cat1) of the form MAIS<3 and MAIS>=3, (3) Injury severity as a dichotomous nominal variable (cat2) of form MAIS<4 and MAIS>=4, (4) Injury severity as an ordinal variable (cat3) in the form MAIS<3, MAIS=3, and MAIS>=3. The explanatory variables examined were derivatives of measured mechanical parameters such as accelerations, deflections, and forces, as well as subject characteristics such as age, mass, and gender.

Analysis of variance and correlation analyses were conducted to identify any biases in the data and to determine the relationship between the explanatory variables such as peak and average forces, accelerations, and deflections under different test conditions and anthropometric characteristics. The normality of the distribution of the explanatory and response variables was examined using Shapiro-Wilk W test and from quantile normal plots (SAS Institute, 1998). Outliers in the data were estimated using Mahalanobis distance measures. When an outlier was identified, test data was examined carefully to justify removing data from data set.

Analysis of variance was conducted to identify the characteristics of the subject (age, mass, and gender) which had significant influence on injury outcome and acted as confounders to models using mechanical parameters as explanatory variables. Then, all subsequent models using injury outcome as the response variable included the effect of the identified confounders. Initial models consisted of the confounding variables and individual mechanical parameters. These models helped identify mechanical parameters having no influence on injury outcome thereby reducing the number of variables for further analysis. Multivariate and discriminant analyses were then conducted using stepwise regression to identify combination of mechanical parameters along with confounders which demonstrated improved predictive ability and goodness of fit measures.

When total number of rib fractures was considered as the response variable, linear regression was conducted. The effect of higher order terms and interaction effects were assessed for each model. The predictive ability of each model was assessed using the p-value of the F-statistics of the total model. The R^2 and adjusted R^2 value, which is a measure of the variance around the mean of the response variable which is explained by the model, was used in assessing the goodness of fit of the model. The higher the R^2 associated with the model, the better is its predictive ability. The effect of individual parameters in the model was assessed using chi-square statistics.

When dichotomous and ordinal categories of maximum AIS level injury - MAIS (cat1, cat2 or cat3) were used as the response variables, logistic regression was used. Details of the methods of using logistic regression with impact biomechanics data is detailed by Kuppa et al. (1998) and Hosmer (1989). The goodness of fit of the full model was assessed using the p-value of the -2*log-likelihood ratio as well as the score statistics. The lower the p-value of the model, the better is its goodness of fit. The predictive ability of the model was assessed using Goodman-Kruskal which is like R^2 in regression analysis, where, a Gamma value of 1 indicates perfect predictive ability while a zero indicates no predictive ability of the model. Higher values of Gamma indicate better predictive ability of the model. Details on the computation of Goodman-Kruskal Gamma are provided in Kuppa et al. (1998). Model building strategies outlined by Hosmer and Lemoshow (1989) were used. The effect of higher order terms and interaction was also assessed for each model.

In some of the 34 tests, due to the unavailability of certain measured mechanical data, some explanatory variables were missing. The missing data was not imputed. Instead, injury predicting models did not consider those tests which did not contain values of the explanatory variable under consideration. Therefore, the number of observations (n) is less than 34 in some models presented in Tables 1-4.

RESULTS OF ANALYSIS

IDENTIFICATION OF OUTLIERS AND CONFOUNDERS: The Mahalanobis distance measure suggested test 3577 was an outlier because of excessive number of rib fractures (45). However, the maximum AIS level, MAIS, which provides a better measure of the overall consequence of the injuries was only 4. Careful examination of the autopsy report for this test indicated that many of the rib fractures in this test were minor or hairline. Eliminating these minor fractures, the total number of observed rib fractures for this test were adjusted to 32. No other test data was considered as an outlier and no data was removed from the analysis.

The analysis of variance using age, gender, mass, test condition, and test center indicated age of the subject at the time of death had a significant influence on injury severity in the form of number of rib fractures or the categorical MAIS ($p=0.005$), while gender of the subjects ($p=0.22$) and mass of the subject ($p=0.9$) had minimal influence on injury outcome. There was no significant difference in injury outcome between the two test centers for the same test condition in terms of mean rib fractures and mean AIS level (p-value=0.2).

ANALYSIS WITH NUMBER OF RIB FRACTURES AS RESPONSE VARIABLE: Table 1 lists some of the best models identified using linear regression with number of rib fractures as the response variable. Since age was found to have significant influence on injury outcome, it was introduced into subsequent analyses as a confounder. Regression analysis suggested that acceleration data filtered with SAE Class 180 filter were better predictors of rib fractures than the corresponding accelerations filtered with SAE Class 60, SAE Class 600 or FIR100 filters. Normalized deflections and accelerations were better predictors of injury than non normalized deflections. In all cases, the interaction terms and nonlinear effects in a model did not improve the R^2 and p-value significantly and so were deemed unnecessary.

