ABDOMINAL PROTECTION IN SIDE IMPACT.INJURY MECHANISMS AND PROTECTION CRITERIA.

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Summary.

Blunt abdominal trauma is a major cause of death in automobile accidents.
In terms of frequency, the lateral collisions represent the second type of accident after the frontal impact, but it constitutes the first position in relation to the other configurations in terms of severity : The abdomen is the part of body most implicated and among the injuried abdominal organs, the liver being the most affected. In order to understand the liver and the abdominal injury mechanisms and determine their impact tolerance, a series of direct impact tests,on the isolated liver and on the right side of the abdomen was undertaken. A tolerance level of 500 N for the liver and three tolerance criteria for the abdomen : deflexion criteria (60 mm), force criteria (440 daN) and viscous criteria (1.98 m/s) have been determined. These levels correspond to a degree of 3 on the AIS injury severity scale.

I.Introduction

The 1986 FARS (1) indicates that 31.8% of passenger car fatalities occur in crashes with the principal direction of force being lateral on the vehicle.
LAU (2) remarks that a high mortality associated with hepatic injuries is generally the result of serious bursting injury with deep lacerations.FREY (3) notes that 26% of the occupants involved in accidents, resulting in hepatic injuries, died.
On the other hand, ROUHANA (4) points out that, on the basis of 5000 accident cases, 40% correspond to lateral impact, of which 25% occur in the abdomen.Many other authors have established the high frequency of serious hepatic injuries.
Furthermore, a study carried out in the Laboratory of Biomechanics associated with Peugeot SA/Renault showed that 41% of the injured involved in lateral impact sustained abdominal injuries (liver and spleen).
However, only a small amount of experimental work has been done to understand this injury mechanism, and to quantify the tolerance parameters for the abdominal organs.This work describes a study in which direct impacts were applied to the liver alone in order to understand quantitatively the relationship between the input parameters (energy, force, deformation, speed) and resulting injuries.

II.Liver injury mechanism and tolerance.

Method and material.

The impacts were performed according to "free-fall" technique in which the impactor speed and it's depression are under control. The impactor fall is guided by 2 directional rails.The liver is put on a dynamometric platform instrumented by 3 load transducers.(figure 1)
The head of the impactor is a 15 cm diameter circular form and 3 transducers are fitted between the disk and the support of the impactor.Thus, this device allows a direct measurement on each side of the impacted liver.An accelerometer is fixed on the impactor for the determination of speed and displacement.In order to control the degree of compression, an adjustable thrust-block was installed.
25 fresh human livers were tested at different speeds and different compressions (table1). These organs were, before the test, injected with a solution of water formol and ink in order to fix and visualize the injuries. The impact and plate efforts were recorded versus time. After a digital processing of data, graphic output was obtained for each measurement.(figure2)
The computation of the deformation sustained by the liver is achieved by a double integration of the acceleration over the time of contact, the starting point is measured by an appropriate device.The force versus deformation is calculated by elimination of the time (figure3). This last function (force/deformation) will be taken into consideration for correlation with the injuries.
The injuries severity will be analyzed according to the AIS injury scale.

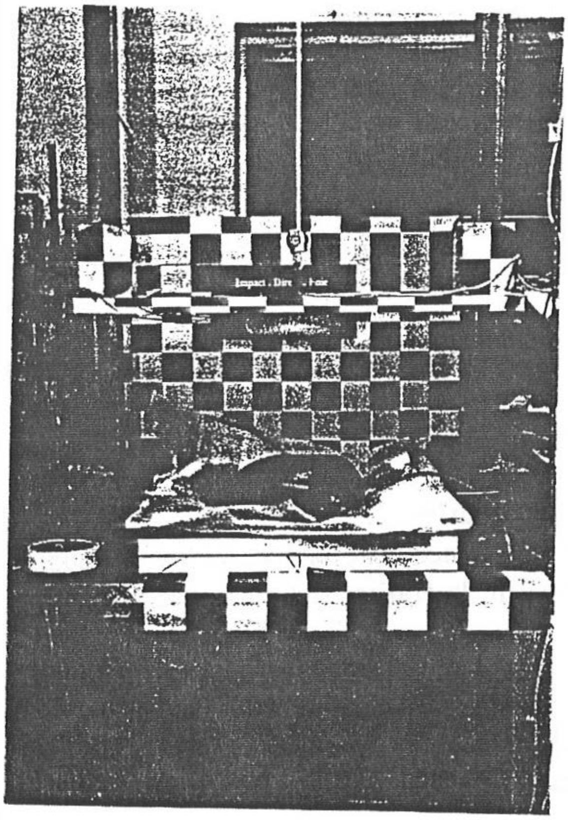


Figure 1 : Experimental device for direct impact of liver.

Tableau 1 : Matrix of tests

Déflexion en %	Vitesse en m/s	Numéro d'essai
8	3.1	IDF 17
15	1.5 1.5 2.4 2.5 4.1 4.1	IDF 24 IDF 19 IDF 15 IDF 14 IDF 9 IDF 23
23	2.5 2.6 1.6 3.1 3.6	IDF 16 IDF 1[illegible] IDF 22 IDF 13 IDF 8
35	1.5 2.5 1.5 2 3.1 3.6	IDF 25 IDF 21 IDF 20 IDF 7 IDF 12 IDF 11
47	3.1	IDF 3
55	3.1 2.5 3.1	IDF 4 IDF 5 IDF 6
75	2.5	IDF 1

