HUMAN THORAX BEHAVIOUR FOR SIDE IMPACT. INFLUENCE OF IMPACT MASSES AND VELOCITIES

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ABSTRACT

This study deals with the knowledge of human behaviour under impact conditions close to those of the real world and the verification of the sensitivity of the lateral criteria deflection and V*C to mass and velocity variation. A series of 11 tests were conducted on unembalmed cadavers with a guided horizontal impactor. The impactor masses used were 12 and 16 kg and the velocities were 6 to 8.5 m/s. The impact surface was flat, rigid and of 15 cm diameter. Identical tests were carried out with a Eurosid-1 dummy.
In these tests conditions, the behaviour of the Eurosid-1 thorax could be improved.
The V*C and the defelction criteria are sensitive to the variations of the impact masses and velocities.

INTRODUCTION

The improvement of occupant protection in side impact crashes is of constant concern in automotive safety. The basis for product improvements is an understanding of crash types and interior contact. The goal of this study is to look for the effects of mass and velocity variations on the biomechanical criteria used for the thorax in the lateral impact.In all previous studies using cadaver lateral impacts, the tests were carried out with an impactor mass of 23.4 kg and impact speeds of less than 9 m/s or against a rigid wall. The analysis of crash tests showed that the effective impacting masses with regard to the thorax were lower than 23.4 kg and the impact velocities were higher than 8 m/s. This study deals with the knowledge of human thorax behaviour and response under impact conditions close to those of the real world ($m = 12$ kg and $m = 16$ kg; $5.9 \text{ m/s} \leq V \leq 8.5 \text{ m/s}$.) since this information forms the basis for the development of applicable injury criteria and for setting human tolerance levels.

MATERIALS AND METHODS.

- **Specimen selection.**

Unembalmed cadavers were provided by the Department of Anatomy at Lyon-Nord Medical University.
They were all aged between 53 and 93 years; the average age was 72 years and mean body mass 59 kg. Anthropometric data were compiled for each subject prior to testing. The anthropometric data are shown in table 1.

Table 1 : Subject anthropometrics.

Subject	Sex	Age	Mass (Kg)	Height (cm)	Thorax width (cm)	C/L gr/cm
LCT01	M	65	55	176	29.0	0.20
LCT02	F	53	78	164	27.7	0.15
LCT03	F	80	30	157	24.5	0.53
LCT04	F	93	43	157	25.2	0.15
LCT05	M	84	42	160	28.5	0.14
LCT06	M	77	68	175	32.5	0.24
LCT07	M	72	82	181	34.0	0.21
LCT08	M	66	59	173	30.0	0.24
LCT09	M	65	66	165	30.0	0.20
LCT10	M	69	56	180	29.7	0.30
LCT11	M	71	71	169	29.0	NA*

*NA : Not available

The criteria for selection of subjects were their condition and cause of death, which limited the selection to specimens not having had a long period of bed rest or to specimens without infectius deseases. For each of the specimens, the time between death and testing was 4 to 6 days.

- **Preparation and instrumentation.**

Cadavers : The subjects were exposed to room temperature for several hours during instrumentation and preparation. Just before the test, the lungs were pressurized by means of a vent tube inserted in the trachea. The subjects LCT01,LCT02 and LCT03 were partially injected because of the atherosclerosis. The other subjects were not injected.
The subject instrumentation was defined to obtain the kinematics of seven points on the head, the spine and pelvic during the impact. The cadaver was instrumented with an array of accelerometers attached to the ribs, spine and pelvis. A triaxial accelerometer was attached to the first, eigth and twelfth thoracic vertebrae and a similar triaxial accelerometer was attached to the sacrum. An angular velocity sensor was attached to the eighth vertebra and another to the sacrum. Uniaxial

accelerometers were attached to the fifth, the sixth and the seventh rib on the impacted side.
Double targets separated from one another by 6 centimeters were attached to the head, the first, the fourth, the eighth and the twelfth vertebrae, similar targets were attached to the third lumbar vertebra and to the sacrum (Figure 1). The double target system allowed the calculation of the vertebrae rotation during the impact.
Dummy : All cadaver tests were duplicated by Eurosid-1 tests. Table 2 gives the entire instrumentation used for the cadavers and Eurosid-1 tests.

Table 2 : Instrumentation used for the tests.

