Biomechanical Response of the Thorax and Estimation of Injury Risk in Side Impact

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ABSTRACT

The purpose of this study is to examine thoracic injury mechanism and to determine the tolerance in lateral impact. The response of the thorax of the human cadaver for a total 21 sled impact tests were analyzed by using University of Heidelberg test data. This report provides a simple mathematical description of the process of thoracic deformation in lateral impact into a rigid wall or into a wall with padding. This analysis has shown that, in the case of impact against a rigid wall, the thorax displays a high velocity of deformation with relatively low compression during a short crash impulse. However, in the case of impact against the wall with soft padding, the compression becomes an important factor in the chest injury. If an injury criterion involves only one of these two factors, it will be not complete, so that it could not correctly be connected with the injury mechanism. Human thorax tolerance has been defined by the probability function of injury risk. A tolerance level of the viscous response (VC)max = 1.03 m/s and of the dissipated energy response (DE)max = 1.34 m/s for the chest in side impact were determined for a 25% probability of serious injury NFR = 4 (number of fractured ribs). Maximum thoracic compression was similarly set at C = 35.4%.

INTRODUCTION

The analysis concerning the cause of fatal injuries in an automobile environnment have showed that the thorax is the corporal region where injury is most serious in relation to other regions in side impact accidents (car/car) [THOMAS et al. 1987, NHTSA 1988]. The mechanism of thoracic injuries is mainly the intrusion of the side wall of the impacted car [CESARI et al. 1978, 1983]. The data about injury distribution of NASS and NCSS concerning mortal accidents in lateral collisions show that appropriately 70% of cases for thoracic traumas have been caused by the lateral structure of vehicle doors [NHTSA 1988]. Hence, occupant protection in side impact crashes has become one of the significant tasks of automotive safety engineers. It is necessary to understand the performance of occupants and the effects of rigidity of interior panels that cause various corporal injuries when a vehicle is struck from the side. Our study aims to understand the mechanical performance of the human thorax in lateral impact and the mechanisms of injury, as well as to estimate the level of thoracic tolerance.

Determination of tolerance level and prediction of risk associated injury has been accomplished in much previous work. In 1982, a series of drop tests of human subjects onto panels covered with different types of material (rigid or shock-absorbing) was conducted by WALFISCH et al. [1982]. 30% compression level (half thorax) was proposed as an appropriate tolerance level for the chest, which corresponded to seven rib fractures.

The viscous criterion has been developed to assess injury severity of the human thorax [VIANO et al. 1985, LAU et al. 1986]. According to this criterion, human tolerance has been defined by the viscous response (VC), which is defined as the product of deformation velocity and compression of the thorax. Using a series of blunt oblique-lateral impacts (60 degree), (VC)max=1.47m/s corresponding to a 25% chance of sustaining severe thoracic injury (AIS>=4) has been proposed by GMRL [VIANO 1989]. It should be noted that, in these tests using the pendulum, the chest deflection was measured based on the whole thoracic deformation. In fact, for a problem of the side impact, examining thoracic deformation characteristics based on the deflection of the half (not whole) thorax is more significant.

On the basis of an analysis of the mathematical properties of the viscous criterion, the Dissipated Energy Criterion (DE) was recently proposed [WANG 1989]. It has been shown that the viscous response of the thorax is given by the integral of the velocity squared with respect to time, instead of V*C. However, this criterion has not been validated for the assessment of injury risk with experimental data.

In this paper, the histories of the deformation velocity and the compression of the human thorax in side impact into a rigid wall or into a soft padding will be examined with biomechanical data, a total of 21 sled impact tests. In this analysis of thoracic mechanical responses, we will particularly observe the characteristics of the chest deformation at different crash stages and estimate in which phase of deformation the injury risk increases and which one of different mechanical factors causing traumas is principal. In addition, the Dissipated Energy Criterion will be validated by the data of impact tests .

DATABASE DESCRIPTION

During 1980-1984, a series of impact tests with unembalmed human cadavers were performed on a deceleration sled at the University of Heidelberg. The basic operation of the sled has been described by SCHMIDT [1974] and KALLIERIS et al. [1981]. 12 accelerometers were arrayed on the thorax and a detailed description was given by MELVIN et al. [1979]. For the acceleration resultas, certain data have been used in the NHTSA research program to develop the dummy SID and the Thoracic Trauma Index (TTI) [EPPINGER et al. 1984]. In this paper, we examine the thoracic dynamic responses of these subjects through the chest velocity of deformation and through the deflection.

Table 1 includes the test conditions of 21 fresh cadavers in lateral impact, conducted against four different impact surfaces: rigid wall, APR padding (made by open cell foam), HNCB padding (made as a honeycomb by fiber glass) and the lateral door of a VOLVO car. The curves of mechanic characteristics of both these padding materials could be found in the reference of MONK et al. [1980].

Table 1 Summary of the impact velocity and type of the impact surface in deceleration sled tests.

Velocity of impact	Rigid wall	APR padding	HNCB padding	VOLVO door
24km/h	6	-	-	-
32km/h	5	4	4	-
16 or 36 km/h	-	-	-	2

HUMAN SUBJECT ANTHROPOMETRY AND THORACIC INJURY

The description of the twenty-one cadaver data is summarized in the table 2. They had an average age of 39.0 years old and body weight of 73.0kg. Their chest breadth varied from 26cm to 38cm with an average value of 31cm. For each test, the detailed injury results are noted and categorized by the code AIS85 [AAAM 1985]. Table 2 presents the anthropometric data of the cadaver tests and the AIS value for the thorax and the number of fractured ribs (NFR, maximum possible value is 24).