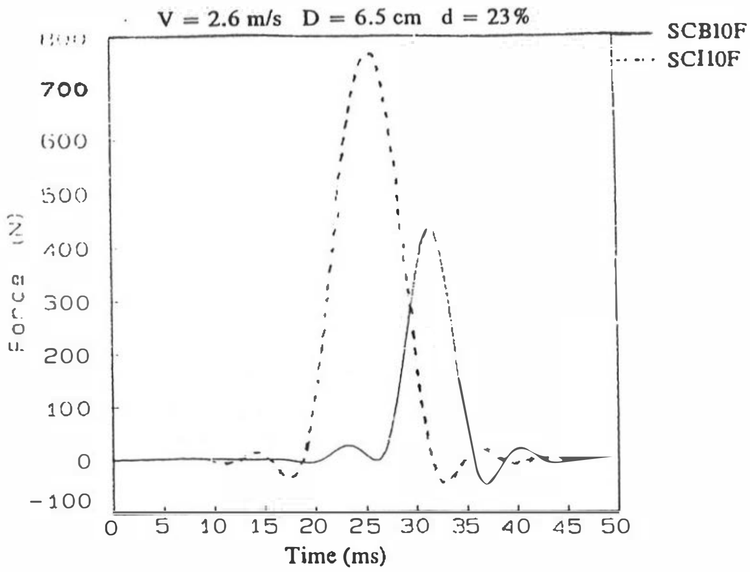


Figure 2 : Curves of force obtained on the impactor (SCI) and on the plate (SCB).

Results.

Figure 4,5 and 6 show an example of the calculated curves.
Figure 4 displays the importance of speed. The higher the impact speed, the higher the maximum of force, for the same percentage of deformation (15%).Figure 5 gives the shape of the risk curve in terms of probability of AIS>3 versus the force on the dynamometric platform. From the force/compression curve (figure 6), a range of force (340N-650N) is obtained, the lower limit of this range (340N) corresponding to an AIS=0 and the higher (650N) corresponding to an AIS=5. The tolerance threshold of force is 500N as an average and corresponds to AIS=3.

Conclusions and comparison.

As regards these tests, it appears that the impact speed is an important parameter which must be taken into account for the injury occurance. The tolerable maximum force is an average of 500N on the impactor, whereas it is of 340N on the dynamometric plate.
The difference corresponds to the absorption of energy by the liver. This result is in adequation with the study of Melvin (5).
The next step of this study concerns the analysis of indirect impacts on a liver protected by its natural elements (skin, muscles, ribs).

III.Abdominal impact tests.

Selection of subjects

A group of seven subjects was tested. The age of the subjects ranged from 42 to 83 years, with an average of 61 years. The weights varied from 53 to 100 kg with an average of 75 kg, and the average height was 1.72 m. Table 2 gives the anthropometric measurements of the subjects.
A preliminary enquiry into the causes of death was carried out before each test, to eliminate any subject whose skeleton condition and abdominal organs might have been deteriorated.
The subjects were fresh unembalmed cadavers. They were tested 3 to 4 days after death. The cadaver instrumentation is designed to record the dynamics of the various parts of the impacted area, namely, acceleration of the ribs and acceleration of the spinal column. The

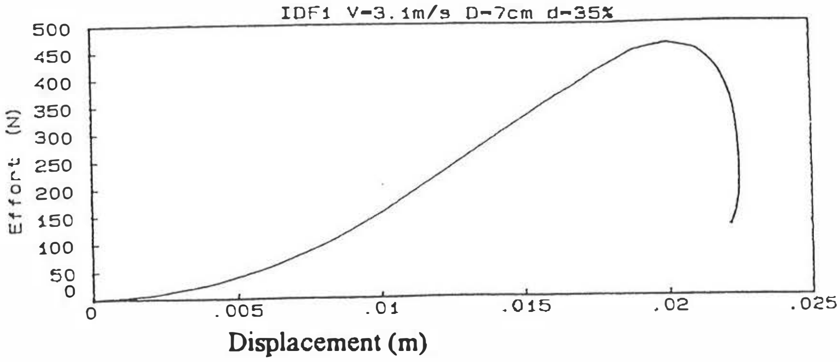


Figure 3 : Curve of Force vs displacement for a test speed of V=3.1 m/s.

Tests for a deflection of 15%.

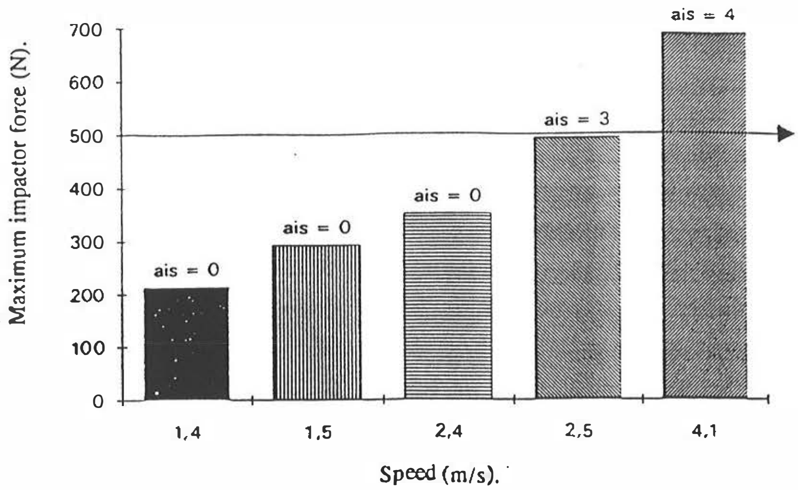


Figure 4 : Impactor force vs speed for a same deflection.

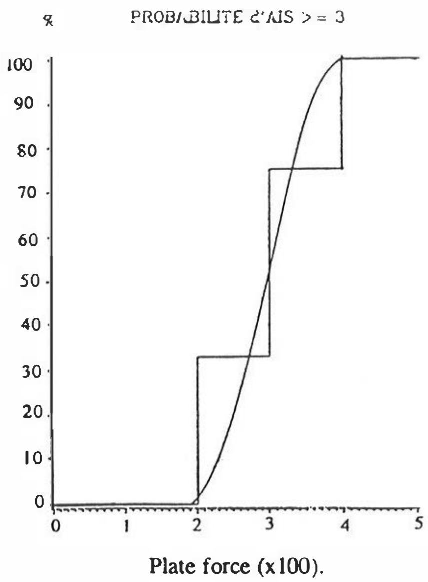


Figure 5 : Probability of risk for an AIS ≥ 3 vs the force on the plate.

