RELATIONSHIP BETWEEN SOME BIOMECHANICAL AND DIMENSIONAL CHARACTERISTICS OF THE SKULL AND THE RISK OF CEREBRAL INJURIES

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Certain studies (1) (2) have shown that skull deformation may have important implications for injury produces by blunt impact to the head.

The purpose of this paper is to study the influence of skull bone characterization on brain injuries as well as on physical parameter criteria (force, H.I.C.).

In order to characterize the resistance of the skulls of subjects used in experiments, we have defined the Skull Bone Condition Factor, so-called "S.B.C.F. Index".

For this analysis we have only integrated twenty-two free fall tests with a head impact localized in the parieto-temporal area ; that is to say, tests in conditions that are almost similar but at different levels of violence.

1. SKULL BONE CHARACTERIZATION

S.B.C.F. index (3) simultaneously takes into account the parameters characterizing the resistance of skulls as well as their anthropometry.

This factor has been obtained by means of factorial component analysis (4) (5).

$$\text{S.B.C.F.} = \frac{0.791\ \text{LTH}-4.32}{1.307\quad 0.080\quad 6} + \frac{-0.236\ \text{RLD}-143}{1.307\quad 6.48\quad 6} + \frac{0.713\ \text{MIM}-0.56}{1.307\quad 0.13\quad 6}$$

$$+ \frac{-0.078\ \text{HDW}-3.79}{1.307\quad 0.49\quad 6} + \frac{-0.034\ \text{APD}-180}{1.307\quad 7.18\quad 6} + \frac{-0.331\ \text{SPD}-86}{1.307\quad 8.1\quad 6}$$

where :

- LTH = thickness of the edge,
- RLD = transversal diameters of the head,
- MIM = average skull cap mineralization,
- HDW = head mass,
- APD = antero-posterior diameter of the head,
- SPD = height of the skull cap.

It should however be noted that in defining this index only the parameters characterizing the quality and the quantity of bone (mineralization (MIM) and thickness (LTH)) have an important weight.

This means that only a subject having a head with dimensions and mass varying considerably from the average will have a S.B.C.F. which will classify it in a way differently from what would have been the case if it had been classified on the basis of bone quality alone.

S.B.C.F. takes into consideration skull thickness which is the average value of six thicknesses measured at different points on the edge of the skull cap. The variations in thickness, however (for example that of the inferior part of the parietal bones), can be considerable and the value thus obtained is not representative of the average thickness of the skull. The most representative parameter of bone quality seems to be the average thickness defined on the basis of the volume and of the surface area of the skull cap. It is this which, in our analysis, enables us to interpret results best. This parameter now available for all subjects will be used in the future in calculating S.B.C.F.

For each subject the S.B.C.F., average thickness value and the principal head measurements are provided in Table 1.

2. METHODOLOGY - INSTRUMENTATION AND DATA PROCESSING

2.1. DESCRIPTION OF STANDARD TEST

The subject lies prone in a metal cradle (see Figure 1). His head, with or without a helmet, protrudes beyond the cradle, as does part of the upper thorax. The unit is released and allowed to fall freely. The head is maintained by means of a suitable device in alignment with the trunk until impact. The surface against which the head strikes is, in most cases, flat, metallic and rigid.

Figure 1 :