The mechanical parameters which best correlated to the number of rib fractures were maximum normalized deflection (dmaxn) (R^2=0.54) , maximum normalized resultant upper spine acceleration (rspul80n) (R^2=0.56), and maximum normalized lower spine acceleration (spll80n) (R^2=0.46). The injury criteria, TTI (R^2=0.34), ASA10 (R^2=0.32), Vmax (R^2=0.31) and VCmax (R^2=0.29) were not significant predictors of the number of rib fractures for this data set. Maximum thoracic, abdominal, and pelvic force (thx_f, abd_f, and pel_f) and the corresponding rate of loading (thx_fr, abd_fr, pel_fr), energy terms (SEC, ESRC) and rate of deflection (vmax) were also poor predictors of injury (R^2<0.25).

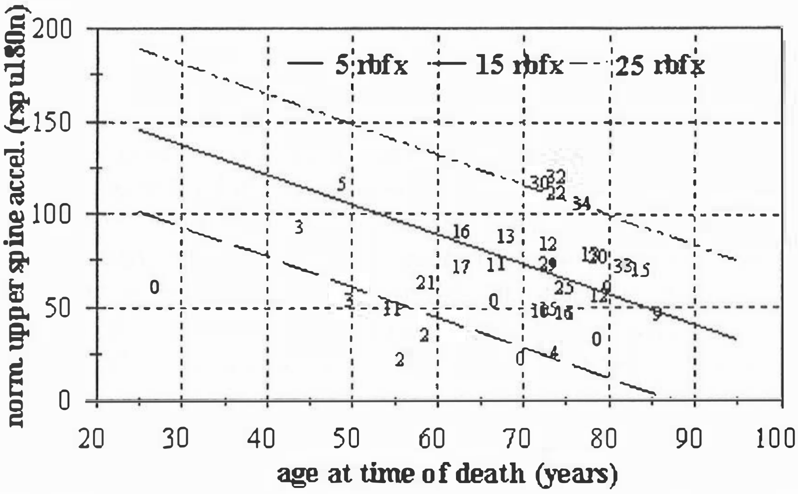

Figure 6: Age of the subject versus normalized maximum upper spine resultant acceleration (rspul80n) for 5, 15, and 25 rib fractures. Test data are shown on the plot as the number of rib fractures sustained by the subject in each test. R^2=0.54 Model 12.

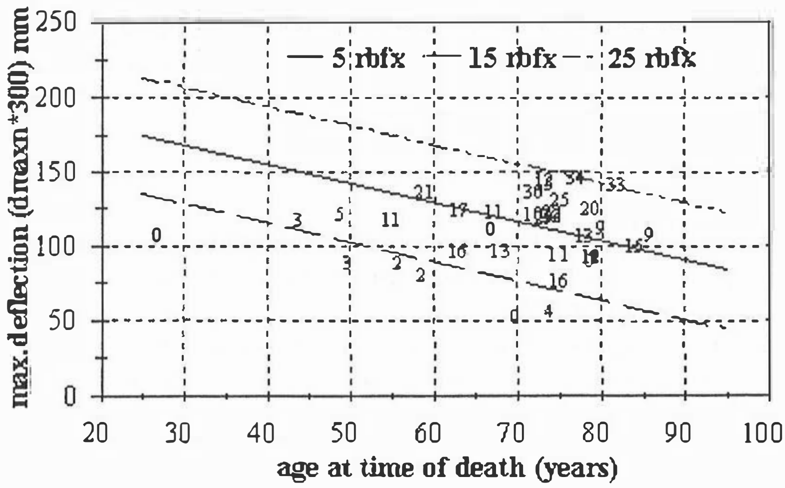

Figure 7: Age of the subject versus normalized maximum chest deflection (dmaxn*300mm) for 5, 15, and 25 rib fractures. Test data are shown on the plot as the number of rib fractures sustained by the subject in each test. R^2=0.51.Model 11.

Stepwise regression identified the linear combination of normalized resultant upper spine acceleration filtered to SAE Class 180 (rspul80n), maximum normalized deflection (dmaxn), and the confounding variable, age, to be a very good predictor of the number of rib fractures (Model 15: R^2=0.64, p-value =0.0001). A linear combination of age and a product of peak normalized deflection and peak normalized resultant upper spine acceleration (rspul80n*dmaxn) also correlated well with number of rib fractures (Model 14: R^2=0.63, p-value=0.0001). Figures 6 and 7 display linear regression lines of maximum normalized resultant upper spine acceleration (rspul80n, Model 12-Table 1) and maximum deflection (dmaxn*chest width of a 50^{th} percentile male =300 mm, Model 11-Table 1), respectively, versus age for 5, 15, and 25 number of rib fractures.