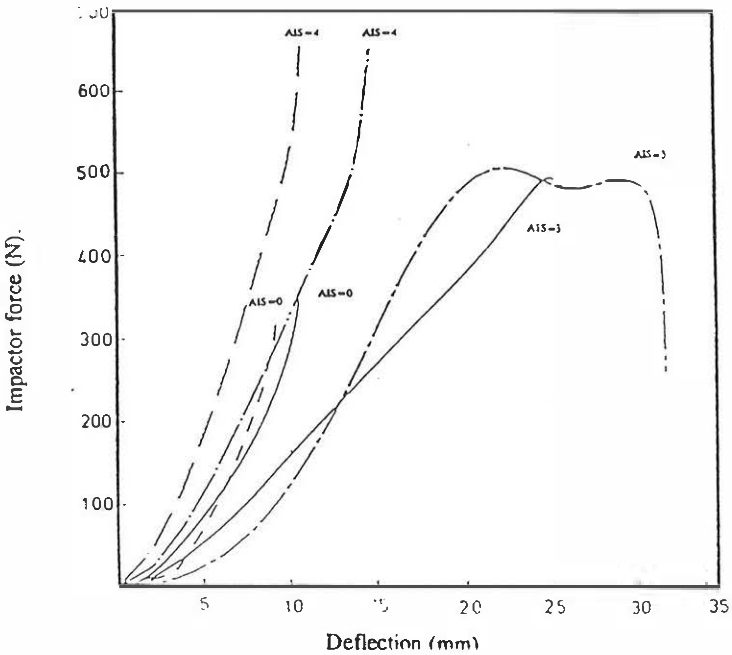


Figure 6 : Impactor force versus deflection with the corresponding AIS values.

dynamic response and kinematics of these parts provide information for characterizing their behaviour.

Test conditions.

Experimental device

The experimental device is a sandows linear impactor. Figure 7 shows a general view of this impactor. The moving mass is a cylindrical metallic rod at the end of which is attached the impactor head. The impacting mass is 23.4 kg. The shape of the impactor head is a disc 15 cm in diameter. The mass of 23.4 kg corresponds approximately to the weight of an equipped car door of a large car and the impacting head is of a standard shape. The range of operating speeds for this device is from 3 m/s to 10 m/s. The impactor speed is calibrated according to the sandows tension. The free travel of the impactor, i.e. from the neutral point of the sandows up to the thrust stop, is 19 cm, the neutral point of the sandows being the point at which the impactor is no longer propelled. The impactor is placed under tension by means of a crank and the release system is a lever which deactivates the restraining hooks.

Determination of the impact zone

The exact position of the impact zone is determined from the diagrams representing the anatomy of the human being (figures 8 and 9). The horizontal median plane of the liver passes through the 12th vertebra in the rear and 7 or 8 cm below the xiphoid process in the front.

These positions are the same as those described in the work of Viano (6). He determines the impact zone for thoracic or abdominal impacts relative to external reference points on the sternum. For an impact on the thorax, the impactor is centred on the xiphoid process, 7.5 cm from the middle of the sternum, and for an abdominal impact the impactor must be centred 7.5 cm below the xiphoid process or 15 cm below the middle of the sternum. Viano observed that the same part of the surface is involved in an impact on the thorax and on the abdomen, and that it corresponds to half of the impacting surface.
Laterally, the surface of the impactor covers the seventh, eighth, ninth and tenth ribs.

Films

Each test is filmed by a high-speed camera at 1000 frames per second. Two-dimensional analysis of the film is performed by means of targets placed on the test subject.

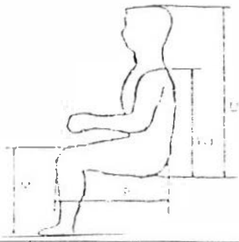
Subjects

Instrumentation
The measuring devices are accelerometers :

- 4 single-axis accelerometers for measuring rib accelerations;
- 1 single-axis accelerometer fastened to the head of the impactor;
- 3 3-axis accelerometers fastened to the spinal column.

In addition, a system for measuring abdominal external deflection and two deflection potentiometers are used.

Table 2



ANTHROPOMETRIC MEASUREMENTS

SUBJECTS / PARAMETERS	MS 423	MS 424	MS 425	MS 426	MS 427	MS 429	MS 430
SEX	M	M	M	M	M	M	F
AGE	67	52	63	83	64	42	55
HEIGHT (m)	173	175	178	151	171	181	167
WEIGHT (kg)	93	100	72	53	74	60	57
U (cm)	91	96.5	95	83	94	93	90
I + J (cm)	71	71	70	59	71	68	65
P. THIGH (cm)	53	57	55	50	54	52.5	50
M. LEG (cm)	54	55	55	47	51	50	50
ABDOMEN THICKNESS (cm)	26	29	20	19.5	22	20	17
ABDOMEN WIDTH (cm)	38.5	32	36	27.5	32	30.5	27
ABDOMEN PERIMETER (cm)	101	120	95	83	91	96	88