PRINCIPLE OF TESTS

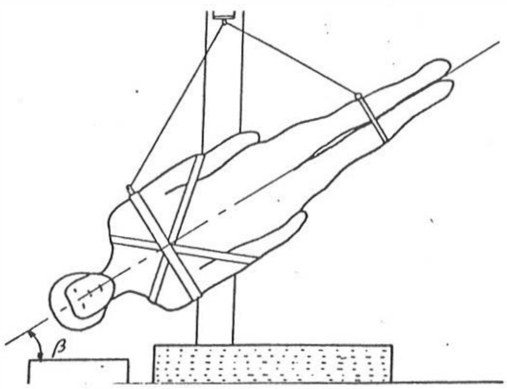


Figure 1 : PRINCIPLE OF TESTS

TABLE 1

CADAVER ANTHROPOMETRIC DATA - FREE FALLS - SIDE IMPACTS

TEST N°	AGE	SEX	HEAD ANTHROPOMETRY (cm)			MASS OF THE HEAD (kg)			SKULL BONY CHARACTERISTICS		
			Antero-Posterior Diameter	Transversal Diameter	Circumference	Head and Neck	Head	Skull*	Mineralization (g/cm^2)	Mean Thickness (mm)	Skull Bone Condition Parameter
63	78	2	18.2	15.0	54.1	4.020	3.28	0.53	0.525	5.81	0.202
64	59	1	19.2	14.5	54.8	4.860	3.92	0.55	0.525	4.42	-0.370
65	57	1	19.4	15.5	57.1	5.020	4.23	0.88	0.790	6.66	0.470
66	82	2	18.2	14.5	53.9	3.560	2.92	0.53	0.555	6.09	0.510
67	82	2	18.2	14.1	55.4	4.430	3.34	0.69	0.635	7.38	1.090
73	55	2	17.5	14.0	56.0	4.780	3.68	0.51	0.505	5.07	0.340
74	74	1	18.0	13.5	56.5	5.220	3.64	0.95	0.835	7.25	1.000
76	75	1	19.2	14.0	55.0	4.290	3.45	0.75	0.565	5.01	-0.006
85	65	1	17.2	14.0	55.0	4.620	3.36	0.72	0.420	3.80	-0.490
86	65	1	19.0	15.0	56.5	3.470	3.00	0.99	0.630	5.20	0.039
87	73	1	20.0	15.0	57.0	5.520	3.73	1.25	0.650	6.66	0.508
99	73	2	18.0	14.5	53.7	4.000	2.80	0.51	0.480	6.56	0.620
111	52	1	18.4	15.2	56.1	4.870	3.64	0.80	0.575	4.68	-0.290
145	68	1	18.0	15.0	54.5	4.220	3.45	*	*	*	-0.260
146	68	1	18.0	15.0	54.8	4.960	3.91	*	*	*	*
272	68	1	18.6	16.4	57.5	4.430	3.57	*	0.370	3.80	*
273	61	1	19.4	15.8	58.0	5.270	4.20	*	0.290	4.33	-0.550
274	64	1	18.9	15.3	57.5	5.150	4.11	*	0.470	5.05	0.098
275	67	1	18.5	13.5	53.0	3.860	3.16	*	0.590	5.74	-0.111
259	57	1	18.8	15.0	54.4	5.140	3.96	*	0.520	5.56	*

* Mass of the cranio-facial bone except the inferior maxillary

Each test is accompanied by anthropometric measurements, as well as those of acceleration, of the percussion force, and of the pressurization of the encephalon according to the method previously described (6). The different tests conditions are shown in Figure 2.

2.2. MEASUREMENTS RECORDED

Three accelerometers are attached to light alloy plates screwed into the subject's skull. Their position and orientation are defined with respect to the head anatomical coordinate system (7).

The position of the accelerometers in relation to this system (7) vary with each type of test. In the event of left parieto-temporal impact, there is an accelerometer on the frontal bone, one on the occiput and another on the right temple.

The measurements of acceleration meet the requirements of the SAE J 211 b procedure.

2.3. MEASUREMENTS OF FORCES

A dynamometric platform was placed beneath the shock-absorbing padding which made it possible to vary the deceleration experienced by the head. The small mass of the padding means that the forces measured were very close actually experienced by the head.

The forces detected by the dynamometric platform were filtered under the conditions used for head accelerations (class 1000).

3. FINDINGS

3.1. KINEMATICS

Generally speaking, the kinematics of the head and neck can be described in a simplified manner, in two phases, as follows :

- a vertical descent of the head into the helmet or the shock absorbent material, with no notable head rotations at the time of the impact ;
- the start of rebound of the head triggers a rotation of the head with relation to the trunk (Table 2) since the head tends to move upwards while the rest of the body continues to move downwards into the shock absorbent mattress.

In this paper meant to precise the part played by the subject's skull bone characterization upon the cerebral injuries and the levels of physical parameters linked with them, we have excluded from this analysis the tests for which we observe a very important relative motion head versus trunk, by rotation (tests n° 70 and 83).

This point will be resumed in chapter 8 (DISCUSSION).

TABLE 2

MEASUREMENT RESULTS - FREE FALLS - SIDE IMPACTS

TEST N°	LINEAR ACCELERATION		HIC		ANGULAR VELOCITY (rd/s)		ANGULAR ACCELERATION		FORCES (daN)	LATERAL TILTING Head/Thorax*	CEREBRAL AIS	SKULL Fract.	QUALITY OF BRAIN RE-PRESS. **
	Maxi (g)	3 ms (g)	Value	Duration of Calculation (ms)	Maxi	3 ms	Maxi (rd/s^2)	3 ms (rd/s^2)					
63	171	113	937	6.0	50.3	47.4	30481	9970	385	52	0	0	2
64	151	118	832	5.9	40.2	39.4	13977	6732	680	72	2	0	2
65	175	130	1250	6.1	44.6	42.6	25759	8653	530	36	0	0	3
66	174	137	1166	5.1	50.1	49.5	18532	9400	560	64	0	0	2
67	251	151	1584	4.4	55.2	54.3	32526	7841	380	61	0	0	2
73	206	107	961	3.5	82.2	80.2	30616	10878	400	30	0	0	2
74	262	109	1082	5.5	65.1	62.1	27028	9791	840	39	4/5	0	3
76	580	200	2500	4.0	*	*	*	*	1240	53	5	1	4
85	254	150	1665	3.7	63.6	61.7	19110	11021	900	58	0	0	1
86	206	146	1571	5.6	50.9	49.6	14373	7996	820	28	5	0	3
87	249	141	1374	5.8	62.3	61.3	18348	8372	1300	55	0	0	1
99	292	140	1600	7.6	25.4	24.2	20626	7083	*	24	4/5	0	3
111	146	106	899	10.2	56.7	55.7	18314	7964	320	55	0	0	3
145	216	178	2000	5.8	*	*	*	*	1160	33	5	1	2
146	144	125	1000	6.6	31.5	29.0	6385	4556	*	15	2/3	0	4
272	*	*	*	*	*	*	*	*	1100	23	*	1	0
273	230	124	1223	3.3	*	*	*	*	800	15	2/3	0	3
274	253	118	1508	3.1	*	*	*	*	940	13	2/3	0	2
275	326	104	1307	2.7	*	*	*	*	1150	30	2/3	1	3
259	*	*	*	*	*	*	*	*	620	25	0	0	3