Table 1: Linear regression results using number of rib fractures (rbfx) as the response. Sorted by increasing R^2 of the model.

No.	model	n	p-value of F-stat	R^2	Adj. R^2
1	5.35+0.14asa15n	33	0.0024	0.2612	0.2374
2	-14.82+0.35age+5.98vcmax	34	0.0045	0.2939	0.2484
3	-17..49+0.36age+0.56vmax	34	0.0021	0.3274	0.284
4	-10.2+0.13ttin	33	0.0004	0.3413	0.3201
5	2.38+0.23*asa10n	33	0.0002	0.3565	0.3358
6	-20.96+0.33age+0.15spl180n	33	0.0001	0.4583	0.4222
7	-30.94+0.43age+0.28rspu100n	34	0.0001	0.4651	0.4306
8	2.5+0.59asa10n*dmaxn	33	0.0001	0.4765	0.4596
9	-5.22+0.264ttin*dmaxn	33	0.0001	0.4883	0.4718
10	-12.26+0.18age+0.1rblu180n	32	0.0001	0.4896	0.4544
11	**-37.56+0.32age+76.46dmaxn**	**34**	**0.0001**	**0.5395**	**0.5098**
12	**-27.43+0.37age+0.23rspu180n**	**34**	**0.0001**	**0.5624**	**0.5342**
13	-22.5+0.27age+0.17rspu180n+0.04rlu180n	32	0.0001	0.6032	0.5606
14	**-23.91+0.35*age+0.50*rspu180n* dmaxn**	**34**	**0.0001**	**0.6329**	**0.6092**
15	**-37.45++0.35age+45.3dmaxn+0.15rspu180n**	**34**	**0.0001**	**0.6389**	**0.6028**

where:

dmaxn: maximum normalized chest deflection
spu180n: maximum normalized lateral upper spine acceleration (SAE Class 180 filter)
rspu180n: maximum normalized resultant upper spine acceleration (SAE Class 180 filter)
rspu100n: maximum normalized resultant upper spine acceleration (FIR 100 filter)
spl180n: maximum normalized lateral lower spine acceleration (SAE Class 180 filter)
rblu180n: maximum normalized lateral upper rib acceleration (SAE Class 180 filter)
asa10: asa10 (Cavanaugh, 1993) normalized as in Equation 3.
asa15: asa15 (Cavanaugh, 1993) normalized as in Equation 3.
tti: defined in Equation 2
vmax: maximum rate of chest deflection
vcmax: maximum VC

ANALYSIS USING CATEGORIES OF MAXIMUM AIS LEVELS: Since the response variables cat1 and cat2 are categorical, and cat3 is ordinal, logistic regression was used. The analyses using maximum AIS level (MAIS) categorized as (1) cat1: MAIS<3 and MAIS≥3 are presented in Table 2. The results using cat2: (MAIS<4 and MAIS≥4) and cat3: (MAIS<3, MAIS=3 and MAIS>3) as response variables are very similar to those using cat1 and are presented in Table 3 and 4. Tables 2-4 provide the basic results of each model. The probability of injury (P) is obtained using Equation 5. The definitions of the independent variables used in the model are provided in Table 1.

$$P = \frac{1}{1+e^{(-\text{logit})}}, \text{ where logit is of form } a + \sum b_i x_i \qquad (5)$$

The trends observed in the logistic regression models were similar to those in the linear regression analysis with number of rib fractures as the response. Again, because the age of the subject at the time of death was determined to be a significant confounder, it was included as an explanatory variable in all the subsequent models. Normalized deflections and accelerations were better predictors of injury than the non normalized deflections. Maximum values of deflection, forces, and accelerations were better predictors of injury than average values. ASA10 was a better predictor of injury than ASA15 or ASA20. TTI (score p=0.0016) was a significantly better predictor of injury than ASA10 (score p=0.015). The best individual predictors of injury were maximum normalized deflection (dmaxn) (score p=0.0005) and normalized resultant upper spine acceleration filtered at SAE Class 180 (rspu180n) (score p=0.0003). For injuries greater than AIS=3, dmaxn (p=0.0001) was a better predictor of injury than rspu180n (p=0.0005). The best predictors of injury were a linear combination of age, dmaxn, and rspu180n (score p-value=0.0001, Gamma=0.858) and a linear combinationof age and rspu180n*dmaxn (score p-value=0.0001, Gamma=0.847).

Interaction effects and higher order nonlinear terms were found not to influence injury response significantly. The results with nominal and ordinal response variables suggest that response can be well characterized by a linear combination of explanatory variables obtained from logistic regression.