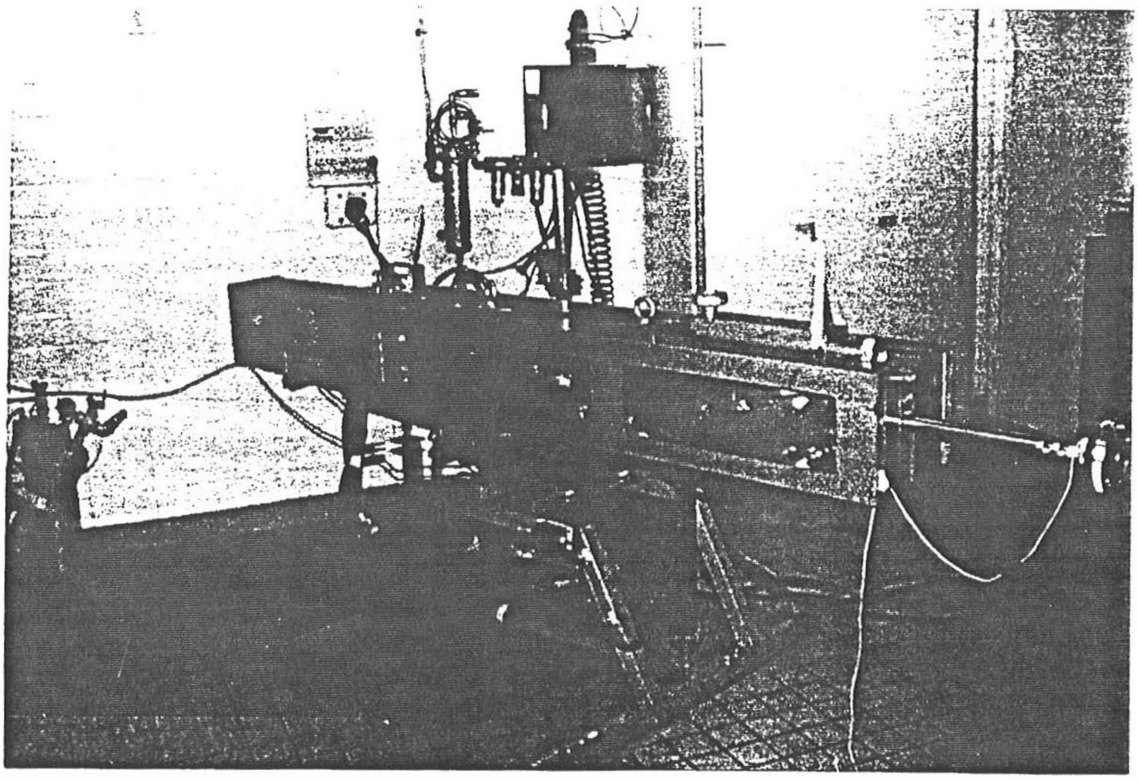


Figure 7: General View of the Linear Impactor

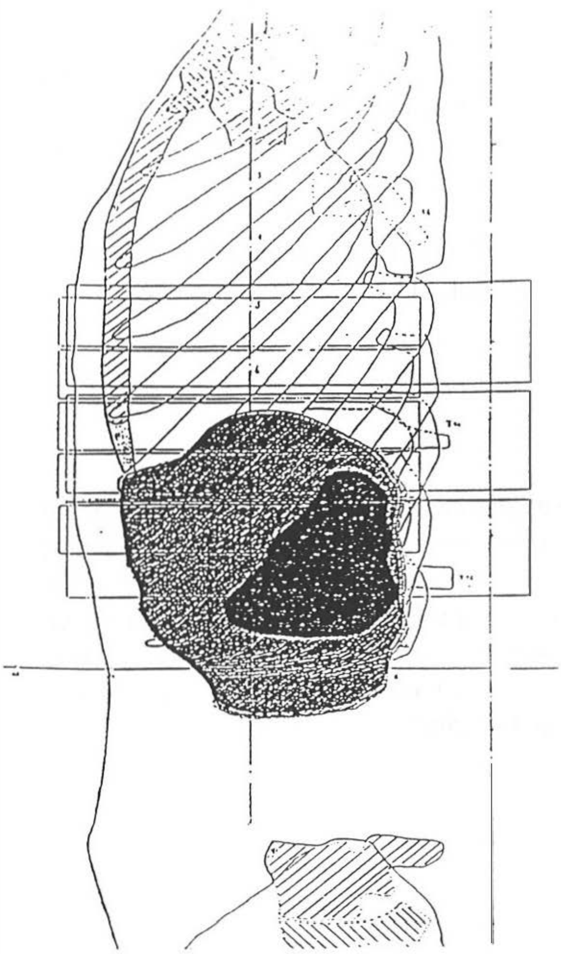


Figure 8 : Side view of the human trunk.

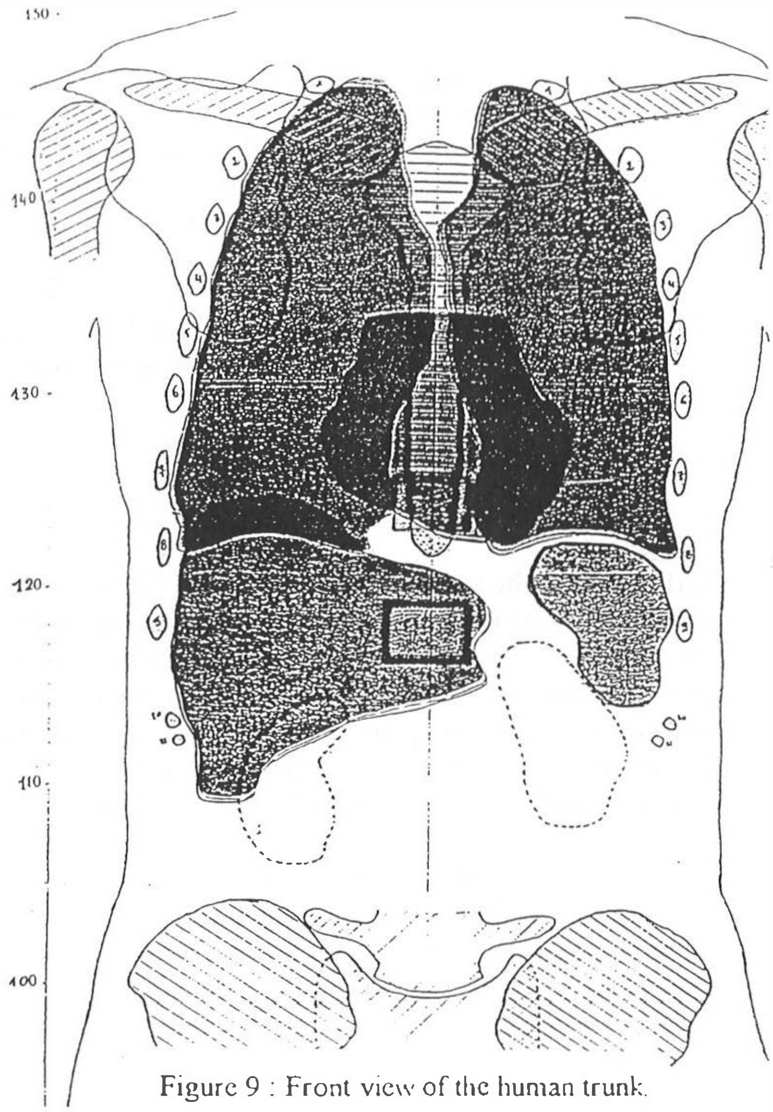


Figure 9 : Front view of the human trunk.