* See Figure 8

0 = No fractures
1 = Fractures

** QUALITY OF BRAIN RE-PRESSURIZATION

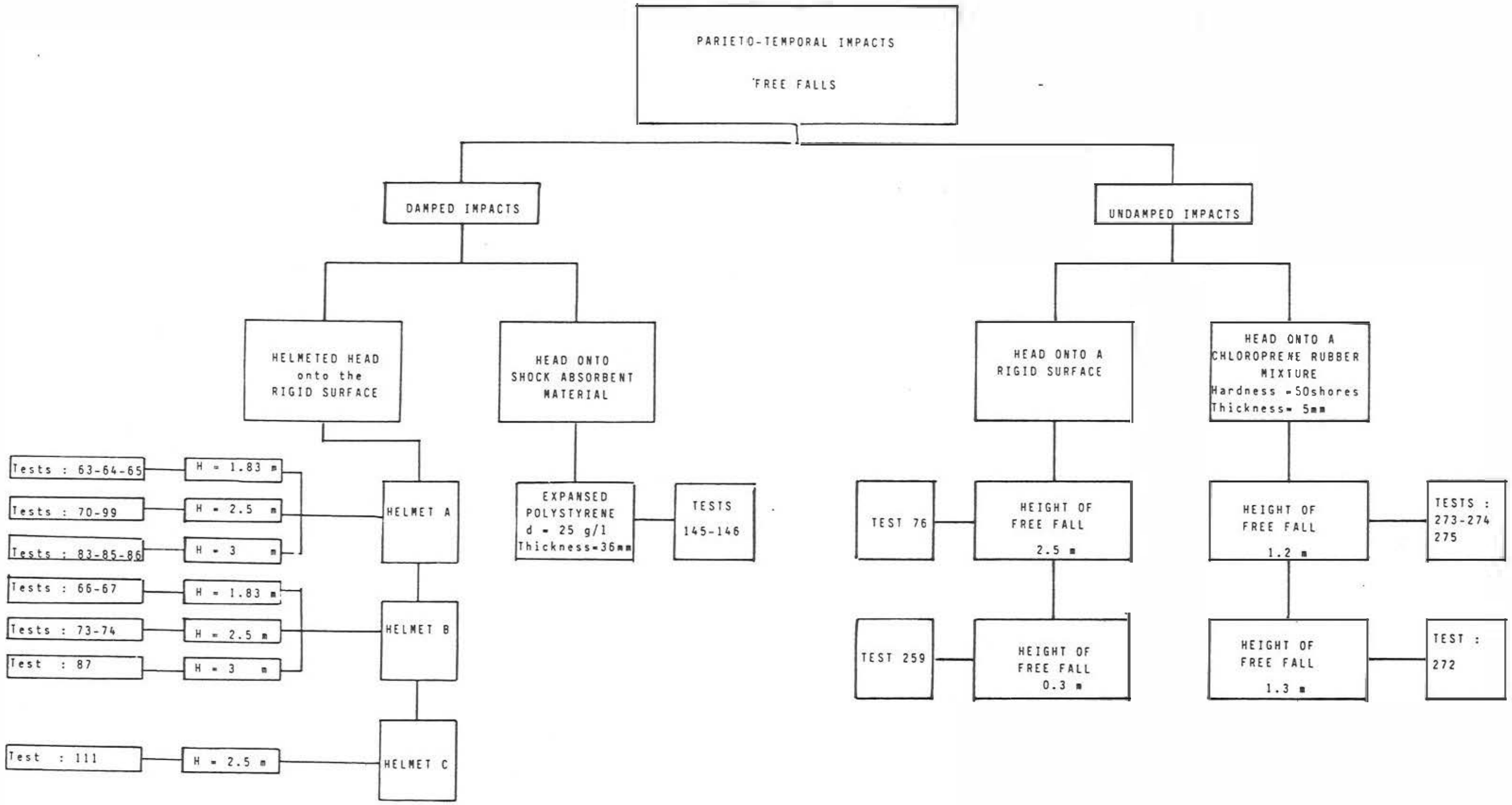


Figure 2 : SIDE IMPACTS - CADAVER TEST CONDITIONS

3.2. ANALYSIS OF HEAD ACCELERATIONS

The general principle in processing acceleration measurements can be defined thus : we calculate the head's angular acceleration and speed at each instant of impact by integrating a system of differential equations linking these variables to accelerations measured on the head's periphery. Following this, we deduce the linear acceleration at the head's center at each instant of impact, and the criteria HIC, SI, γ 3 ms, γ max.

The calculating method is of the 3-3-3 type (8), generalized by APR in order to process from 6 to 9 available channels.

4. INJURIES ANALYSIS IN PERIETO-TEMPORAL IMPACTS

For each subject involved in this study, injury severities are expressed in terms of AIS (9) - See Table 2. Cerebral lesions are summarized in Table 3.