Table 2 Anthropometric data and injury data for cadaver tests

No. Test	sex (M/F)	age (year)	weight (kg)	height (m)	breadth (cm)	NFR	AIS	No. Test	sex (M/F)	age (year)	weight (kg)	height (m)	breadth (cm)	NFR	AIS
8011	M	27	89	1.80	30	1	1	8018	M	21	61	1.66	30	0	0
8014	F	60	84	1.69	34	3	2	8208	M	61	99	1.72	38	11	4
8017	M	38	70	1.75	30	6	3	8221	M	48	99	1.80	36	13	4
8215	M	18	69	1.82	29	2	2	8222	M	50	77	1.67	33	15	4
8218	F	28	85	1.81	29	9	3	8021	M	29	63	1.80	31	0	0
8219	F	47	67	1.65	31	7	3	8023	F	41	82	1.59	33	8	3
8024	M	24	65	1.76	29	0	0	8111	M	43	59	1.65	28	0	0
8102	M	57	65	1.65	32	14	4	8112	F	33	46	1.56	26	4	3
8104	M	56	80	1.65	32	16	4	8308	M	45	78	1.78	33	0	0
8214	F	22	61	1.78	29	12	4	8321	M	38	58	1.65	29	14	4
8220	M	41	73	1.80	32	11	4								

Considering that the numerical code AIS is not linear progressive but a simple distinctive among different injury levels, we use the number of fractured ribs as an indictor to present the severity of chest injury. In fact, this choice allows the injury gravity of the global thorax to be indicated by the injury severity level of the chest skeleton and does not cause an underestimation. We have perviously confirmed this in another study [TAO et al. 1992a]. In that paper, data were collected on thoracic injuries, taken from 116 cadaver impact tests on lateral impact with impactor, deceleration sled, or with tests of reconstruction collision (car/car). Thoracic injury severity has been classed by the AIS code for examining the organs and skeletal trauma respectively.

That analysis showed a very small possibility (6%) that the severity of intrathoracic organ lesions is larger than the severity of skeletal lesions. This result may be confirmed by the accident data furnished by the APR [HENRY 1983]. Using the same method to class the severity of thoracic trauma by examining the organ lesions and the skeletal lesions respectively, with APR data, the severity of organ trauma is about 11% greater than that of skeletal trauma. Moreover, about 60% of persons injured in the thorax carry only skeletal trauma without organs lesions. If we examine only the results of 49 reconstruction tests [LENZ et al. 1982, KLAUS et al. 1984] in the light of the AIS code, we should see that the severity of human thorax trauma can be wholly determined by the number of fractured ribs. No organ trauma has been observed in the absence of fractured ribs.

These analyses have shown that: (1) the risk of intrathoracic injury is essentially linked to the number of fractured ribs. The intrathoracic injury risk increases with the number of fractured ribs; (2) It is feasible that the severity of skeletal injury indicates the whole severity of thorax injury.

Hence, in current research, the number of fractured ribs could be considered as the indicator of the severity of chest injury for estimating the thoracic injury risk and determining the impact tolerance of the thorax without involving the organ injury.

TREATMENT SIGNALS

All dynamic responses for each test have been recorded by using a multiplexed FM type [ASG 1985]. The data is subsequently digitized at 1600 samples per second for part of the test, at 2000 samples per second for the other part. In our process of reanalysis of the rib and spine acceleration signals, using those data set, a digital filter has been effected using a finite impulse response (FIR) filter with the logicial DADISP2 [DSP 1990]. This had a pass band frequency of 100Hz, and a stop band frequency of 189Hz for data with 1600 samples per second (209Hz for data with a 2000Hz sampling rate) and stop band attenation=-50dB, passband ripple =0.0225dB [MARCUS 1984].

PRESENTATION OF CADAVER RESPONSES

The dynamic responses of the thorax are calculated based on the rib and spine accelerations with the simple and double integration of the acceleration of the chest transverse deformation. They include the accelerations of the 4th and 8th left ribs (Acc(4lr) and Acc(8lr)) and of the 1st and 12th spinal vertebra (T1 and T12), the velocity of chest deformation (V) and the compression (C), normalized thoracic deflection by half chest breath. A product of V and C gives viscous response VC. The response Dissipated Energy (DE), based on WANG proposed criterion, is given by the integral of the velocity squared with respect to time and the value of this response is normalized by the dimension of the half chest breadth. A detailed description of the developed process has been reported elsewhere [TAO et al. 1992b]. Table 3 includes the main results of 21 sled tests: the maximal transverse accelerations of the ribs and spine, maximum chest compression Cmax, maximum velocity of deformation Vmax, maximal viscous response (VC)max and (DE)max.