Table 3

Subjects instrumentation.

ABDOMEN	- Accelerations of the 7th, 8th, 9th and 10th right ribs (y) 4 measurement channels: CFC 180 filtering - Acceleration of the twelfth vertebra (x, y, z) 3 measurement channels: CFC 180 filtering - Front and rear deflection of the abdomen 2 measurement channels: CFC 180 filtering
THORAX	- Acceleration of the fourth vertebra (x, y, z) 3 measurement channels: CFC 180 filtering
PELVIS	- Sacrum acceleration (x, y, z) 3 measurement channels: CFC 180 filtering
IMPACTOR	- Acceleration (y) 1 measurement channel: CFC 180 filtering
TOTAL	16 measurement channels

Deflection measurement system

The system used was designed and built in the laboratory. It consists of four parts, including one moving part which, linked to the rods of two potentiometers, gives the real-time deflection of the abdomen during the impact, and three stationary parts, fixed to the subject.

The two potentiometers measure the abdominal deflection on a horizontal plane passing through the twelfth vertebra which corresponds roughly to the plane passing through the middle of the liver.

By taking two measurements of abdominal deflection, front and rear, the system's reliability can be checked and the symmetry of the device can be ensured. The moving part generates no great inertia, its weight being 175 g.

Table 3 lists the instrumentation used.

Tracheotomy

After death, the various operations performed on the subject cause the air to be expelled from its lungs. The intra-thoracic viscera (particularly the diaphragm and lungs) must be brought back to it's "normal" position. This is performed just before the test by means of a tracheotomy. A suitable device allows a volume of air ranging between 2 and 3 litres to be blown in, depending on the anthropometric characteristics of the subject's thorax. This technique allows the viscera and the whole thoracic cage to regain mechanical properties similar to those of the thorax of living people (e.g., viscoelasticity).

Pressurisation of the vascular system

This is one of the fundamental aspects of the methodology employed for tests performed with human subjects. This pressurisation is essential when investigating the human organs, and particularly the liver.

The reproduction of an arterial pressure close to the average arterial pressure of a living person has numerous effects which allow any injuries observed on an experimental subject to be interpreted as a prognosis of the injuries that would have been sustained by a living human impacted under the same conditions.

Its main effects are as follows:

- it restores to the tissues the relative rigidities, masses and volumes which characterize tissues perfused at a sufficient pressure;

- it marks vascular damage by black effusions on the level of ruptures, having the appearance of haemorrhages in living people (the black colour is due to the presence of carbon particles in the injected mixture);
- it allows arterial or capillary ruptures to be viewed. The advantage of carbon particles is that they are entrained very well by the injected liquid, and their size means that they cannot leave the vessels if there is no rupture (their diameter is close to that of red corpuscules).

The presence of formol allows rapid fixing of the hepatic tissue which prevents the progression of hepatic autolysis. The action of the formol before the impact is too brief to alter the physical characteristics of the perfused tissue.

The subjects are injected just before the test; the injection pressure is 0.4 bar for one minute.

Positioning.

Thus instrumented, the subjects are then taken into the test room. They are installed on a height-adjustable frame and held in position by straps to which is fastened an electro-magnet.

DESCRIPTION OF INJURIES.

Autopsy

After testing, the cadaver is autopsied by an anatomical pathologist and special attention is paid to the abdomen. The doctor determines the severity of injuries on the AIS scale. The autopsy enables a check on the positioning of accelerometers after testing.

The fourth and fifth, right and left ribs are taken off to analyse their mineralization and determine the maximum bending force in order to characterize the bone condition of the subjects.

Injuries observed

Table 4 summarizes the injuries that occurred during the tests.

Of the 7 subjects tested, MS 425 will be left out of the analysis because rib fractures existed prior to the test, due to a heart massage ignored by the investigating doctor.

It should be noted that for those subjects sustaining injury (MS 423, MS 424, MS 429), the abdominal injuries consist of liver injuries plus small wounds of the diaphragm at the level of the rib fractures. The liver injuries are in the form of parasagittal ruptures of the right lobe at the level of the impactor (MS 423), small superficial wounds of the lower part (1 mm deep, MS 424), or multiple ruptures at the same level on the lower part (MS 429). The rib fractures occur at high impact speeds (6.5 and 7 m/s); They are located at the level of the accelerometers, the ribs probably being weakened in these locations by the presence of the sensor supports.

For MS 424, there are no rib fractures but internal contusion over an area of approximately 5 x 3 cm, and superficial wounds.

The shape and direction of the liver tears indicate that the mechanism responsible for these injuries is the compression of the ribs against the hepatic tissue, resulting in a fracture in the region opposite the costal interstices (MS 429) (observation during the autopsy).

ANALYSIS.