The probability of AIS≥4 thoracic injury versus the linear combination of maximum normalized chest deflection (dmaxn), and maximum normalized resultant upper spine acceleration (rspu180n) of Model 12 in Table 4 for a 30, 45, and 60 year old subject is presented in Figure 8.

Table 2: Logistic Regression Results Using cat1: (MAIS<3 and MAIS≥3) as the response Sorted by increasing Goodman-Kruskall Gamma value of the model.

No.	Logit of Model	n	-2logLR	score P-Value	Gamma
1	-1.017+0.048asa15	33	6.142	0.05	0.508
2	-2.196+0.091asa10	33	9.594	0.0156	0.61
3	-8.58+0.11age+0.037spl180n	33	12.873	0.0025	0.75
4	-9.66+0.066TTI	33	14.86	0.0016	0.8
5	-10.1+0.12age+0.03rblu180n	32	17.043	0.0009	0.833
6	-4.12+0.089*TTI*dmaxn	33	14.447	0.0011	0.84
7	-15.36+0.18age+0.083spu180n	34	18.41	0.0007	0.865
8	**-14.91+0.14age+19.75dmaxn**	**34**	**17.59**	**0.0005**	**0.865**
9	-16.57+0.18age+0.11rspu100n	34	19.45	0.0003	0.875
10	-17.54+0.19age+0.069rspu180n+0.021rblu180n	34	21.093	0.0012	0.896
11	**-15.67+0.18age+0.084rspu180n**	**34**	**20.2**	**0.0003**	**0.904**
12	**-17.13+0.18age+8.51dmaxn+0.061rspu180n**	**34**	**20.98**	**0.0006**	**0.913**
13	**-15.19+0.188age+0.186*dmaxn*rspu180n**	**34**	**21.12**	**0.0003**	**0.923**

The definitions of the variables used in the models are provided in Table 1. .

Table 3: Logistic regression results using cat2: (MAIS<4 and MAIS≥4) as the response Sorted by increasing Goodman-Kruskall Gamma value of the model.

No.	Logit of Model	n	-2logLR	score P-Value	Gamma
1	-1.02+0.02asa15	33	3.23	0.0886	0.544
2	-5.705+0.053age+0.028spl180n	33	8.505	0.0225	0.55
3	-5.212+0.0419age+0.0189rblu180n	32	9.01	0.0194	0.578
4	-1.917+0.044asa10	33	6.724	0.0169	0.581
5	-5.0313+0.028TTI	33	8.867	0.0056	0.647
6	-11.66+0.1age+0.088rspu100n	34	14.08	0.0037	0.655
7	-10.073+0.09age+0.067spu180n	34	14.85	0.0026	0.66
8	**-12.34+0.10age+0.082rspu180n**	**34**	**19.84**	**0.0005**	**0.778**
9	-7.23+0.11*TTI*dmaxn	33	20.61	0.0001	0.805
10	**-19.96+0.08age+38.88dmaxn**	**34**	**24.42**	**0.0001**	**0.854**
11	**-19.492+0.165age+0.323*dmaxn*rspu180n**	**34**	**27.59**	**0.0001**	**0.875**
12	**-41.29+0.20age+49.91dmaxn+0.124rspu180n**	**34**	**32.309**	**0.0001**	**0.931**

Table 4: Logistic regression results using cat3: (MAIS<3, MAIS=3, and MAIS>3) as the response. Sorted by increasing Goodman-Kruskall Gamma value of the model.

No.	Logit of Model for MAIS 4+	n	-2logLR	score P-Value	Gamma
1	-1.117+0.021asa15	33	4.117	0.0461	0.305
2	-2.1488+0.049asa10	33	8.567	0.0077	0.53
3	-7.64+0.08age+0.028spl180n	33	12.953	0.0049	0.57
4	-5.969+0.033TTI	33	12.681	0.0012	0.637
5	-7.7+0.0729age+0.0208rblu180n	32	15.421	0.0023	0.642
6	-13.86+0.13age+0.094rspu100n	34	21.417	0.0005	0.675
7	-11.98+0.11age+0.068spu180n	34	21.014	0.0005	0.71
8	**-16.513+0.11age+24.66dmaxn**	**34**	**26.587**	**0.0001**	**0.761**
9	-6.1+0.089*TTI*dmaxn	33	22.923	0.0001	0.762
10	**-13.77+0.12age+0.079rspu180n**	**34**	**26.429**	**0.0001**	**0.778**
11	**-15.66+0.148age+0.22*dmaxn*rspu180n**	**34**	**32.619**	**0.0001**	**0.847**
12	**-19.97+0.137age+17.96dmaxn+0.057rspu180n**	**34**	**32.698**	**0.0001**	**0.858**