Table 3 Test conditions and value of mechanic response peak

Test	velocity (km/h)	Surface of impact	Acc(4lr) (g)	Acc(8lr) (g)	Acc(T1) (g)	Acc(T12) (g)	C(max) (%)	V(max) (m/s)	(VC)max (m/s)	(DE)max (m/s)
8011	24	rigid	116.19	-	93.74	87.32	21.06	4.34	0.547	0.706
8014	23	rigid	115.12	-	136.28	131.93	12.27	3.91	0.316	0.373
8017	24	rigid	85.20	-	102.95	70.14	35.25	4.23	0.693	1.016
8215	24	rigid	80.27	128.29	91.14	96.88	15.77	3.14	0.306	0.366
8218	23	rigid	64.25	86.22	82.65	69.55	45.72	4.81	1.336	1.494
8219	23	rigid	92.14	135.24	113.70	83.72	38.16	5.98	1.159	1.630
8024	33	rigid	119.05	-	112.24	135.20	9.38	2.56	0.145	0.200
8102	33	rigid	115.55	-	109.70	128.91	44.30	5.78	1.758	1.890
8104	32	rigid	121.95	-	112.74	126.42	36.89	5.89	1.061	1.525
8214	32	rigid	170.53	220.25	124.28	186.09	26.25	6.19	1.040	1.407
8220	31	rigid	166.12	188.38	126.86	157.74	36.77	7.97	1.619	2.167
8018	31	APR	72.31	-	83.59	62.15	39.91	2.94	0.807	0.879
8208	31	APR	51.74	77.65	44.36	80.11	66.72	4.13	1.897	2.137
8221	32	APR	53.92	115.78	59.54	73.46	67.48	5.20	1.403	1.880
8222	32	APR	103.60	108.18	83.00	106.40	54.72	6.78	1.977	2.654
8021	32	HNCB	112.20	-	61.90	55.71	42.96	4.63	1.165	1.304
8023	33	HNCB	124.80	-	104.10	84.12	48.26	5.50	1.386	1.741
8111	32	HNCB	71.80	-	86.16	92.59	12.88	1.70	0.135	0.161
8112	32	HNCB	107.40	-	104.91	113.16	35.99	3.14	0.585	0.727
8308	16	car door	66.51	-	65.41	32.34	18.58	3.45	0.379	0.433
8321	36	car door	114.81	165.09	123.68	161.59	33.54	7.03	1.515	1.855

Table 4 contains a summary of the mechanic response average and a value of standard deviation according to the test types. They are RW24, RW32, i.e., the impact into a rigid wall with a striking velocity 24km/h, 32km/h respectively; APR32, HNCB32, i.e., the impact into APR padding and HNCB padding respectively with a striking velocity 32km/h. The averages and the standard deviations of the accelerations of rib and of spine, showed in table 4, are the results which the accelerations are normalized by introducing a coefficient $1/\mu$ to diminish the individual effect of the geometric properties of each test subject for the measured response during experimentations [EPPINGER et al. 1984]. This coefficient μ is defined as

$$\mu = (Ms/Mi)^{1/3}$$

Ms: mass of standard subject (75kg), Mi: mass of test subject.

Table 4 Summary biomechanic data for sled impact

type of tests	no. test	Cmax (%)	Vmax (m/s)	(VC)max (m/s)	(DE)max (m/s)	Acc(4lr) (g)	Acc(8lr) (g)	Acc(T1) (g)	Acc(T12) (g)	NFR
RW24	6	28.04 ±13.53	4.40 ±0.95	0.726 ±0.433	0.933 ±0.546	92.27 ±22.88	114.97* ±21.89	102.55 ±16.38	90.89 ±24.83	4.7 ±3.1
RW32	5	30.72 ±13.55	5.68 ±1.96	1.125 ±0.635	1.433 ±0.754	134.42 ±25.73	196.14** ±13.36	113.78 ±8.36	142.21 ±21.87	10.8 ±6.5
APR32	4	57.21 ±12.93	4.76 ±1.63	1.524 ±0.539	1.887 ±0.745	7198 ±22.17	107.11* ±20.99	68.93 ±15.55	83.43 ±20.37	9.8 ±6.7
HNCB 32	4	35.02 ±15.59	3.63 ±1.53	0.818 ±0.569	0.983 ±0.688	97.86 ±25.93	- -	80.59 ±20.33	80.21 ±19.04	3.0 ±3.8

Note: 1) * nomber of test = 3; ** nomber of test = 2 .