Table 3

SUMMARY OF CEREBRAL LESIONS

TYPE OF IMPACT	N. OF SUBJECTS	N. OF SERVICEABLE SUBJECTS	INJURED	BRAIN STEM LESIONS	OTHER CENTRAL BRAIN INJURIES	PERIPHERICAL BRAIN INJURIES			HEMORRHAGE OF THE MENINGES
						Impact Area	Opposite Area	Others	
Temporo-Parietal	25/19	22/16	12/8	7/7	10/5	2/2	5/1	5/2	3/1

Note : First figure : all subjects
Second figure : helmeted subjects, or equivalent cases

4.1. QUALITY OF BRAIN RE-PRESSURIZATION

In a certain proportion of cases, which varies according to cadaver selection criteria, the mere fact of performing injection into the vessels of the brain is not enough to allow interpretation of the experiments in all vascular regions. Since this inadequacy can be limited to an arterial vessel or to the brain as a whole, it is in consequence indispensable to provide accurate details of the quality of injection undertaken and of its exact location. We use a code from 0 to 4 to describe the degree of success of injection, 0 representing a nil injection and 4 a very high quality injection into all brain territories.

In this analysis, the only tests that have been included are those in which the quality of injection was given a ranking 1 (see Table 2).

4.2. SKULL FRACTURES

Among the 20 subjects considered we have only observed 4 cases with a skull fracture (cases n° 76, 145, 272 and 275). The fractures observed at autopsy are shown Figure 3. Among these 4 cases, 1 is associated with brain injury and 2 with a haemorrhage of the meninges.

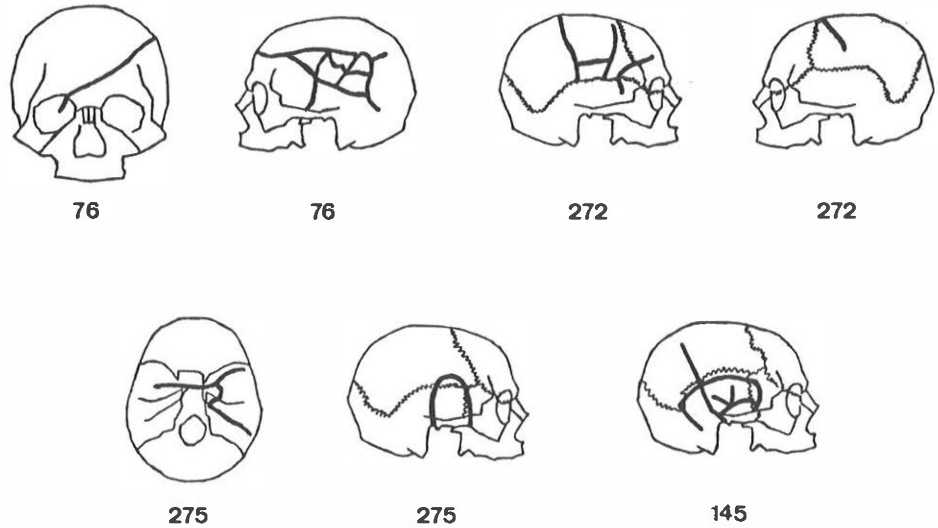


Figure 3 : SKULL FRACTURES IN SIDE IMPACTS (Free Fall Tests)

It has to be emphasized that none of these injuries is related to the skull fracture. The only doubt remains for the diffuse haemorrhage of the meninges observed for case 76. But equivalent injury without skull fracture (cases 207 and 250 in APR sample as examples) was found.

5. THE RELATIONSHIP BETWEEN FORCE, SKULL BONE CHARACTERIZATION AND BRAIN INJURY

This analysis was performed on the basis of forces measured in the vertical axis by a dynamometric platform. The film analysis of these tests enables us to state that the forces transmitted to the head are essentially vertical.

5.1. EVALUATION OF THE IMPACTING MASS

Assessment of this effective mass was undertaken by using the relationship :

$$Me = \frac{\int_0^{\tau} F(t).dt}{Vo}$$

τ corresponding to the instant at which the speed of the head becomes nil. This relationship is thus calculated during the loading phase of impact ; Vo being the impact speed.

5.1.1. Fall of helmeted subjects

On the F(t) curve, we can generally speaking observe two successive peaks. The first corresponds to the moment at which the helmet stops on the marble and then force decreases more or less according to the tests, this phase corresponding to the smoothing out of the play between the head and the shock-absorbing material. After this, a second and greater peak of force is observed, this being engendered by head impact against the helmet's shock-absorbing material.

Examination of some representative cases (Table 4) shows that in our test conditions of forehead and parieto-temporal impact to helmeted subject's heads, the average equivalent mass during the crushing phase of the shock-absorbing material can be taken to be that of the head mass alone.

Table 4

FALL OF HELMETED SUBJECTS

TEST N°	IMPACT TYPE *	HEAD MASS (kg)	HELMET MASS (kg)	CALCULATED EQUIVALENT MASS (kg)
74	L	3.6	0.9	4.39**
73	L	3.6	0.9	3.06
107	F	2.3	1.3	2.22
110	F	4.1	1.3	4.01

* L = Lateral impact
F = Frontal impact

For frontal impacts as for those that are lateral the results obtained on certain of the cases analysed (Tables 4 and 5) vary between 0.8 and 1 time the mass of the head alone of human subjects.

** In this table we should note that the equivalent mass of test n° 74 for which we obtain a value that is slightly above that of the head mass alone (lower than the head + neck target which is 5.2 kg). This result can be explained by the fact that the angle of the body as a whole in relation to the horizontal (angle β in Figure 1) is particularly high for this test at the moment of impact (44°) whereas for the other lateral impacts it varies between 25 and 35°. Also this case is not take into account in this analysis.