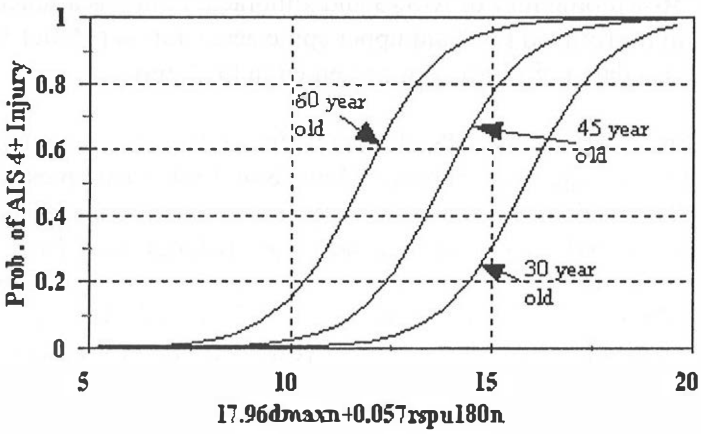

Figure 8: Probability of AIS ≥4 thoracic injury for a 30 year, 45 year and 60 year old subject as a function of maximum normalized deflection (dmaxn) and maximum normalized resultant upper spine acceleration (rspu180n) from Model 12 of Table 4.

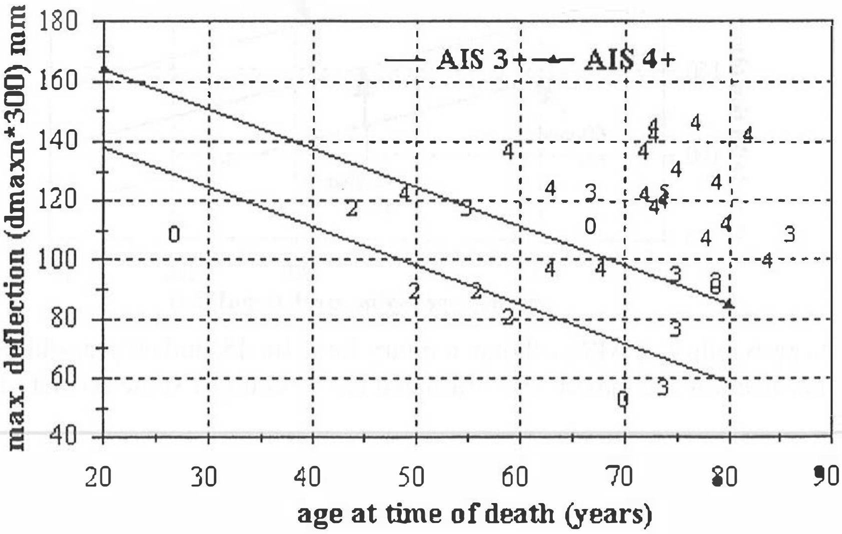

Figure 9: Lines of 30% probability of AIS≥3 and AIS≥4 thoracic injury as a function of age of the subject and maximum chest deflection (normalized chest deflection * chest width of a 50[th] percentile male=300 mm) (Model 8, Table 4). The maximum AIS injury of the test data points are also presented in the figure.

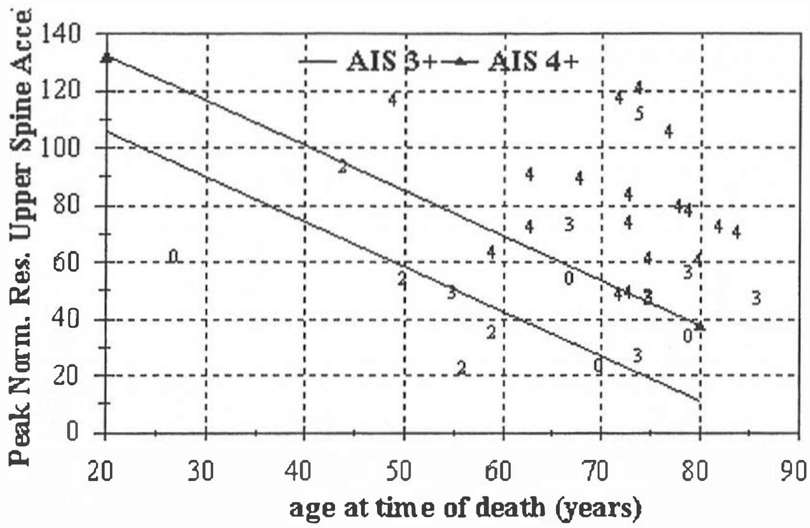

Figure 10: Lines of 30% probability of AIS≥3 and 4 thoracic injury as a function of age of the subjects and maximum normalized resultant upper spine acceleration (Model 10, Table 4). The maximum AIS of the test data points are also presented in the figure.