ACCELERATION OF THE RIB AND THE SPINE

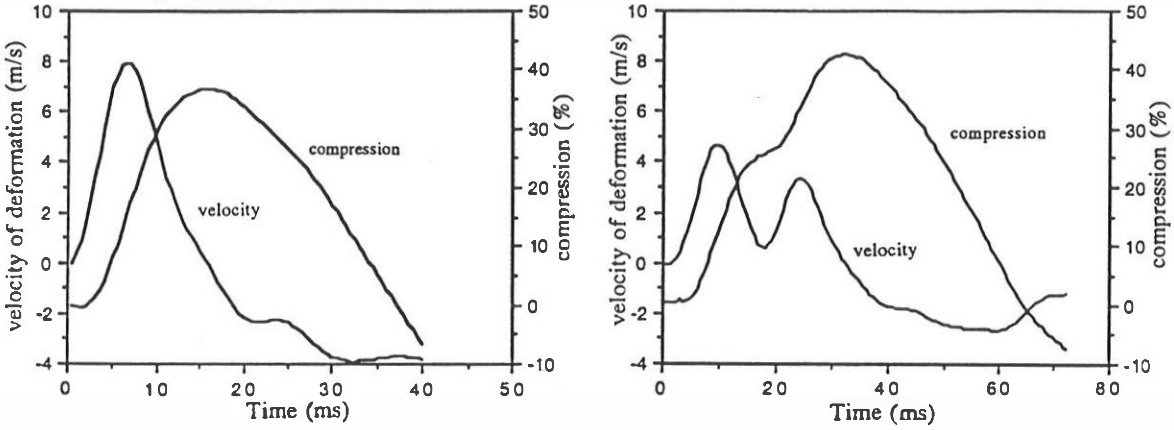
The data in the table 4 show that the response acceleration of the 4th rib and of the spine in group RW32 displays a level higher than those in other groups. In particular, the responses Acc(T1) and Acc(T12) in the case of impact into an absorbed energy material of APR padding or HNCB padding, are evidently lower than in the case of impact into a rigid wall. This fact indicates that the response acceleration measured from the thorax depends essentially on rigidity of the impact surface. For the same collision velocity (ex. RW32 and APR32), the value Acc(T12) determined from the case of impact into a rigid wall (average 142.2g) is approximately twice as high as the one from crashing into the APR soft padding (83.4g). A similar level of acceleration could correspond either to the case of a crash against a rigid wall with a low impact velocity or to the case of a crash into a padded wall at a high impact velocity, for example Acc(4lr) in the case RW24 and HNCB32. However, in these cases, the difference of injury level is evident (NFR=4.7±3.1 against NFR=3.0±3.8). The Acc(4lr) in the group APR32 is lowest as compared with other data set. In the contrary case, the average of the number of fractured ribs in this group (NFR=9.8±6.7) is larger than the one in the groups HNCB32 and RW24.

The influence of the rigidity of the panel on the thoracic acceleration is also evident in the cases of impact into padding. The Acc(4lr) average in the case with HNCB padding is larger than that obtained with APR padding, because of the rigidity difference of these two types of padding. Our analysis show that thoracic accelerations are sensitive to the impact strength sustained by the subject, while it has little relationship with the thoracic injury severity and the injury mechanism.

THORACIC COMPRESSION AND ITS DEFORMATION VELOCITY

Figure 1 gives two representative examples of the history of the compression and of the velocity of deformation in function of time during thoracic impact into a rigid wall or a padding. When we examine the peak of dynamic responses, it is found that the thorax sustains a large compression at the time of impact into a surface with padding (57.2% for APR32 and 35.0% for

HNCB32) with a relatively low velocity of deformation (3.63m/s for HNCB32 and 4.76m/s for APR32). These two deformation velocities are obviously lower than one obtained from the case of impact into a rigid wall with a same impact velocity (5.68m/s for RW32). In the case of impact into a rigid wall, it is found that the impulse of deformation velocity happens during a short duration with a high peak. On the other hand, in the case of impact into a wall with padding (both APR and HNCB), the thoracic deformation lasts over a long period with a relatively low maximal value. For example, in the case of impact against a rigid wall with an impact velocity of 32km/h, the impulse of the deformation velocity lasts 14.8ms with the average of Vmax 5.68m/s and Cmax 30.7% respectively. In the case of the impact against the APR soft padding, the impulse of deformation velocity lasts 41ms with the average of Vmax 4.76m/s and Cmax 57.2% respectively.


(a) Test N°8220 (rigid wall)

(b) Test N°8021 (HNCB padding)

Figure 1 History of the velocity of thoracic deformation and of compression as a function of time, a) impact into a rigid wall, b) impact into a padding.