Table 5

FALL OF UNHELMETED SUBJECTS

TEST N°	IMPACT TYPE *	HEAD MASS (kg)	CALCULATED EQUIVALENT MASS (kg)
259	L	3.96	3.3
272	L	3.57	3.8
274	L	4.11	4.1
275	L	3.16	3.04
143	F	3.72	3.61
144	F	3.91	4.1

* L = Lateral impact
F = Frontal impact

In conclusion, whatever the test conditions, we can consider for our test patterns that the inclination of the body at the moment of impact is not sufficiently important to influence in any significant way the effective mass (taken to be that of the head mass alone) taking part in the impact. The head mass was unconnected with that of the rest of the body.

From this lack of connexion, the problem of the absence of cadavers' muscular tonicity arises as a factor increasing head versus trunk kinematics.

5.2. EVALUATION OF THE EQUIVALENT STIFFNESS

The maximum values of force applied to the head are brought together in Table 2.

We have shown in Figures 4 and 5 the relationship between the equivalent stiffness and, successively, the average thickness of the skull and the S.B.C.F. (Skull Bone Condition Factor). For each of these parameters the position of the average population of cadavers has been established on the basis of a sample of 146 subjects and is indicated on each one of these figures.

Let us now compare the behaviour of the head at impact with a simple system of a spring mass type having a certain degree of freedom and calculate its stiffness :

- for each test, it will be $K = \dfrac{F^2}{MV^2}$

where : - F is the force measured by the dynamometric platform,
- M is the mass of the subject's head,
- V is the impact speed.

The relating of Equivalent Stiffness calculated with the different parameters of skull bone resistance (EPM, SBCF) shows up the two classes of impact in our sample :

- impacts without shock-absorption,
- shock-absorbed impacts.

5.2.1. Impacts without shock-absorption

Concerning the tests with the direct impact of the skull onto a rigid or a slightly padded surface, or onto a material which is loaded up to its limits of deformation (tests n° 76, 145, 259, 273, 274, 275), we observe that the Equivalent Stiffness increases as a function of the subject's skull bone resistance (greater average thickness or S.B.C.F. index).

The special position of test n° 275 in Figure 5 is due to the fact that the calculation of the S.B.C.F. parameter takes into consideration the head's anthropometric characteristics and that for this subject these tend to have low values (see Table 1).

In these test conditions the taking into consideration of inter-individual skull bone resistance differences is of major importance at the stage of analysis and interpretation of the results using human subjects.

5.2.2. Shock-absorbed impacts

Concerning the impacts that are damped, the variation in average skull thickness plays a small role for just so long as the shock-absorbing material remains below its capacity to be deformed. Nevertheless, for damped impacts it is probable that the head's anthropometric characteristics play a role which during this brief analysis we have unfortunately not had the time to examine separately. For tests 85, 86 and 87, the subjects were equipped with the same type of protective helmet as for the impacts that were damped. Their impact speed on the other hand was higher (h = 3 m whereas for the other damped impacts it was $1.8 \text{ m} < h < 2.5 \text{ m}$).