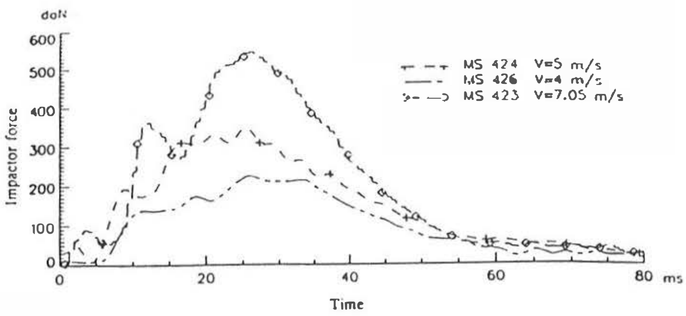
The initial phase is the compression of the half width of the abdomen, during which phase deflection culminates without the subject's body being subjected to movement; phase two is the phase in which the whole body is entrained. Figure 11 shows that maximum deflection is reached in the initial moments of impact. Analysis of the film confirms these kinematics.

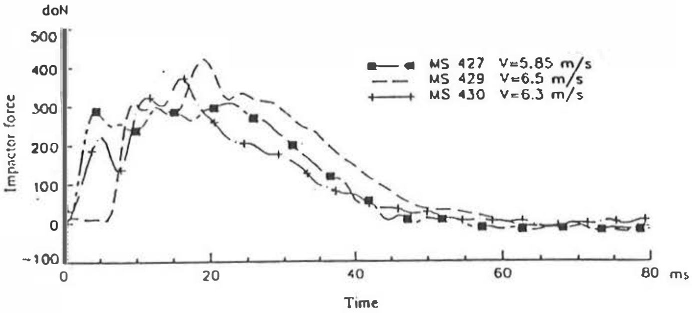
The responses in terms of force versus time for all the subjects are given in Figure 10, with a table showing the maximum force values and the corresponding times.

Figure 11 gives the shape of the deflection curves. By taking two measurements of deflection it is possible to check that the impact is well centred with a 90° direction characterizing a pure side impact; as a matter of fact, it is known to be well centred when both potentiometers give the same deflection value to within 5 mm. The curves obtained are a mean of the two measurements, front and rear, taken for each subject. The shape of the curves indicates that maximum deflection is reached in the initial moments of the impact.

In Table 5, the various injury criteria generally used to characterize injury severity are calculated.

Figure 10: Response in Force vs Time





	Maximum force (daN)	Time at maximum force (ms)
MS 423	546.399	26.1000
MS 424	349.322	25.3333
MS 426	224.095	26.0000
MS 427	307.205	22.6667
MS 429	422.687	19.3333
MS 430	371.977	16.0000

Table 4
Summary of injuries observed.

Test No.	Speed (m/s)	Autopsy results	AIS 1990
MS 423	7.05	Fractures of the 7th, 8th and 9th right rib at the level of the accelerometer. Several parasagittal ruptures of the right hepatic lobe of varying lengths (3 to 6 cm) and shallow depth (3 mm). Tearing of the right parietal pleura and the diaphragm at the level of the rib fractures. AIS 3	4
MS 424	5	No rib fracture. Small diaphragm wounds on the right side at the level of the side sub-costal in ertion. Small superficial wounds of the lowerpart of the right lobe (1 mm deep, 3 em long). Internal contusion of the hepatic parenchyma over an area of approximately 5*3 cm located in segments VI and VII.	3
MS425	3.9	Heart massage which cau ed fractures of left ribs 1 to 6 on the median arch and of right ribs 4 and 5 on the anterior arch. Fractures of the 7th and 8th right ribs at the level of the sensor location. AIS 1. Fracture of the right lobe of the liver sector VI (2 injuries 10 mm deep and 20 mm long).	2-3
MS426	4	Absence of hepatic injury. Fracture of the median arch of the 8th right rib in front of the sensor.	0
MS427	5.85	Absence of abdominal injury. No rib fracture.	0
MS 429	6.5	Fractures of the 8th, 9th and 10th ribs. Multiple fractures of the liver, including 3 at the impact point, 1 fracture 5 cm long and more than 3 cm deep.	4
MS430	6.3	Absence of injury. Hepatic metastasis unknown to the clinical doctors.	0

TABLE 5
Summary of the various injury criteria.

Test No.	Speed (m/s)	d (mm)	D (mm)	F (daN)	TTI (g)	C (%)	V*C (m/s)	AIS 1990	Nb Rib fractures
MS423	7.05	62.9	192.5	544	168.7	32.5	1.98	4	3
MS424	5	55	180	349	116.7	30.5	0.67	3	0
MS426	4	56	137.5	224	158.3	41	0.81	0	1
MS427	5.85	48	151	337	183.7	32	0.68	0	0
MS429	6.5	60.6	150	443	146.3	40	2.31	4	3
MS430	6.3	52.6	135	390	151.3	39	1.21	0	0

TTI = Thoracic Trauma Index
C = Half-abdomen compression
F = Maximum impactor force
V*C = Viscous criterion
d = Abdominal deflection
D = Width of half abdomen

The TTI criterion, relating to the thorax, is also given in the table5. Since the calculation of TTI is based on rib and spinal column accelerations, it seemed interesting to calculate this value for the abdomen taking into account ribs and T12 accelerations, to see whether it is correlated to the degree of severity (AIS) or to the number of rib fractures.

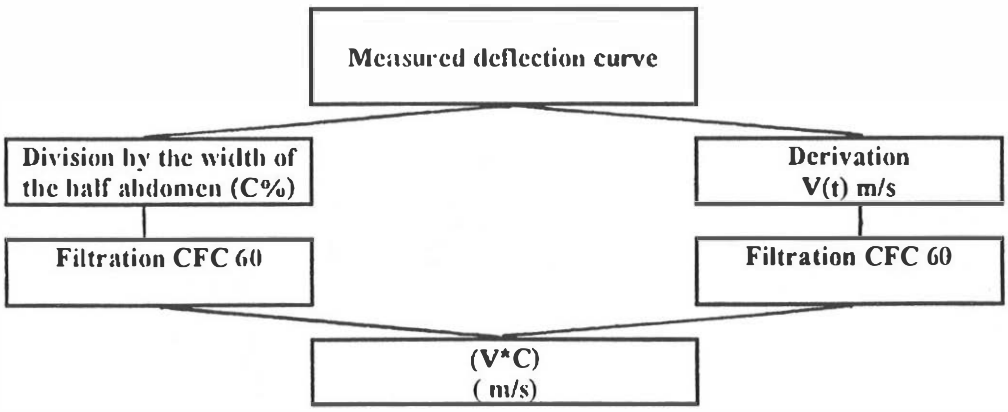
Correlations between these various parameters were studied. Table 6 gives the various functions used with their correlation coefficient.