	Eurosid-1	Cadaver
Head acceleration	X,Y,Z	
Acceleration (T1)	X,Y,Z	X,Y,Z
Acceleration (T8)		X,Y,Z
Acceleration (T12)	X,Y,Z	X,Y,Z
Pelvic acceleration	X,Y,Z	X,Y,Z
Rib acceleration (1,2,3)	Y	
Rib acceleration (5,6,7)		Y
Pubic force	Y	
Rib deflection (1,2,3)	Y	
Angular velocity (T8)	ω	ω
Angular velocity (Sacrum)	ω	ω

- **Autopsy**

Autopsy was performed by a qualified physician and special attention was paid to chest injury.
In order to assess the subject mineralization, a 6 centimeter sample was taken from the fourth, the fifth and the sixth ribs.

- **Test configuration**

Impactor : The tests were carried out with a linear impactor. The impactor masses were 12 kg and 16 kg. The impactor interface was a rigid, flat, 15 centimeter diameter disc. The impactor was propulsed by bungee cords. The impact speed was calculated by a time interval counter and a known distance on the impactor.
Subject positioning : The subject was seated on a sheet of teflon. A suspension system, which held the neck, ensured that the subject was positionned, as required, with a straight back. The longitudinal axis of the impactor was aligned with the xiphoïd process. The arm was not involved in the impact. Each subject was impacted on the right side. Figure 1 shows a general view of the test configuration

Determination of the test matrix :
To determine the test conditions, that is to say, the impact masses and velocities, an analysis was made from vehicle tests with dummies used under ECE95 regulation conditions. The European side impact test procedure is a global test on a stationary vehicle struck laterally by a deformable moving barrier. The barrier velocity was 50 km/h.
This analysis was carried out to calculate the impact velocity of the inner side of the door during the crash. The impact velocities were obtained by integrating the acceleration of the door at a point located at the level of the middle rib of the dummy.
The analysis of several tests showed that impact velocity values were from 8 to 12 m/s with an average value of 10.9 m/s. These variations were due to the different stiffnesses of the doors of the vehicles tested.

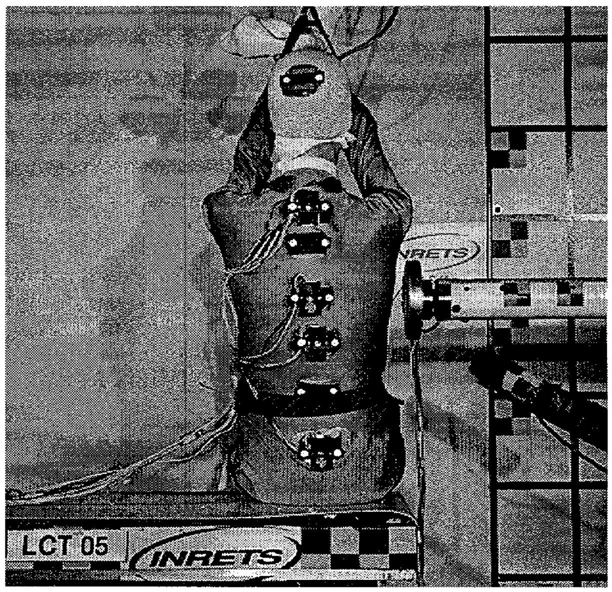

Figure 1 : General view of the experimental set-up.

Eleven cadaver tests and eighteen Eurosid-1 tests were carried out. Tables 3 and 4 respectively give the test conditions for cadavers and Eurosid-1.

Data analysis :

The tests was filmed at 1000 frames per second from behind the subject.
The half thorax deflection was considered to be equal to the displacement of the impactor with respect to the spine displacement at the eighth vertebra. For these tests, two methods of computing the deflection were used. The first method was the difference between the double integration of the T8 and impactor accelerations. The second method was a film analysis.

Table 3 : Experimental test conditions for the cadaver tests.

Test	Mass (kg)	Velocity (m/s)	Energy (J)
LCT01	12	5.96	213
LCT02	16	5.93	281
LCT03	16	6.06	294
LCT04	12	6	216
LCT05	12	8.19	402
LCT06	12	8.48	431
LCT07	16	7.16	410
LCT08	16	7.03	395
LCT09	16	5.7	260
LCT10	12	5.32	170
LCT11	12	8.53	436

A frame by frame analysis of the impact formed the basis for the instantaneous deflection data. These two methods allow the comparison of the data obtained and permit the validation of the results. Figure 2 shows a comparison of the deflections obtained from the two methods. The deflection value of the LCT02 test is 87.2 mm and this value is validated by the two methods. In all the results analysis, the deflection curves used are from the accelerometric method.