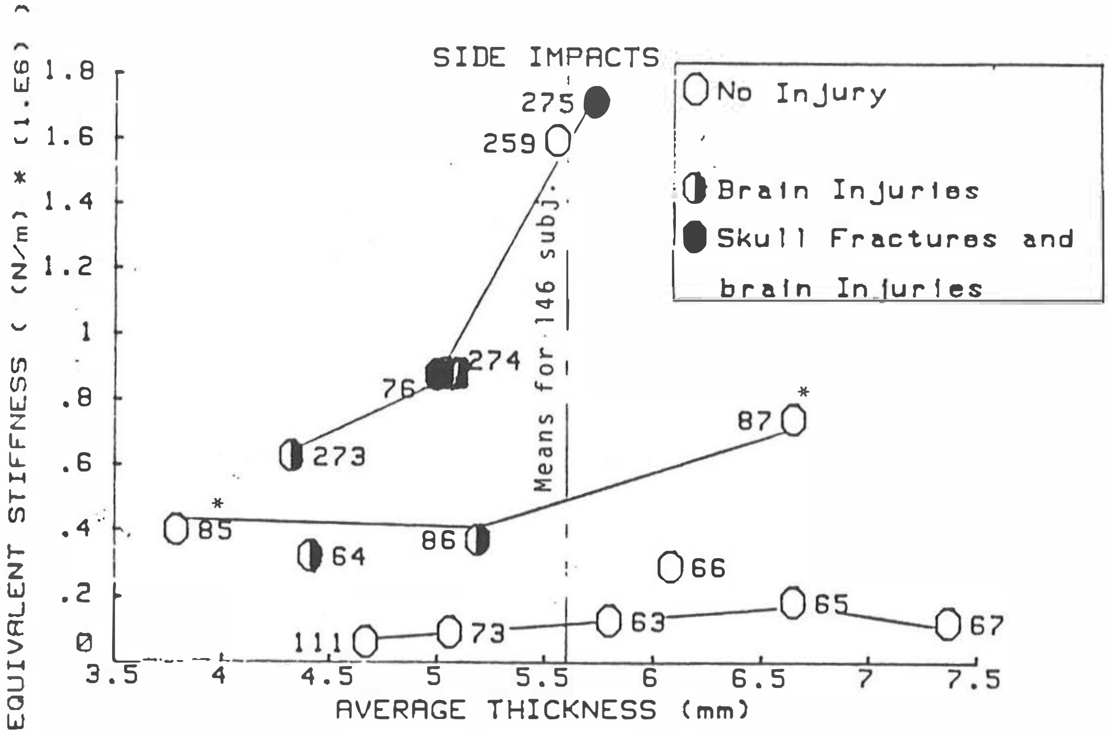


Figure 4 : HEAD EQUIVALENT STIFFNESS VERSUS AVERAGE THICKNESS

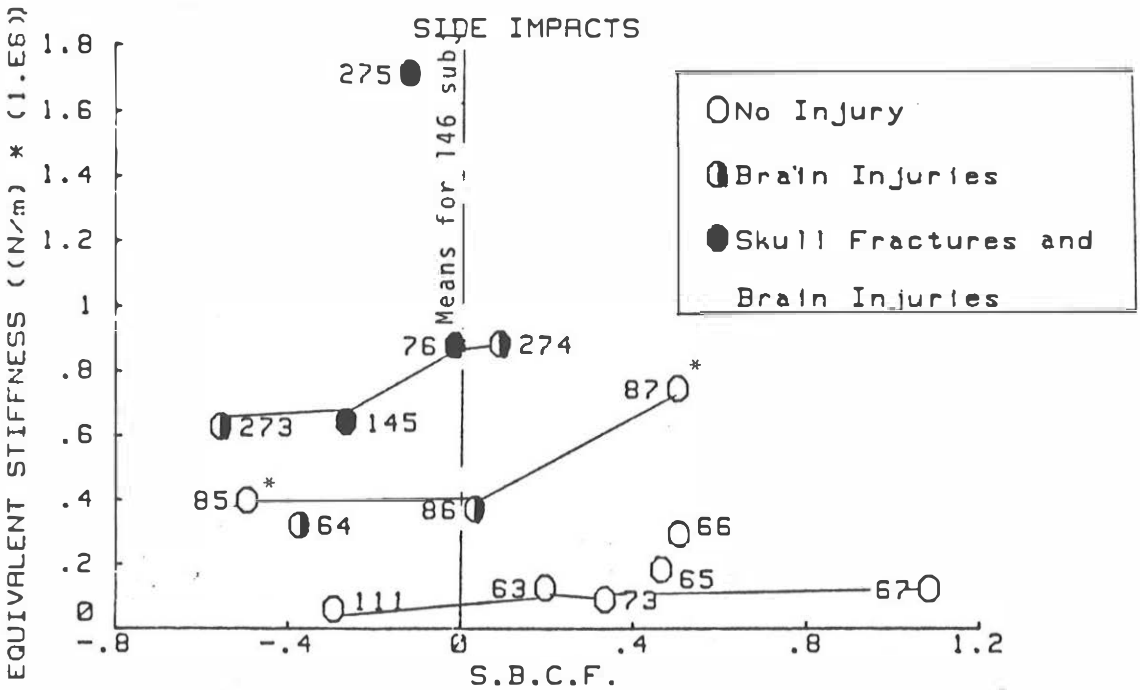


Figure 5 : HEAD EQUIVALENT STIFFNESS VERSUS SKULL BONE CONDITION FACTOR (S.B.C.F.)

* Poor quality of brain re-pressurization (See Table 2)

This change in observed thickness for these damped impacts can be attributed to a problem of visco-elasticity of the material used but above all to its being close to the saturation of its shock-absorbing capacity for this level of impact violence.

These statements deserve deeper thought and improved analysis but they already make it possible to say that the forces transmitted to the head are well related to the bone resistance of the skull and to the head's anthropometry. Force is therefore acceptable for defining the skull's tolerance to fracture on condition that the characteristics of the cranial structure are taken into consideration.

The relating of the S.B.C.F. parameter to the equivalent stiffness of the striking system allows us to make the same statements as those obtained using average thickness.

By analogy, these characteristics of stiffness, dimensions and masses have to be representative of the average population exposed to risk. Such head characteristics could be applied to a crash dummy (13).

6. RELATIONSHIP BETWEEN HIC, SKULL BONE CHARACTERIZATION AND BRAIN INJURIES IN SIDE IMPACTS

The main results of accelerometric measurements are brought together in Table 2. Only a few of the cases performed in the same test conditions are available.

We have nevertheless tried to show up (see Figure 6) the influence of inter-individual scatter in terms of SBCF upon the level of HIC for those tests carried out in the same conditions (height of drop, type of shock-absorbing material).