Table 6

FUNCTIONS	CORRELATION COEFFICIENT
F = f (speed)	0.93
F = f (V * C)	0.78
F = f (AIS)	0.73
F = f (d)	0.81
F = f (c)	0.35
V * C = f (AIS)	0.71
V * C = f (d)	0.80
d = f (AIS)	0.85
TTI = f (No. of rib fractures)	0.14

All the correlation coefficients are obtained by linear regressions.

Method of V*C calculation
The V*C is calculated by the following method



The maximum force is strongly correlated to the speed (0.93) and less strongly correlated to deflection (0.81); the TTI shows no correlation at all with the number of rib fractures (r = 0.14).
Figures 12 and 13 give the regression curves of impactor force/speed and impactor force/deflection respectively, while Figure 14 shows the curves obtained by calculation of the viscous response [V*C] (t), the maximum value of which for each test is given in Table 5. The numbers indicated on curves 12, 13 and 14 are the corresponding AIS values.

The results of Table 6 show a weak correlation between the maximum impactor forces and compression as a percentage of the half width of the abdomen (r = -0.35), whereas the

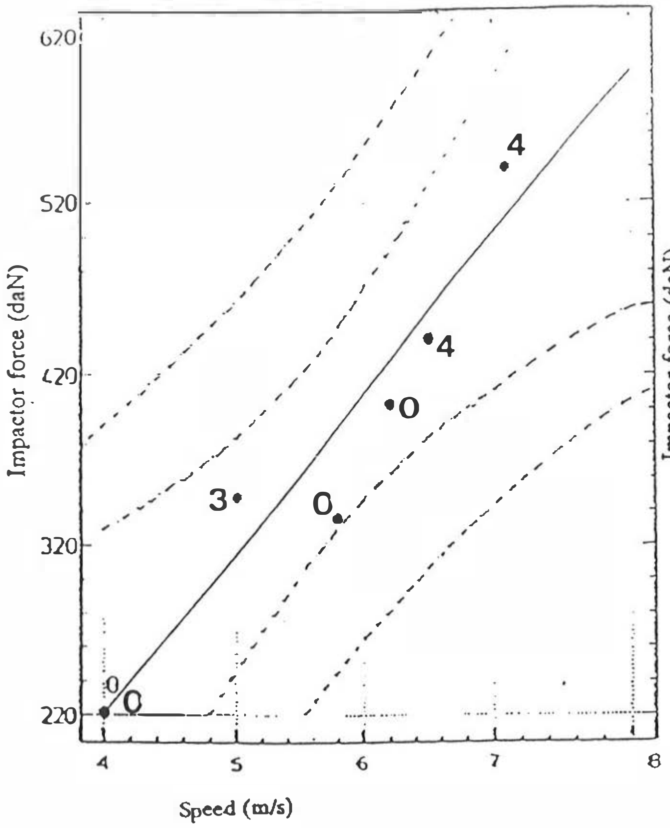


Figure 12 Linear regression curve
Force/Speed with corresponding AIS values. r = 0.93

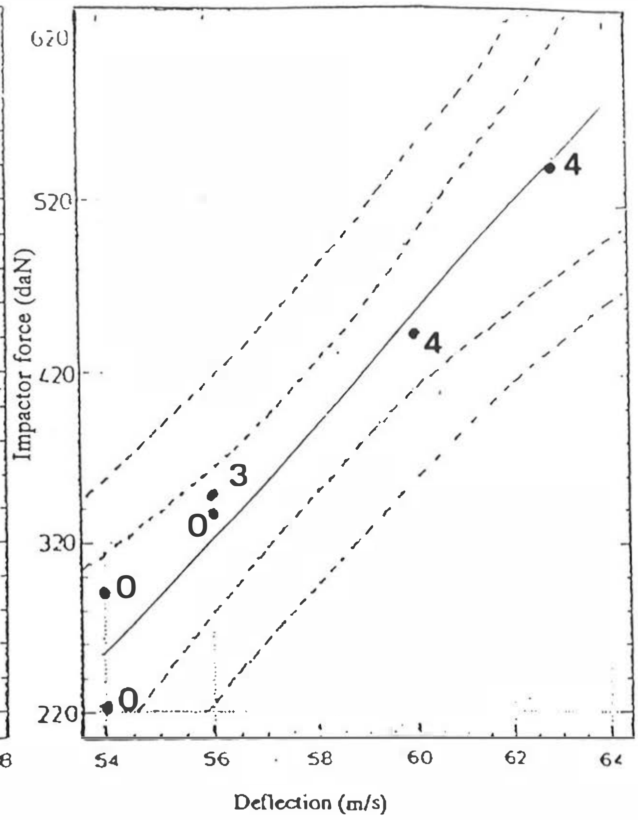


Figure 13 Linear regression curve
Force/Deflection with corresponding AIS values. r = 0.81

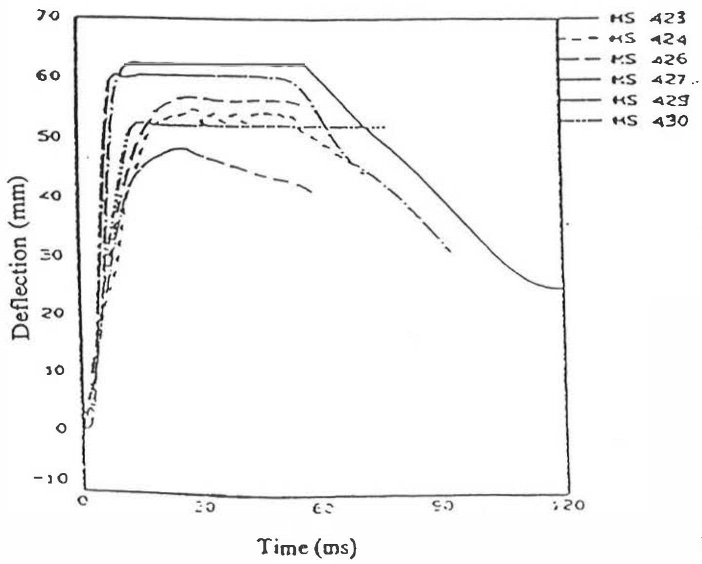


Figure 11 . Mean deflection of the abdominal half width corresponding to measurement of deflection at the front and rear.