The 30% probability of AIS≥3 and AIS≥4 thoracic injury lines as a function of maximum chest deflection (dmaxn*300) and age of the subject (Model 8 of Table 4) are presented in Figure 9. The 30% probability of AIS≥3 and AIS≥4 thoracic injury as a function of maximum normalized resultant upper spine acceleration (rspul80n) and age of the subject (Model 10 of Table 4) are presented in Figure 10. The 30% probability of AIS≥4 thoracic injury lines for a 30, 45, and 60 year old as a linear combination of dmaxn*300 and rspul80n (Model 12 of Table 4) are presented in Figure 11. The sample data has an average subject age of 68.5 years, with rspul80n ranging between 20-120 g's (Figure 10) and dmaxn*300 ranging between 50-150 mm (Figure 9). Within this range of data it was found that the hyperbolic function of Model 11 in Table 4 is almost linear and is similar to the 30% probability of injury lines presented in Figure 11.

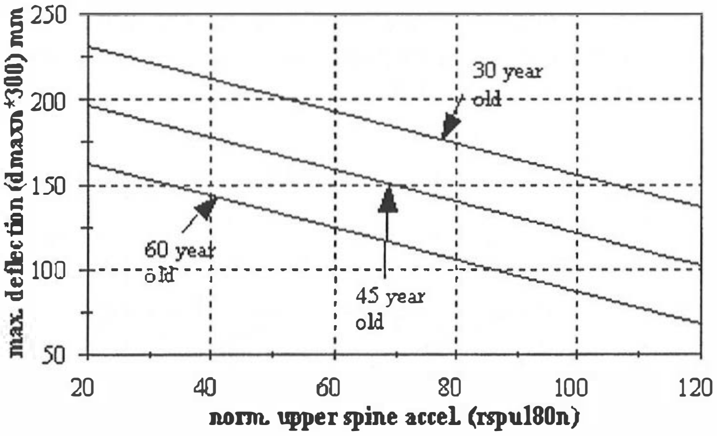

Figure 11: 30% probability of AIS≥4 thoracic injury for a 30, 45, and 60 year old as a function of maximum chest deflection and maximum normalized resultant upper spine acceleration (Model 12, Table 4).

DISCUSSION

A detailed statistical analysis was conducted using data from 34 side impact sled tests to evaluate and develop injury criteria. Thoracic and abdominal soft tissue injury was minimal and was also associated with low AIS levels. The maximum AIS was determined by the number of rib fractures and associated soft tissue injury (pneumothorax) due to rib fractures. Analyses were conducted using the number of rib fractures as well as the categorical maximum AIS levels. The variable "number of rib fractures" (rbfx) used in this data set included all observed rib fractures but does not distinguish between severe fractures (compound or displaced rib fractures) from the minor fractures (hairline, simple, or incomplete fractures). In some tests a number of the rib fractures noted were hairline fractures which would have minor if no injury consequence. On the other hand, the reported MAIS levels in the data set provided a good estimate of the overall severity of the injuries sustained by the subject, which even included associated soft tissue injury. Therefore, the results using logistic regression models using MAIS categories may pertain more to the severity of injury (i.e. threat-to-life) than the linear regression rib fracture models which are a more mechanistic outcome descriptor.

In this data set, the age of the subject at the time of death had significant influence on the injury severity while gender of the subject did not influence injury severity. The non-significance of gender may be associated with the small sample size of the female subjects (8 females) in this data set. Since this data set has very few soft tissue injuries, it is reasonable that injury criteria such as VC, which are particularly developed as soft tissue injury criteria, were not significant predictors of injury. The procedure for VC computation is plagued with amplification of measurement errors due to the differentiation of deflections. This may also contribute to the non-significance of VC as an injury predictor.

The chest deflections were computed from chest bands wrapped externally around the body. Therefore the computed deflections include the deformation of the skin and flesh as well as the ribs. The analysis in this paper only considers total deflection which includes the deformation of the flesh and skin. In order to obtain the rib deflections, which may be a more appropriate injury predictors than total deflection, a portion of the skin and flesh thickness may have to be subtracted from the total deflections. The computed chest deflections are the chest deflections along the total width of the thorax as shown in Figure 1. However, the side impact dummies measure only half thorax chest deflections. Therefore, in order to apply the developed injury criteria on the dummies, either the chest deflections would need to be adjusted to represent half thorax deflections or the dummies be modified to measure full thorax deflections.