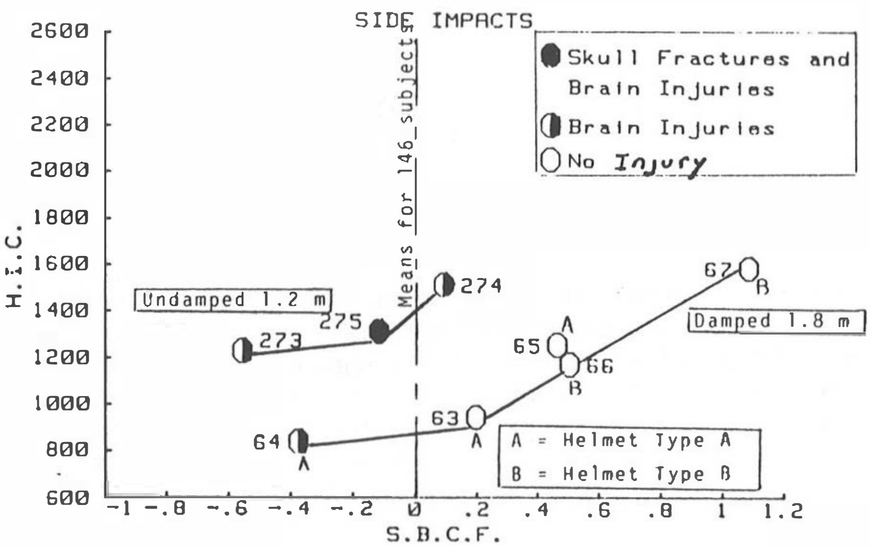


Figure 6 : H.I.C. VERSUS S.B.C.F. FOR THE IDENTIFICAL TEST CONDITIONS

Tests 273, 274 and 275 are impacts of unhelmeted heads from a height of 1.20 m onto a stiff surface. Tests 63, 64, 65 (helmet A), 66 and 67 were performed with helmeted subjects (helmet B) from a height of 1.83 m.

The examination of this figure shows clearly that the HIC value obtained in identical conditions increase as a function of the stiffness of the subject's head.

This result can be explained by the increase in skull stiffness when the SBCF itself increases.

The definition of cerebral tolerance should take into consideration the skull's bone characterization for experimental subjects. That enables us to present Figures 7 and 8 with all the experimental cases available.

On the basis of Figures 7 and 8, it is possible to identify two areas ; one corresponding to AIS = 0 and a second to AIS $>$ 0.

Whatever the SBCF value, we don't observe in your sample any lesion classified AIS $\geqslant$ 3 for HIC value $\leqslant$ 1223.

The vertical axis drawn in not solid line (see Figure 8) corresponds to the value SBCF = 0. This value symbolises the average index of skull bone characterization (SBCF) of cadavers ; it has been calculated on the basis of a range of 146 subjects.

If we consider only the subjects of skull bone characterization superior or equal to the average (SBCF $\geqslant$ 0) the first case of lesion (test n° 274) associates an AIS 2 or 3 (admissible value) to an HIC equal to 1508.

We thus see that tolerance expressed in terms of HIC, increases with SBCF until it reaches the level of 1500 with the highest values for SBCF or average thickness.

It is to be stressed that the values (SBCF) are very probably weaker than those expected from the population exposed to a risk. Therefore SBCF area superior or equal to the average, could prove to be fairly representative of the living population.

7. STATISTICAL ANALYSIS OF DATA

Bearing in mind the scatter of results due especially to the difficulty of the experiments, to inter-individual differences between the subjects used, and to the imprecision of kinematic data (high margins of error), as well as to the non-linearity and the subjective influence in coding injuries using the AIS scale ; for all these reasons we cannot hope to obtain very detailed results so far as criteria are concerned. Because of this we are obliged to have recourse to a statistical processing of data.