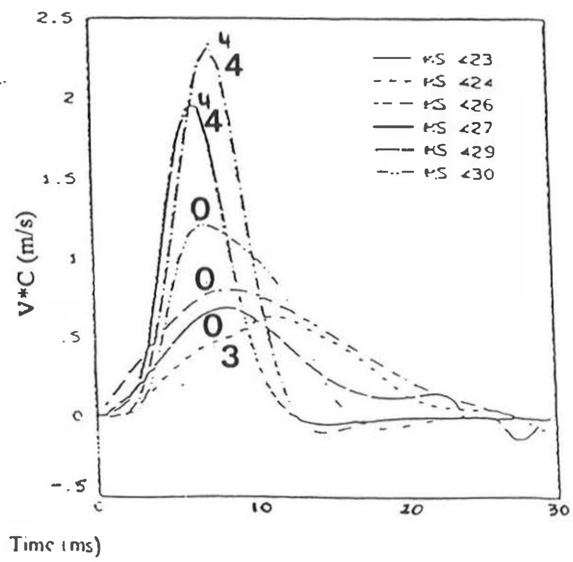


Figure 14 Results of viscous response calculation with the corresponding AIS values.

correlation between the first parameter and the deflection measured is fairly good (r = 0.81). This points to deflection as possibly one of the criteria which could quantify the tolerance limits. Data concerning rib resistance to impact and their ability to sustain deflection without fracturing, are schown in Table 5. From this information it can be deduced that for a deflection value less than 60 mm there are no rib fractures except for MS 426 where the only fracture observed may be an artefact due to the presence of a rigid sensor support. On the other hand, deflection d is also strongly correlated with the AIS (0.85): tests MS 423 and MS 429, for which the greatest deflection was recorded (62 mm and 60 mm), correspond to subjects with injuries of AIS 4. Hence, an initial threshold of deflection tolerance can be established at 60 mm, and the deflection parameter therefore appears to be a good indicator of injury severity, in agreement with existing data.
The second injury criterion taken into account is the viscous criterion [IV*C]. On the basis of two tests, injuries appear for V*C values greater than 1.98. It is clear that to determine and confirm this value more precisely, many more tests than those performed in this study would be required; while tests MS 423 and MS 429 resulted in AIS values of 4 for V*C values of 1.98 and 2.31 respectively, MS 424 has a V*C of 0.67 for an AIS value of 3, whereas test MS 430 (female) has a V*C = 1.21 with a total absence of injuries. Nevertheless, this value can be adopted provisionally as an initial approximation of the tolerance threshold.
The third and final criterion taken into account is the maximum force recorded on the impactor, i.e. the external force applied to the abdomen. Once again, the number of tests performed does not make it possible to be as affirmative as could be wished, but trends can be seen. The maximum force is fairly well correlated whith the deflection and whith [V*C] and has average correlation with AIS (r = 0.73). If we exclude the result of test MS 424 (F = 349 daN), which poses the same problem as for the [V*C] criterion, a maximum tolerable force value of 440 daN corresponding to an AIS value of 3 can be adopted.

Conclusion

This study can be considered as constisting of two parts. The first part concerns direct impacts on the liver. These experiments allowed the establishment of 2 tolerance levels : the first is a level below which there is no injury risk; this is estimated to be around 360 N. The second level is that, below which, despite the sustaining of injuries (assuming that the first level has been exeeded), these injuries are not sufficiently severe to seriously impair the functioning of the liver : it is estimated at 500 N.
The second part concerns abdominal lateral impacts on human beings. On the basis of 6 subjects tested laterally, it was possible to find relationships or tendencies between the different mechanical parameters; the force is closely correlated with the speed (r=.93), the deflection (r=.81) and the injury severity (r=.73). A maximum force level of 440 daN (in accordance with the results given by Walfisch (7)), corresponding to AIS=3, is established as well as a deflection of 60 mm. The value of viscous criterion found (V*C =1.98 m/s) is the same as that given by Viano (6).

REFERENCES :

(1) NHTSA (National Hightway Traffic Safety Administration)
"Fatal Accident Reporting System 1986."
Report n° DOT-HS-807-245 Washington D.C., March 1988.

(2) LAU L.K. and VIANO D.C.

"Influence of impact velocity on the severity of non penetrating hepatic injury."
Journal of Trauma Vol 21 n°2 1981.

(3) FREY C.H. and TROLLOPE M.
"A fifteen year experience with automotive hepatic trauma."
Journal of Trauma Vol 13 n°12 1973.

(4) ROUHANA S.W. and FOSTER M.E.
"Lateral impact. An analysis of the statistics in the NCSS."
29 th Annual proceeding STAPP Car Crash Conference Paper n°851727.

(5) MELVIN J.W., STALNAKER R. and TROLLOPE.
"Impact injury mechanisms in abdominal organs."
17 th Annual proceeding STAPP Car Crash Conference Paper n°730968.

(6) VIANO D.C.
"Biomechanical responses and injuries in blunt lateral impact."
33 rd Annual proceeding STAP Car Crash Conference Paper n°892432.

(7) WALFISCH G., FAYON A., TARRIERE C. and ROSEY J.P.
"Designing of a dummy abdomen for detecting injuries in side impact collisions."
Proceeding of the 5th International IRCOBI Conference, September 1980.