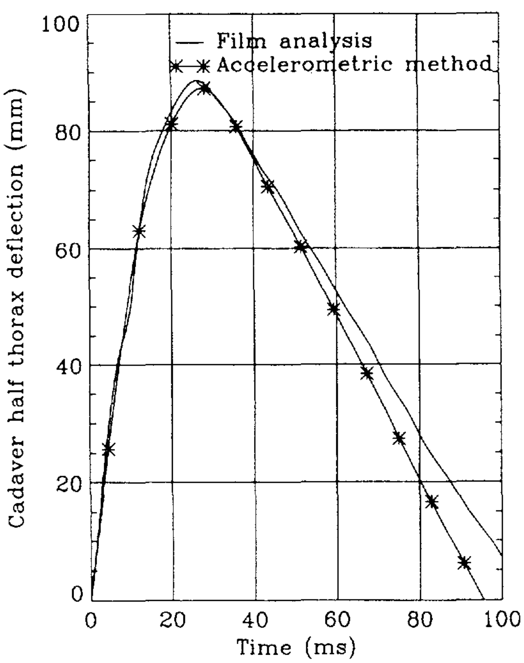

Figure 2 : Comparison of the deflection curves from accelerometric and film analysis.

The deflection data were processed using an established algorithm by Viano and Lau [1] and Lau and Viano [2] to derive the viscous response (V*C).
Contact was indicated by a flash on a movie frame and a simultaneous electrical signal from a switch. This defined time zero.

Table 4 : Experimental test conditions for Eurosid-1 tests

Test	Mass (kg)	Velocity (m/s)	Energy (J)
LMT01	12	6.10	223
LMT02	12	7.46	334
LMT03	12	5.39	174
LMT04	12	6.06	220
LMT05	12	9.02	488
LMT06	12	8.97	483
LMT07	16	5.90	278
LMT08	16	5.78	267
LMT09	16	8.32	554
LMT10	16	8.33	555
LMT11	12	4.81	139
LMT12	12	8.21	404
LMT13	11.4	6.00	205
LMT14	11.4	6.02	207
LMT15	11.4	8.58	420
LMT16	11.4	8.58	420
LMT17	16	7.18	412
LMT18	16	7.17	411

RESULTS

- Cadaver tests : Biomechanical responses.

The acceleration channels were filtered at CFC 180.
For the cadaver tests, peak biomechanical responses, in terms of force, deflection and viscous criterion, and resulting injuries are summarized in table 5.
The injury evaluation is given by the number of fractured ribs and the severity is given by the A.I.S. (Abreviated Injury Scale). All the subjects were injured. The injuries were essentially rib fractures. All subjects sustained one or more fractures on the 5th, the 6th and the 7th ribs. Some of them can be attribuated to the accelerometer mounting. That's why fractured ribs number is more able to avaluate the severite of the impact. Two subjects sustained more than rib fractures : (LCT02 and LCT07). These injuries were liver lacerations (stared wound of 4

centimeters in diameter for test LCT02 and a hemorrhagic wound of the right part of the liver for test LCT07). Comparisons between the number of fractured ribs and the energy, force and deflection were made. There were no relationships between these parameters and the number of fractured ribs.

The cadaver responses in terms of forces and deflections were gathered for energy values of 190 ± 26 J , 278 ± 18 J and 415 ± 20 J.

Table 5 : Cadaver responses and injuries for a lateral impact.

Test	Force (daN)	Deflection (mm)	V*C (m/s)	NRF	NFR	AIS
LCT01	223	62.5	1.33	3	3	2
LCT02	288	87.2	1.75	10	5	3
LCT03	187	63.6	0.93	18	7	4
LCT04	176	72.6	1.36	16	8	4
LCT05	294	102	2.59	9	7	3
LCT06	379	85.4	2.15	14	6	4
LCT07	394	96.8	1.70	11	6	4
LCT08	281	99.3	1.77	16	6	4
LCT09	262	73.9	1.26	6	6	3
LCT10	250	73.6	1.79	8	4	3
LCT11	384	80.5	2	6	4	3

* NFR = Number of fractured ribs
* NRF = Number of rib fractures

The results are given in figures 3 and 4. Figure 3 shows the thorax deflection curves versus time and figure 4 shows the impactor force versus time. On figure 4 and for the energy of 190 ± 26 J, we have added the iso corridor obtained from [4]. This corridor was obtained with the HSRI impact tests [5] with an impacto mass of 23.4 kg and a velocity of 4.3 m/s. For this level of energy, the impactor force curves are within the corridor.