DYNAMIC RESPONSE CHARACTERISTIC OF THE THORACIC DEFORMATION

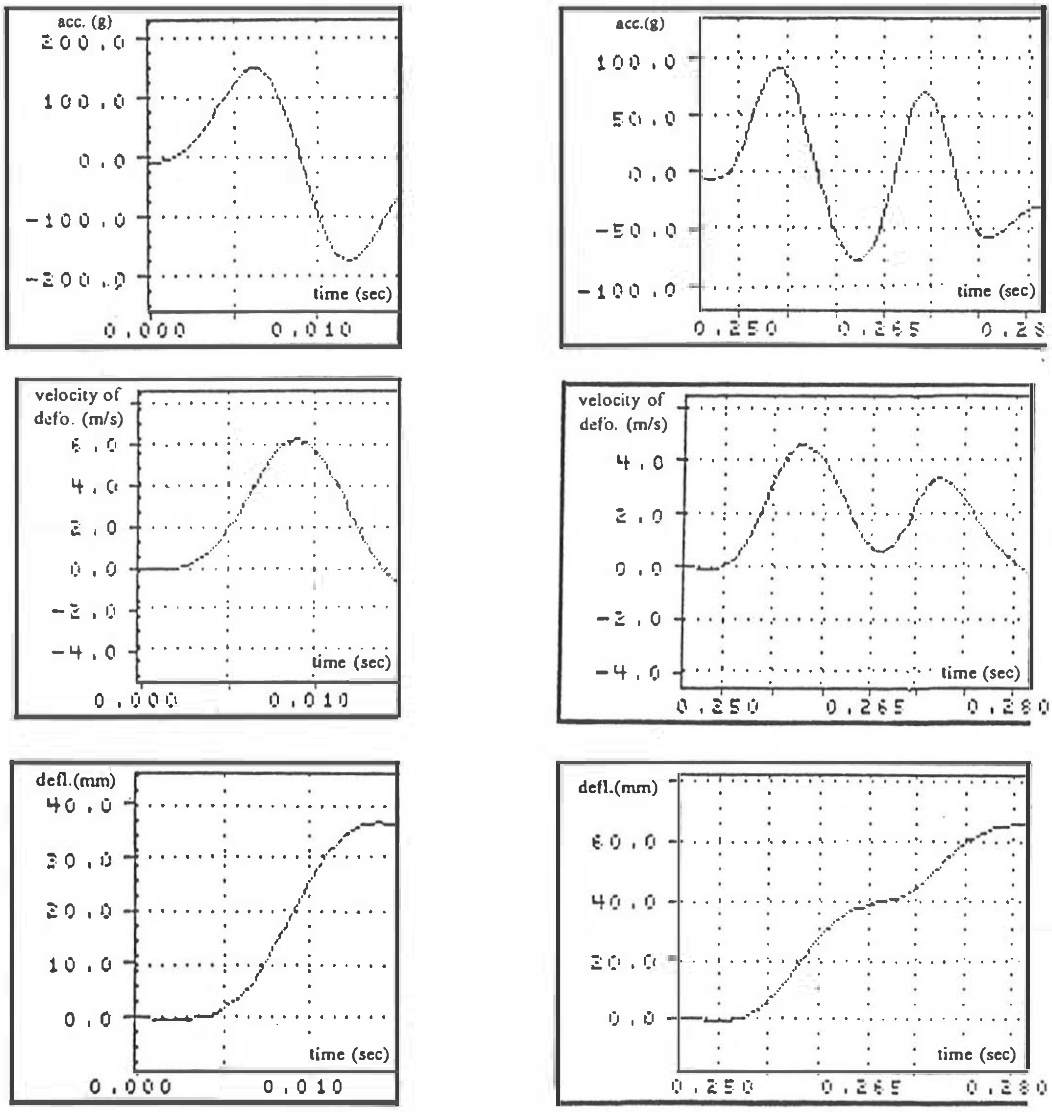
The difference of the dynamic responses of the chest in lateral impact is observed not only on its maximum but also in the process of the crash that leads to the injury of the thoracic skeleton and interior organs with a difference mechanism. In particular, when we attempt to estimate the moment at which the injury occurs, it is necessary to examine the whole process of chest crash.

Figure 2 shows a representative example of a number of dynamic curves. It includes the response of the acceleration, the velocity of deformation and the chest deflection in an impact. Our observation will be limited to the phase of thoracic deformation from 0 to maximum in the case of the impact against a rigid wall or against a padding, and will not touch upon the recovery phase of thoracic deformation.

These processes can be expressed approximately by a trigonometry function as following:

$$y = (t-0.5\sin 2t)/2$$
$$\dot{y} = (1-\cos 2t)/2$$
$$\ddot{y} = \sin 2t$$

and are illustrated in the Figure 3. If we examine only an interval of time from 0 to π, for the case of impact into a rigid wall, we could see that the mathematical expressions above represent the mechanical response of the test subjects more realistically, so that it is possible to study the thorax compression process from this simple mathematical description. For the thoracic response in the case of impact into a padding, the progress of the deformation have two stages, separated by a landing and the deformation velocity shows two peaks. This process could be expressed similarly by the trigonometric equation with an interval of time 0 to 2π.



a) N° 8214, rigid wall, b) N° 8021, HNCB padding.

Figure 2. Two examples of thoracic mechanic responses: acceleration, velocity of deformation and compression, a)impact into a rigid wall, b) impact into a padding.

ESTIMATION OF INJURY RISK

--Impact into a rigid wall

In order to facilitate our examination, the thoracic deformation in impact could be described as three phases in the theoretical model presented above (Figure 3). In the first phase, the velocity of deformation increases from 0 (initial stat) to a maximal value, and the chest compression is kept at a low level with a monotone and progressive increase and, even at the moment where the velocity of deformation grows to the maximum, the deformation is only about half of the maximum. Based on experimental data quoted above, the average of C (compression) at this moment is 12.05% from RW24 and 14.87% for RW32 (these correspond respectively to 43.0% and 48.4% of the maximal value of chest compression). Hence, in the first phase of deformation the chest sustains a lower level of compression which gradually increases. In the this stage, we could think that the thoracic injury risk is low. The tests with human volunteers [KROELL 1976] showed that the chest compression up to 20% in quasi-static loading produced no injury and was fully reversible. As the compression grew to greater than 20%, the tests with human cadaver at impact velocity between 5 and 7m/s, the risk of skeletal fractures in the rib cage increased. In experimental data used in this paper, among 11 tests with impact against a rigid wall, two subjects only arrive at more than 20% compression when V rises up to the maximum (23.46% to the test No.8218 and 26.97% to the test No.8102). On the other hand, when the deformation velocity reaches its maximum, the compression is less than 20% in 9 of 11 cases. So we would foresee that the chest injury risk is low when the compression velocity does not reach its maximum in the situation of impact.