Maximum normalized chest deflection (dmaxn) was found to be a better predictor of injury than any other existing injury criteria with TTI being the next best predictor of injury severity based on AIS. A 30% probability of AIS$\geq$4 injury is associated with TTI=155 and an ASA10=27 which are similar results as that reported by Morgan (1986) and Cavanaugh (1993). The model using the product of TTI and maximum normalized deflection (dmaxn) was a reasonably good predictor of injury (Gamma=0.76, p-value=0.0001) as was noted by Pintar et al. (1996).

The model using a linear combination of age, and the product of maximum normalized deflection and resultant normalized upper spine acceleration, dmaxn*rspu180n, (Model 11, Table 4) was as good a predictor of injury as the model using a linear combination of age, dmaxn, and rspu180n (Model 12, Table 4). This is because within the range of data, the hyperbolic function of the product of rspu180n and dmaxn in Model 11 is approximately linear and similar to the linear function of Model 12. This data set exhibited mainly linear behavior between the response and explanatory variables. There was no significance of nonlinear effects or interaction terms and so were not included in any of the injury predictor models.

The model using a linear combination of age, maximum normalized resultant upper spine acceleration (rspu180n), and normalized deflection (dmaxn) was the best predictor of thoracic injury (p=0.0001, Gamma=0.858) among all those examined. This result is similar to that observed in analysis of frontal impact sled tests (Kuppa et al., 1998). For a 45 year old, 50th percentile male occupant, a chest deflection of 130 mm and a resultant upper spine acceleration of 90 g's is associated with a 30% probability of AIS$\geq$3 injury.

FUTURE RESEARCH

Though this data set is significantly larger than previous research efforts where chest deflections were measured, a larger data set could obviously offer better insights and predictive relationships. Therefore, future research will concentrate on increasing the number of observations in the data set. Changes to cadaveric subject preparation are also being investigated in order to make the frequency and severity of soft tissue injuries more in line with field observations. Efforts will also be made to combine the sled test data from Wayne State University (Cavanaugh, 1993) and the previous Heidelberg tests (Morgan, 1986). Application of the developed injury criteria to side impact test dummies will also be examined.

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APPENDIX: Summary of Test Data

Test no.	sex	age	mass	MAIS	rbfx	tstcfn	thx_f	abd_f	pel_f	thx_fr	abd_fr	pel_fr	dmaxn	vmax	vcmax	TTI
		yrs	kg				N	N	N	N/ms	N/ms	N/ms	m/m	m/s	m/s	
3120	M	73	89	4	15	RLF	5534	1919	3451	244	55	326	0.477	35.1	8.9	188
3122	M	27	72	0	0	RLF	6853	1963	8613	527	1302	491	0.364	12.2	2.1	85
3155	M	55	76	3	11	RLF	4866	5227	3257	594	435	290	0.394	7.3	1.9	160
3276	M	70	71	0	0	PLF	3485	1914	5612	147	175	390	0.176	5.2	0.5	154
3277	M	56	64	2	2	PLF	14940	1625	4945	509	70	566	0.300	4.4	0.9	125
3278	M	50	93	2	3	PHF	12981	3112	6841	528	165	366	0.299	16.8	1.1	153
3320	F	82	74	4	33	PHF	5774	3414	8490	201	156	701	0.477	11.0	3.2	170
3321	F	75	42	4	25	PHF	6100	3707	8424	147	93	394	0.437	9.2	3.1	191
3322	M	73	72	4	12	RHF	4255	9629	9950	431	1134	4539	0.484	26.1	5.1	275
3323	F	59	81	4	21	PHF	8589	4332	8658	303	230	949	0.458	9.2	2.8	156
3324	M	77	75	4	34	RHF	9558	5809	17230	516	1320	1900	0.490	22.2	3.2	255
3325	M	63	61	4	16	RHF	8432	3893	15887	919	877	2307	0.325	19.9	3.1	213
3422	M	44	83	2	3	RHF	16097	3328	9745	1318	262	731	0.395	10.9	2.2	158
3423	M	49	62	4	5	RHF	6958	3253	17229	289	303	3449	0.410	9.7	2.1	172
	M	78	88	4	13	RLO	3650	486	10664	155	579	917	0.359	8.3	1.4	188
	M	84	76	4	15	RLO	3879	551	14308	498	347	1640	0.335	6.9	1.4	.
	M	79	93	3	12	RHO	4360	1914	20632	366	1381	2101	0.312	7.2	1.2	202
	M	74	77	5	22	RHF	7297	2036	17928	977	324	3258	0.412	11.8	2.6	232
	F	74	52	4	45	RHF	7615	4639	12969	291	389	1104	0.403	15.6	2.3	215
	F	73	51	4	29	RHF	9216	5675	26689	354	2351	11056	0.397	14.9	3.1	212
	M		98	4	13	RHF	11109	4546	17092	593	1772	6661	0.326	13.2	2.2	300
	M		56	3	16	PHF	6860	4075	10378	187	118	593	0.258	6.2	0.8	156
	F		45	4	9	PHF	6913	4700	10291	176	136	631	0.375	12.2	1.6	183
	M			4	30	RHF	10386	4969	16417	494	345	4031	0.458	16.4	2.8	247
	M			4	20	PHF	4776	2294	6097	218	156	673	0.423	7.8	2.0	254
	M			4	17	PHF	7894	3732	8488	372	154	622	0.417	9.3	2.6	210
	M				10	PLF	4121	2253	5137	99	65	380	0.409	6.7	1.5	142
	M				11	PHF	7480	3495	8657	311	181	500	0.412	8.8	2.1	170
	M				4	PLO	3443	717	9048	149	462	486	0.191	4.1	0.4	129
	M					PLO	3035	615	7409	168	189	371	0.270	4.6	0.9	116
	F					PLF	3689	2181	7835	87	57	634	0.318	6.6	1.3	153
	F					RLF	4957	2981	5733	227	443	870	0.374	9.2	2.2	164
	M					RLF	5727	2454	8838	384	1896	741	0.364	6.7	1.7	195
	M					PLF	4125	1969	7908	144	134	941	0.305	6.2	1.2	155