Figure 5 shows the force/deflection curves. These curves represent the characteristic responses of the biomechanical behaviour of the thorax subjected to lateral impact. For those test conditions, response corridors were defined for each level of impact energy.

- Eurosid-1 tests : Biofidelity.

The Eurosid-1 biofidelity was assessed by comparing the responses of the dummy with those of the cadaver.

The characteristic responses of the Eurosid-1 thorax in terms of force versus deflection were obtained.

Figure 6 shows the curves of force/deflection for the three energy levels; to evaluate the biofidelity of the Eurosid-1, corridors obtained from cadaver tests were added to the graphs in figure 6.

For these impact energies and for the test configurations of this study, the Eurosid-1 behaviour was not biofidelic compared to the cadaver behaviour.

The force response of the Eurosid-1 thorax is twice as high as that of the human being. whereas the thorax deflection response of the dummy is half that of the human.

Criteria sensitivity.

To study the sensitivity of the impact response parameters to the test conditions, tests at isoenergy and tests at isomass were analysed.

- **Isoenergy tests**

Cadaver and Eurosid-1 tests at isoenergy level (but different masses and velocities) were analysed.

Table 6 gives,with the test conditions, the peak values of the force, the deflection and the V*C for the cadavers and table 7 gives the results for the Eurosid-1 tests for the same energy.

Table 6 : Cadaver tests at isoenergy (415 ± 20 J)

Test	Mass (kg)	Velocity (m/s)	Force (daN)	Deflection (mm)	V*C (m/s)
LCT05	12	8.19	294	102	2.59
LCT06	12	8.48	376	85.4	2.15
LCT11	12	8.53	384	80.5	2
LCT07	16	7.16	394	96.8	1.7
LCT08	16	7.03	281	99.3	1.77

From the results presented in table 6, it can be seen that for the higher velocity tests (LCT06 and LCT11) the V*C values are higher than (16.6 % higher) at the lower velocities. Furthermore, for the lower velocity tests (LCT07 and LCT08), the deflection values are higher than at the higher velocity tests.

For the same energy of impact, the V*C and d responses are sensitive to mass and velocity variations. Thus, the V*C increases with the impact velocity whereas the deflection decreases.

Table 7 : Eurosid-1 tests at isoenergy.

Test	Mass (kg)	Velocity (m/s)	Force (daN)	Deflection (mm)	V*C (m/s)
LMT12	11.4	8.21	873	48.2	1.37
LMT15	11.4	8.58	1135	47.2	1.30
LMT16	11.4	8.58	950	49.5	1.26
LMT17	16	7.18	827	46.9	0.99
LMT18	16	7.17	864	47.5	1.02