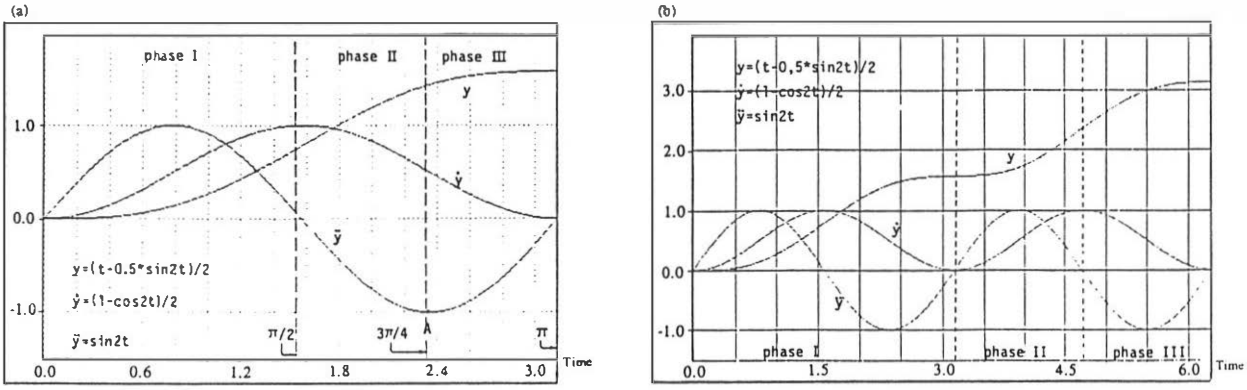


Figure 3 . Similar mathematical description of the process of chest deformation, a) impact into a rigid wall, b) impact into a padding.

At the point of departure of the second phase, the chest is in a state where the deformation is fast and the compression increases continuously. After reaching maximum velocity, the deformation velocity decreases as a result of resistance of the cage thorax. This reduction becomes faster and faster with time until the maximum deceleration appears (last point of the second phase). In this moment, the chest compression is near to its extreme and could reach 60-75% of its maximum, according to the test data. At this stage, intrathoracic organs sustained a compression that became progressively heavier. Hence, we would consider that, in this stage, the thorax has a larger injury risk as the velocity of deformation and compression, two essential mechanic factors, both maintain a higher level. The result of these two factors acting together is that the possibility of occurrence of trauma of the chest cage and of the organs is larger than in the first phase. We notice that the peak of viscous response takes place in the second deformation phase defined above and, moreover, it has been observed that, in a blunt impact to a cadaver thorax, the moment corresponding to the peak of viscous response is very close to occurrence of rib fractures [LAU et al. 1988]. In the 3rd phase of chest deformation, the thoracic compression approaches its maximum with a low velocity. The deformation process will stop and the return stage will start. If a trauma has been produced in the second phase of deformation, in this phase, the impact leads to an aggravation of thorax injury.

--Impact into a padding

In the case of the impact into a soft padding (both APR and HNCB), the crash process of the chest is longer and, moreover, two peaks of the deformation velocity appear. In our observation, seven subjects present this typical dynamic response (figure 3b).

Because the human and the padding are both deformable objects, they were deformed by a mutual crash during impact. At first, the body sustains a lower level of deformation under the effect of padding. At the first peak of velocity, corresponding chest deformation is at a low level (11.64% on average) with an average 3.8m/s of velocity of deformation. Afterwards, the effect of padding reduces thoracic deformation velocity and then a deformation plateau appears. If we accept that the chest deformation process may be divided into three stages, this landing could be considered as the border between the first two stages (phase I and II). Examining the whole process of deformation, we notice that the chest deformation velocity is generally low in relation to the case of impact against a rigid wall. The maximal velocity of deformation is generally reached at its first peak and the value of deformation is low at this moment. So it could be foreseen that, if the injury risk estimated is only based on the criterion of velocity, it will result in certain error when a padding is used. For an impact process with a large thoracic deflection but a low velocity, the compression must be consisted as an important factor.

DETERMINATION OF THE HUMAN THORAX TOLERANCE IN SIDE IMPACT

--Injury risk function

Human thorax tolerance is determined by means of statistical methods using the Weibull function. It is a exponential function with a variable (x) and three parameters (θ, β, δ). This function relates the probability of injury occurrence W(x) to the magnitude of a mechanic parameter x (for example, compression C, viscous response VC, etc.) based on a statistical fit to a sigmoid function.

$$W\,(x;\,\theta,\beta,\delta) = 1 - \exp\left(-\left(\frac{x-\delta}{\theta-\delta}\right)^{\beta}\right)$$

The Weibull function is chosen in our research because it shows a more reasonable distribution of probability than normal distribution within the interpretation of biomechanical data [RAN et al. 1984, MORGAN 1984]. Moreover, for a series of identical biomechanical data, the weibull distribution could give a higher value of likelihood than a normal distribution. In this paper, the method of numerical estimation is used to find these parameters [KAPUR et al. 1977].

--Tolerance of the human thorax

Tolerance of the human thorax in side impact would be estimated according to the injury severity of chest skeleton, expressed in NFR. Because four ribs fractured corresponds to a inferior limit value of serious lesions (AIS=3), therefore NFR=4 could be considered as an acceptable injury level. Because the cumulative frequency of 50% probability of thoracic lesions with flail chest (AIS=4) corresponds to about nine ribs fractured, NFR=9 is chosen as the other limit for estimating the risk of thoracic injury corresponding to a severe lesion level.

The injury probabilities are plotted in Figure 4 for the probability of serious injury as a function of the viscous response (VC) or of the dissipated energy response (DE) of the chest. Table 5 gives the value of three parameters of the Weibull function and the thorax tolerance level with 25% probability of serious or severe injury for each mechanical response.

A tolerance level of VC=1.03m/s for the chest was determined for a 25% probability of serious injury (AIS=3). Maximum compression was similarly set at C=35.4% and maximum velocity of thoracic deformation was set at V=4.73m/s. With maximum DE response, DE=1.32m/s may be used as a threshold value for human tolerance in blunt lateral impact to the chest.