test configuration:-- R=rigid, P=padding, H=32 kph impact, L=24 kph impact, O=offset wall, F=flat wall
rbfx: number of rib fractures; **thx_f:** max. thoracic force; **abd_f:** max. abdominal force; **pel_f:** max. pelvic force;
thx_fr: max. rate of thoracic loading; **abd_fr:** max. rate of abdominal loading; **pel_fr:** max. rate of pelvic loading;
dmaxn: maximum normalized deflection; **vmax:** maximum chest velocity; **vcmax:** maximumchest VC; **TTI:** thoracic trauma index;

APPENDIX: Summary of Test Data (Continued)

Test no.	ASA10	ASA15	ASA20	spu180n	spl180n	rspu180n	rspl180n	pel180n	rpel180n	rlu180n	rll180n
	g	g	g	g	g	g	g	g	g	g	g
3120	43	49	51	50	48	50	50	.	.	101	113
3122	14	15	16	60	58	62	58	75	76	43	.
3155	22	23	24	49	51	50	57	20	64	183	112
3276	24	63	71	23	68	24	70	32	33	37	62
3277	30	30	28	23	76	23	76	35	37	23	57
3278	41	44	45	51	54	54	56	57	59	135	174
3320	70	70	70	55	70	73	70	61	61	.	101
3321	30	29	30	47	107	62	117	58	91	150	120
3322	53	58	59	60	149	84	152	107	108	190	.
3323	63	71	73	58	86	64	87	65	68	100	90
3324	91	95	145	93	135	106	.	96	112	170	361
3325	48	53	57	56	129	91	132	96	114	167	.
3422	35	45	51	94	62	94	90	76	79	88	140
3423	32	33	35	111	74	117	87	60	92	135	124
3535	27	30	31	79	35	80	38	54	56	139	44
3536	.	.	.	70	.	71	.	65	82	84	114
3537	34	43	67	56	54	57	55	66	69	132	106
3538	69	101	124	103	103	112	109	67	76	142	164
3577	69	76	85	121	94	121	103	71	87	261	273
	45	122	131	70	140	74	148	129	155	177	391
	111	187	217	78	161	89	163	136	145	175	340
	56	59	59	44	69	48	72	70	78	117	68
	61	61	61	49	79	61	82	61	63	154	228
	67	70	75	111	119	118	119	136	136	182	234
	128	137	141	72	78	78	86	82	83	152	175
		61	78	65	87	73	92	63	64	.	201
		25	31	45	29	49	.	37	37	63	111
		52	57	73	93	74	112	51	.	60	130
		26	27	26	31	27	32	23	23	44	65
		11	23	35	33	36	33	30	30	46	.
		29	30	42	51	48	53	35	39	81	106
			45	52	63	54	66	41	42	102	95
			33	47	41	47	50	46	82	183	67
			24	33	48	34	81	35	37	92	111

spu180n: max. norm. lateral upper spine acceleration (SAE Class 180); **spl180n:** max. norm. lateral lower spine acceleration (SAE Class 180); **rspu180n:** max. norm. resultant upper spine acceleration (SAE Class 180); **rspl180n:** max. norm. resultant lower spine acceleration (SAE Class 180); **pel180n:** max. norm. lateral pelvic acceleration (SAE Class 180); **rpel180n:** max. norm. resultant pelvic acceleration (SAE Class 180); **rlu180n:** max. norm. lateral upper left rib acceleration; **rll180n:** max. norm. lateral lower left rib acceleration.