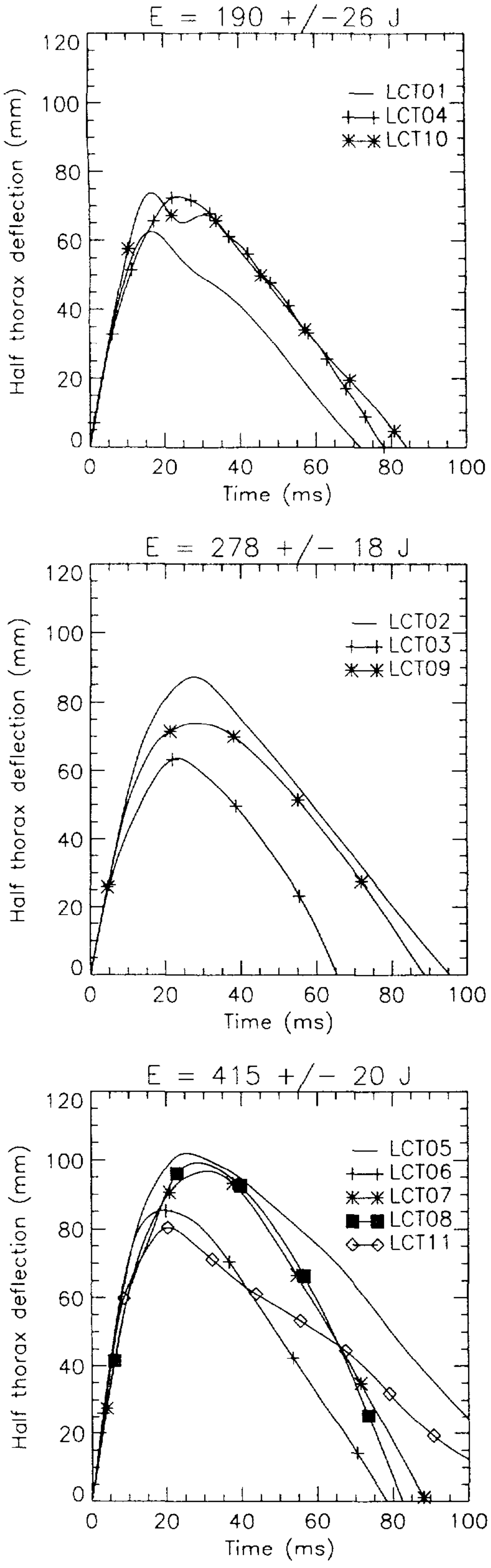

Figure 3 : Result of cadaver deflections for different energies

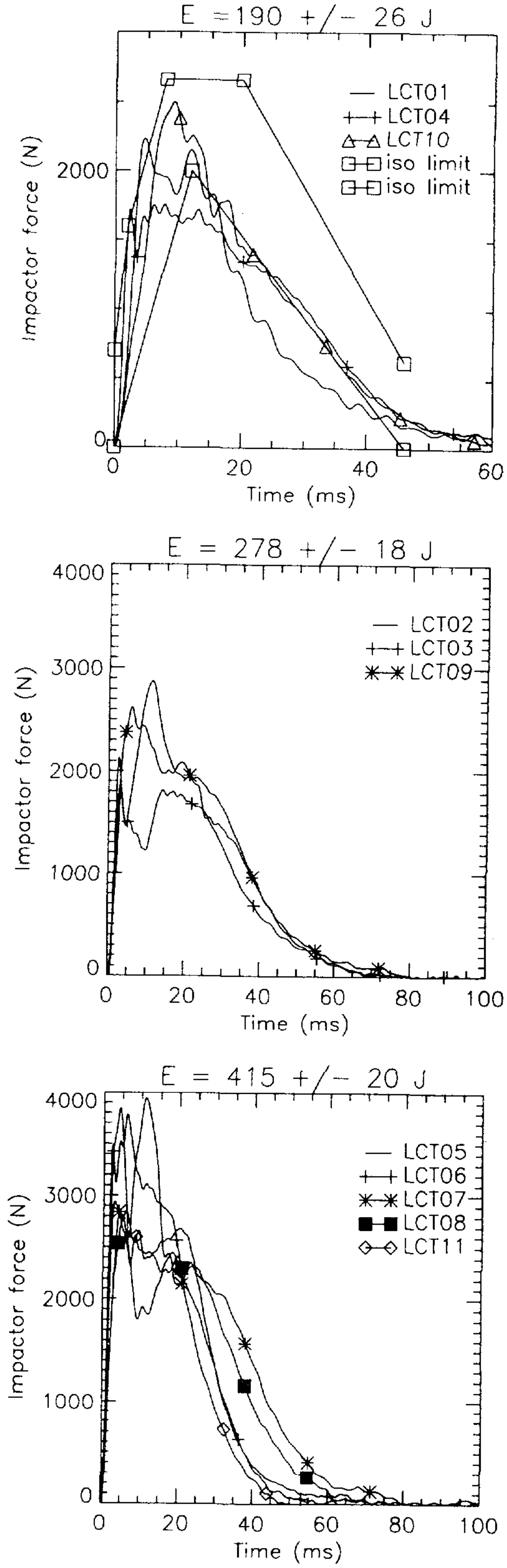

Figure 4 : Result of impactor forces for different energies