Table 5. Tolerance levels of the chest injury and parameters of the Weibull function based on 25% probability of injury (n=21).

(a) for gravity of the injury NFR≥ 4

response	θ	β	δ	tolerance
Vmax	6.166	4.713	0.0	4.731 (m/s)
Cmax	49.15	1.864	21.0	35.42 (%)
(VC)max	1.543	3.083	0.0	1.030(m/s)
(ED)max	1.925	3.325	0.0	1.323 (m/s)

(b) for gravity of the injury NFR≥ 9

response	θ	β	δ	tolerance
Vmax	6.239	5.747	0.0	5.349 (m/s)
Cmax	55.786	3.683	0.0	39.78 (%)
(VC)max	1.692	4.842	0.0	1.308(m/s)
(ED)max	2.053	1.952	1.126	1.616 (m/s)

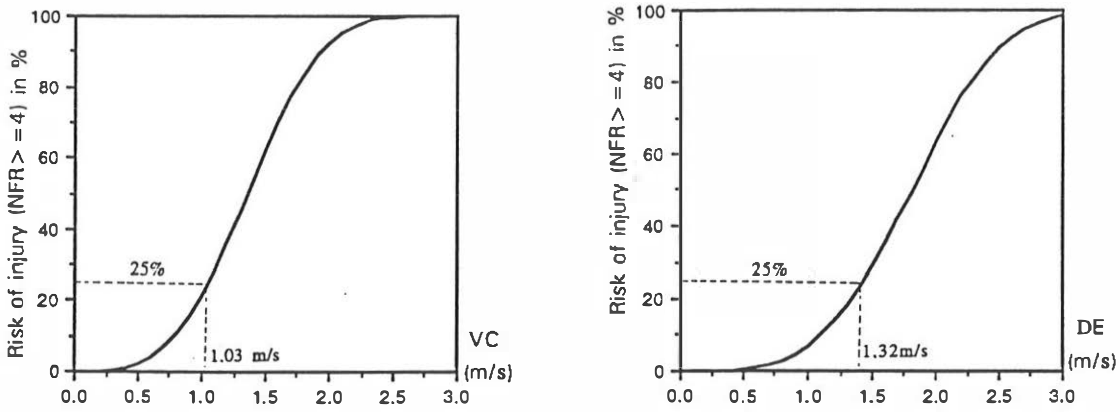


Figure 5. Risk of serious injury as a function of the maximum viscous response or the maximal dissipated energy response for lateral chest impact of human cadavers.

CONCLUSIONS

-Chest deformation mechanisms in side impact are different in an impact against a rigid wall and against a padding. The human thorax sustains a large deformation in the last case. For the same impact velocity, the deformation velocity in the last case is clearly lower than that in the process with a rigid wall. On the other hand, in the case of impact against a rigid wall, the peak of the deformation velocity is higher and the impulse of the deformation velocity is of short duration. Moreover, the thorax compression is relatively larger.

-In the process of chest deformation, mechanical responses present different characteristics. The risk of injury occurrence arises when the deformation velocity and the compression are both situated at a higher level. A criteria developed based on only one of these factors - velocity and deflection could not be correctly connected with the injury risk and could not correctly describe the injury mechanism. The estimation of injury risk must be viewed from the angle of the crash process of the body and from the effects of the divers mechanical factors, but we can not merely consider the maximum of certain responses.

-The tolerance level of (VC)max=1.03m/s and of (DE)max=1.34m/s for the chest in side impact were determined for a 25% probability of grave injury NFR=4 (number of fractured ribs). Maximum half thoracic compression was similarly set at C=35.4%.

ACKNOWLEDGMENTS

The authors gratefully thank Dr. J. MARCUS , the head of Biomechanic Division of the Office Crashworthiness Research, NHTSA, for providing band type that records original data of impact tests, and Dr. D. KALLIERIS in the University of Heidelberg for providing details of records of cadaver injuries for all tests. The views expressed in this paper are entirely those of the authors and do not reflect any opinions of the suppliers of data.

REFERENCES

AAAM (1985) *"The Abbreviated Injury Scale (1985 Revision)"*, AAAM, 1985. - 80p.

ASG (1985) *"NHTSA Data Tape Reference Guide"*, Automated Sciences Group, Inc., Contract N° DTNH22-84-C-07368 avec Office of Vehicle Research of the NHTSA, August 1985.

Césari D., Ramet M. and Herry-Martin D. (1978) *"Injury mechanisms in side impact"*, SAE Paper N° 780897, Proc. of the 22nd Stapp Car Crash Conference, Ann Arbor, 1978. - p. 429-448.

Césari D. and Zac R. (1983) *"Evaluation of Side Impact Protection in Barrier to Car Tests"*, SAE Paper N° 831532, Proc. of the 27th Stapp Car Crash Conference, San Diego, October 1983. - p. 399-406.

DSP (1990) *"'DADISP' User's Mannual, Version 2"*, DSP Development Corporation, 1990.

Eppinger R. H., Marcus J. H. and Morgan R. M. (1984) *"Development of Dummy and Injury Indexfor NHTSA's Thoracic Side Impact Protection Research Program"*, SAE Paper N° 840885, 1984 - 28p.

Henry C. and Tarrière C. (1983) *"Evaluation of the Risk of Internal Thoracic lesions in Side Impact: Consequences Regarding protection Criteria."* Document ISO/TC22/SC12/GT6 No. 141, Working Group 6, 1983 - 9p.