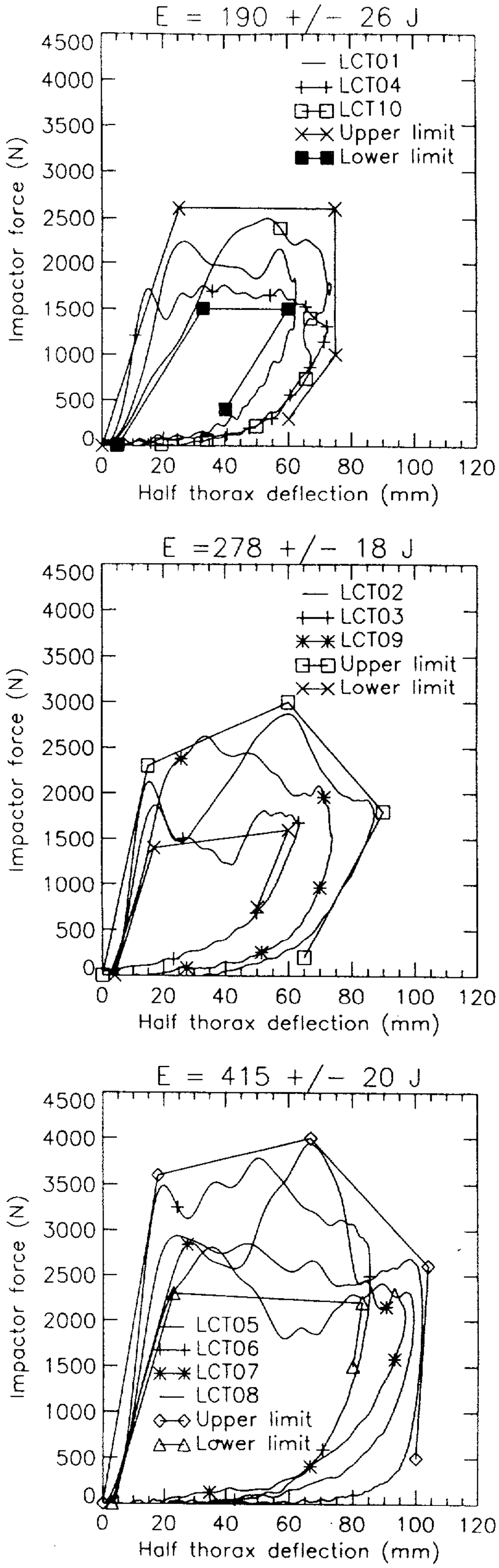

Figure 5 : Cadaver corridors
for different energies.

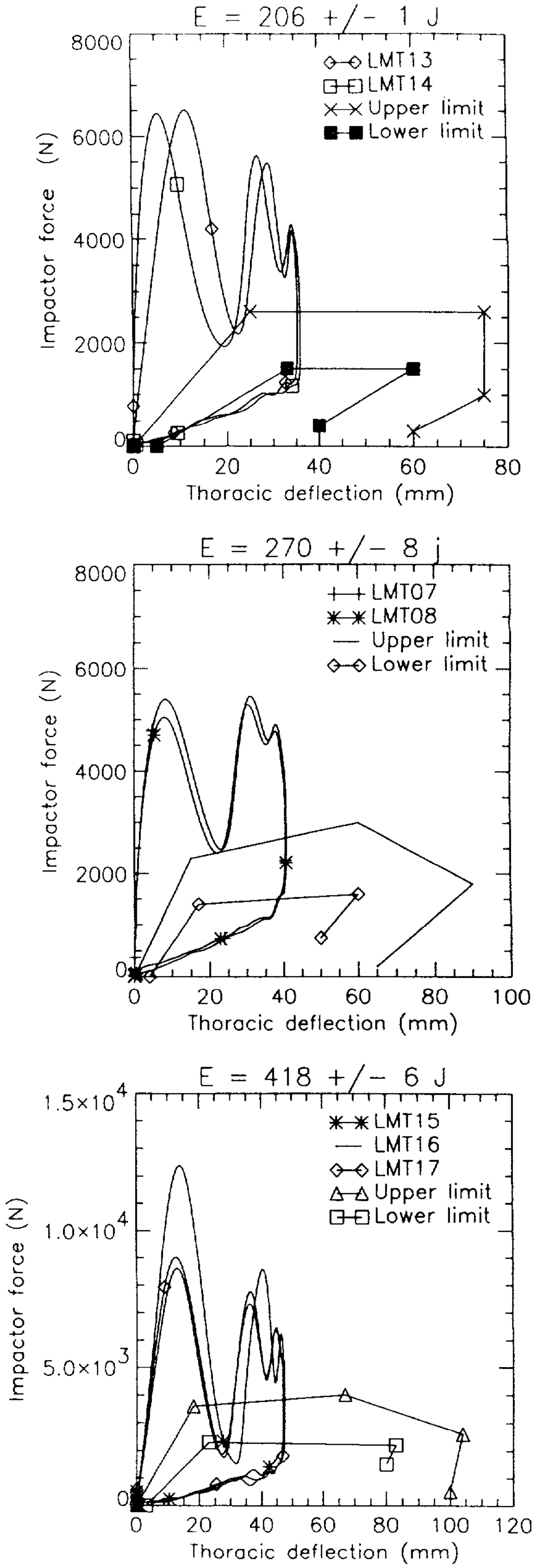

Figure 6 : Comparison of cadaver data
versus Eurosid-1 data for different energies.

The same reasoning was applied to the Eurosid-1 tests. The analysis showed that (as for the cadaver tests), tests with a lower mass (LMT12, LMT15 and LMT16 with m = 12 kg) have a V*C values greater than those of higher mass (LMT17 and LMT18 with m = 16 kg). The force values show a limit between the tests at the two velocities: (V ≥ 8.21 m/s ⇒ F ≥ 873 daN and V ≤ 7.18 m/s ⇒ F ≤ 864 daN).

The V*C value is very sensitive to the impact velocity. The Eurosid-1 thorax deflection is less sensitive to the impact variations. The mean value of the deflection for those tests is 48 mm.

Comment

A parametric study showing the energy distribution and (d) and (V*C) criteria sensitivity has been carried out with a mathematical model of Eurosid-0. The results of the tests with isoenergy showed that when the velocity increased and the mass decreased, the V*C increased and the deflection was constant. Those tendancies on the model are close to our experimental results on the dummy.

- **Isomass tests.**

The aim of this analysis was the obtention of a set of curves V*C = f(d) for different impacting masses.

This would help to understand why for each test condition, there is a different V*C = f(d) and different values of parameters (V*C,d). For the cadaver tests, figure 7 shows three curves of V*C versus deflection for impacting masses of 12, 16 and 23.4 kg. One can note that for the same deflection, the more the mass decreases, the more the V*C increases. However, for a constant value of V*C, the deflection increases when the impacting mass increases. That is to say that there is different criteria values for different impacting masses and velocities.

For example, simulations have been made with the mathematical model of the Eurosid-1 thorax. The result is that the criterion values V*C = 1 m/s and d = 42 mm (which are the values obtained for the ECE95 regulation conditions) are obtained with an impacting mass of m=7kg and a velocity V = 11 m/s.

The result of this analysis is, for each test condition (a given impacting mass and velocities) there is a different V*C = f(d). Thus the V*C and the deflection can't describe the same kind of injury .

For the Eurosid-1 tests, figure 8 gives the curves for m = 12 kg and m = 16 kg. The tests with m=23.4 kg are not available

The results of the analysis of the other physical parameters like force are given in figures 9 and 10. Figure 9 shows, for cadaver tests, a group of curves of force versus impact velocity. Figure 10 shows, for cadaver tests, a group of curves of force versus half thorax deflection for different masses. The force is a function of the test conditions and is correlated with the impact velocity. When the forces applied to the thorax are linked to the thoracic deflection (figure 10), we can see a weak correlation between these 2 parameters (r = 0.25 for tests with m = 23.4 kg; r = 0.25 for tests with m = 12 kg and r = 0.62 for tests with m = 16 kg).

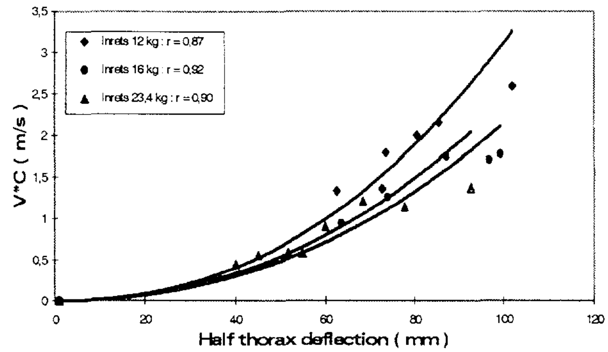

Figure 7 : Cadaver tests on thorax.
Sensitivity of the criteria to the mass.

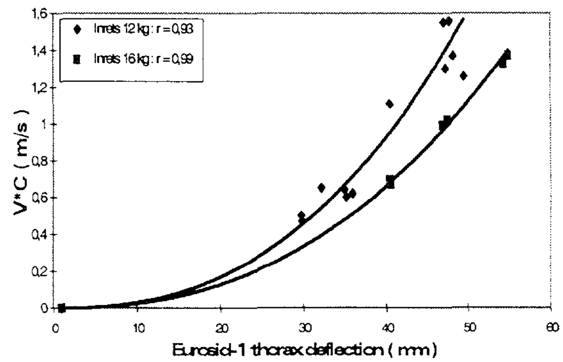

Figure 8 : Eurosid-1 tests on thorax.
V*C versus the deflection.