Kallieris D., Mattern R., Schmidt G. and Eppinger R. (1981) *"Quantification of Side Impact Responses and Injuries"*, SAE Paper N° 811009, Proc. of the 21st Stapp Car Crash Conference, San Francisco, September 1981. - p. 329-368.

Kapur K. C. and Lamberson L.R. (1977) *"Reliability in Engineering Design"*, New York: John Wiley & Sons, 1977.- 586p., ISBN 0-471-51191-9.

Klaus G., Sinnhuber R. and Hoffman G. (1984) *"Side Impact - A Comparison Between Dummies and Cadavers, Correlations Between Cadaver Loads and Iniury Severity"*, SAE Paper N° 841655, Proc. of the 28th Stapp Car Crash Conference, Chicago, November, 1984.- p. 237-259

Kroell, C. K. (1976) *"Thoracic response to blunt frontal loading"*, SAE Publication P-67: "The Human Thorax—Anatomy, Injury, and Biomechanics", Society or Automotive Engineers, Warrendale, PA. 1976.

Lau I.V. and Viano D. C. (1986) *"The Vscous Criterion - Bases and Applications of our Injury Severity Index for Soft Tissues"*, Proc. of the 30th Stapp Car Crash Conference, San Diego, October, 1986. - p.123-142.

Lau I.V. and Viano D. C. (1988) *"How and When Blunt Injury Occurs - Implications to Frontal and Side impact Protection"*, SAE Paper N° 881714, Proc. of the 32nd Stapp Car Crash Conference, Atlanta, October 1988. - p. 81-100.

Lenz K.H. et al. (1982) *"Joint Biomechanical Research Project KOB"*, Unfall Und Secherheitsforschung Strassenverkehr, Vol 34. 1982. p. 1-138, BASt Cologne F.R. Germany.

Marcus J. H. (1984) *"The Biomechanics Data Base"*, SAE Paper N° 840867, SAE Publication P-146: "Mathematical simulation of occupant and vehicle kinematics", 1984. - p. 137-142.

Melvin J. W., Robbins D. H. and Benson J. B. (1979) *"Experimental Appiication of Advanced Thoracic Instrumentation Techniques to Anthropomorphic Test Devices"*, Proc.of the 7th Conference ESV, 1979. - p. 416-427.

Monk M. U., Morgan R. M. and Sullivan, L. K. (1980) *"Side Impact Sled and Padding Development"*, SAE Paper N° 801307, Proc. of the 24th Stapp Car Crash Conference, Troy, October, 1980. - p. 25-326.

Morgan R. M. (1984) *"Analysis of Injury vs. Exposure Data Using WEIBULL Distribution Function"*, Proc. of the 12th Annual International Workshop: Human Subjetcts for Biomechanical Research, Chicago, November 1984. - p.101-117.

NHTSA (1988) *"Preliminary Regulatory Impact Analysis New Requirements Side Impact Test"*, (FMVSS 214) NHTSA, Report N° DOT-HS-807-220, Washington D. C., January 1988.

Ran A., Koch M. and Mellander H. (1984) *"Fitting Injury Versus Exposure Data Into A Risk Function"*, Proc. of the 1984 International Conference on the Biomechanics of Impacts (IRCOBI), Delft, September 1984, p. 89-100.

Schmidt G., Kaillieris D., Barz J. and Mattern R. (1974) *"Results of 49 cadavers Tests Simulating Frontal Collision of Front Seat Passengers"*, Proc. of the 18th Stapp Car Crash Conference, Ann Arbor, December 1974. - p.283-291

Tao X. T. et al. (1992a) *"Etude d'indicateur courant de la gravité de blessure du thorax entier: le nombre de côtes fracturées (NCF)"*, (to apper).

Tao X. T., Cécari D., Rumelhart C. and Boivin M. (1992b) *"Analyse du comportement du thorax humain en choc latéral"*, Congrès de la Société Canadienne de Génie Mécanique: "Transport 1992+", Montréal, juin 1992.

Thomas C., Henry C., Hartemann F., Chamouard F. and Tarrière C. (1987) *"Injury Pattern and Parameters to Assess Severity for Occupants Involved in Car-to-Car Lateral Impacts"*, Proc. of the 11th Experimental Safety Vehicles Conference, Washington, May 1987.- p. 49-62.

Viano D.C. and Lau I.V. (1985) *"Thoracic Impact: A Viscous Tolerance Criterion"*, Proc. of the 10th Experimental Safety Vehicle Conference, Oxford, England. 1985. - p. 104-114.

Viano D C. (1989) *"Biomechanical Responses and Injuries in Blunt Lateral Impact"*, SAE Paper N° 892432, Proc. of the 33rd Stapp Car Crash Conference, Washington, October, 1989.- p. 113-142.

Walfisch G., Chamouard F., Lestrelin D., Fayon A., Tarrière C., Got C., Guillon F. and Patel A. (1982) *"Tolerance Limits and Mechanical Characteristics of the Human Thorax in Frontal and Side Impact and Transposition of these Characteristics into Protection Criteria"*, Proceedings of the conference IRCOBI (1982).

Wang J. T. (1989) *"Analytical Studies of Injury Criteria for the Thorax"*, J. of Biomechanical Engineering, Vol. 111, p. 128-135, May 1989.