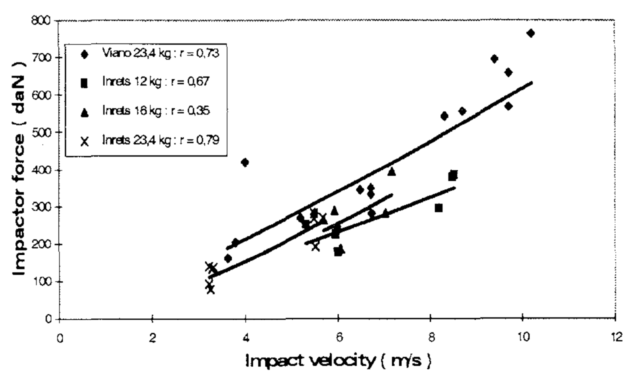

Figure 9 : Cadaver tests on thorax.
Impactor force versus the impact velocity.

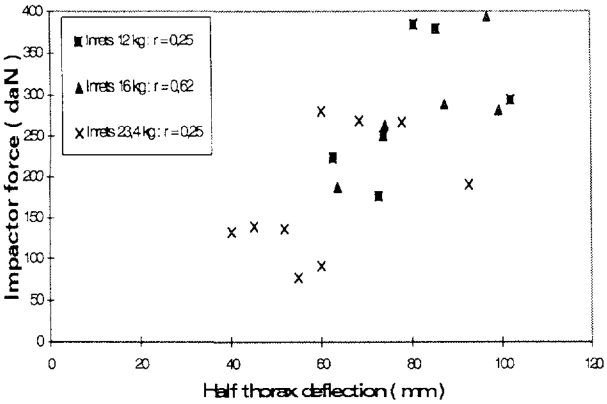

Figure 10 : Cadaver tests on thorax.
Impactor force versus the deflection.

Tolerance limit value :

Comparison has been made between the cadaver test results and Eurosid-1 test results. This comparison was made for tests under identical conditions. The values of (V*C) were related to the injury obtained.

Table 8 gives the peak values for the deflection, the V*C and the corresponding A.I.S. From these results and for cadaver tests, one can see that the lowest V*C value for AIS3 is 1.26 m/s. On the other hand, subject LCT01 who sustained AIS2 level injury has a V*C value of 1.33 m/s.

Table 8 : Cadaver and Eurosid-1 results comparison.

Test	Mass (kg)	Velocity (m/s)	Deflection (mm)	V*C (m/s)	AIS
LMT12	11.4	8.2	48.2	1.37	-
LCT05	11.9	8.2	102	2.59	3
LMT15	11.4	8.6	47.2	1.3	-
LCT06	11.9	8.5	85.4	2.15	4
LMT17	16.0	7.2	46.9	0.99	-
LCT07	16.0	7.2	93.8	1.70	4
LMT18	16.0	7.2	47.5	1.02	-
LCT08	16.0	7.0	99.3	1.77	4
LMT01	11.7	6.1	34.6	0.63	-
LCT01	12.0	6.0	62.5	1.33	2
LMT07	16.0	5.9	40.5	0.68	-
LCT09	16.0	5.7	79.8	1.26	3
LMT11	11.9	4.8	29.9	0.47	-
LCT10	11.9	5.3	73.6	1.79	3

CONCLUSIONS

- The isoenergy cadaver tests analysis show that the V*C and the deflection are sensitive to mass and velocity variations. The V*C increases when the velocity increases and the mass decreases. The deflection decreases when the velocity increases and the mass decreases. The isonergy Eurosid-1 tests show that V*C increases when the velocity increases whereas the deflection is constant when the velocity and the mass vary.
- The isomass test analysis shows that for given test conditions, a V*C = f(d) curve, and different values of the criteria can be established. To establish realistic values of V*C and d criteria, tests have to be carried out with test conditions close to those of the ECE95 regulation conditions.
- The response of the cadaver in terms of forces versus time is within the ISO corridor defined for the lateral impact conditions.
- Kinematic and dynamic analyses have permitted the determination of the response corridors in terms of force/deflection. They allow the assessment of the biofidelity of the Eurosid-1. The behaviour of the Eurosid-1 could be improved.

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