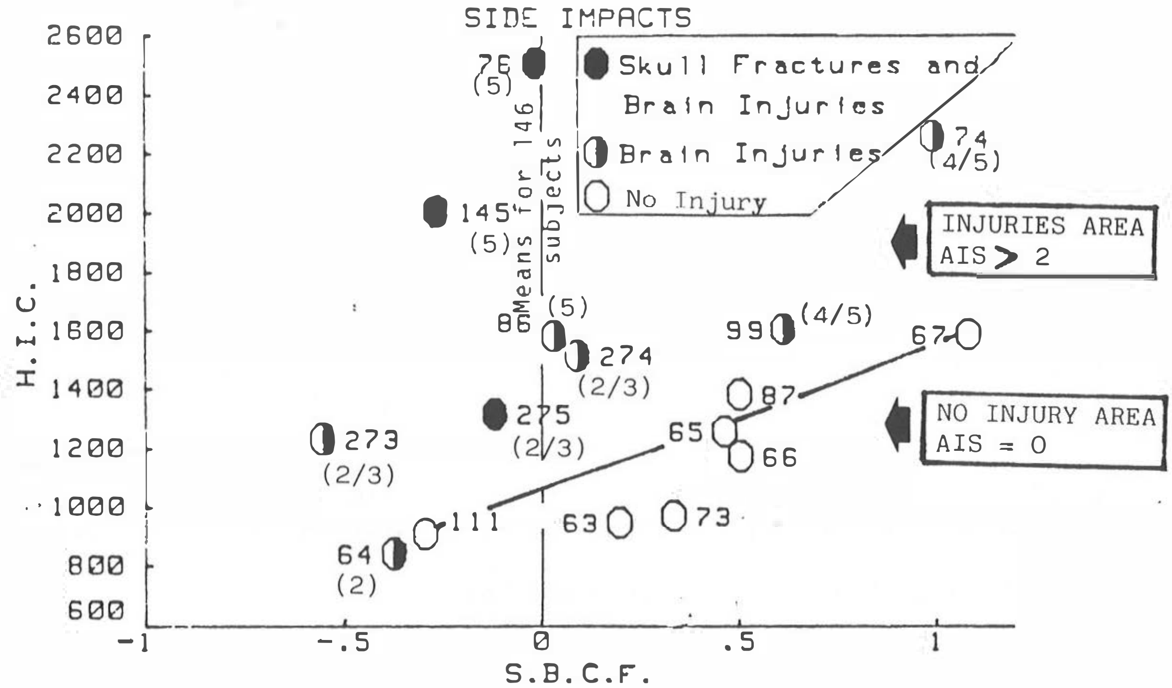


Figure 7 : H.I.C. VERSUS SKULL BONE CONDITION FACTOR

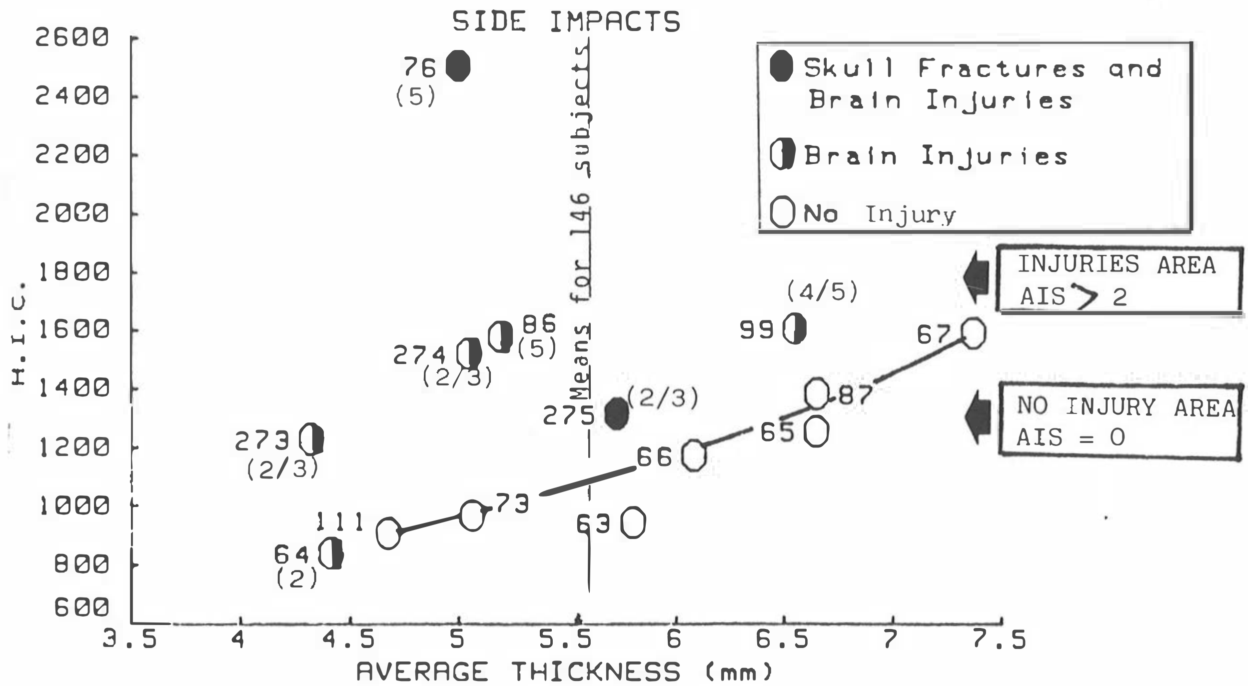


Figure 8 : H.I.C. VERSUS AVERAGE THICKNESS (Vol/surf)

* The figures in brackets are AIS indices

7.1. A PREDICTIVE FUNCTION OF BRAIN INJURY RISK IN SIDE IMPACT

We have performed a multiple linear regression analysis as follows :

$$AIS = K1.HIC + K2.SBCF + C.$$

This regression analysis concerned 15 subjects in free-fall experiments where the point of impact was situated in the parieto-temporal area and in which experiments considerable movement of the head relative to the trunk was observed. The multiple correlation coefficient and the value of the FISCHER index obtained show that this function is statistically significant ($r = 0.84$ - $F = 14.77$). Figure 9 illustrates the relationship between AIS observed in cadaver tests and that AIS value predicted by the use of the function. In consequence, for our impact conditions a predictive function based upon the use of a calculated HIC value or upon the center of gravity, and bearing in mind the cadaver's skull bone characterization index, enables us to predict an AIS value within the limits of the HIC and SBCF values taken into account in the analysis. The function obtained is as follows :

$$AIS = (0.005 \times HIC) + (-2.527 \times SBCF) - 3.859.$$

On the basis of this function we deduce that, for a subject having a skull bone resistance index (SBCF) representative of the average of the population of our cadaver subjects, a value of 1300 HIC predicts a value classified 2.6 on the AIS scale.

8. DISCUSSION

In this paper meant to precise the part played by the subject's skull bone characterization upon the head injuries risk (fractures or/and cerebral injuries) and the levels of physical parameters linked with them, only the cases that correspond to a translation movements without any head/trunk relative movement, by rotation, as been taken into account.

The linear accelerations can't account for injury risk to which a head is exposed in lateral impact.

As a matter of fact relative motion head/trunk, by rotation, may provoke specific injuries at this kinematic (brain stem injuries associated or not with haemorrhage of the meninges and with or without osteo-ligamentary injuries of the cervical vertebral column) (11). This is the case of tests n° 70 and 83 for this sample of free fall tests (10).

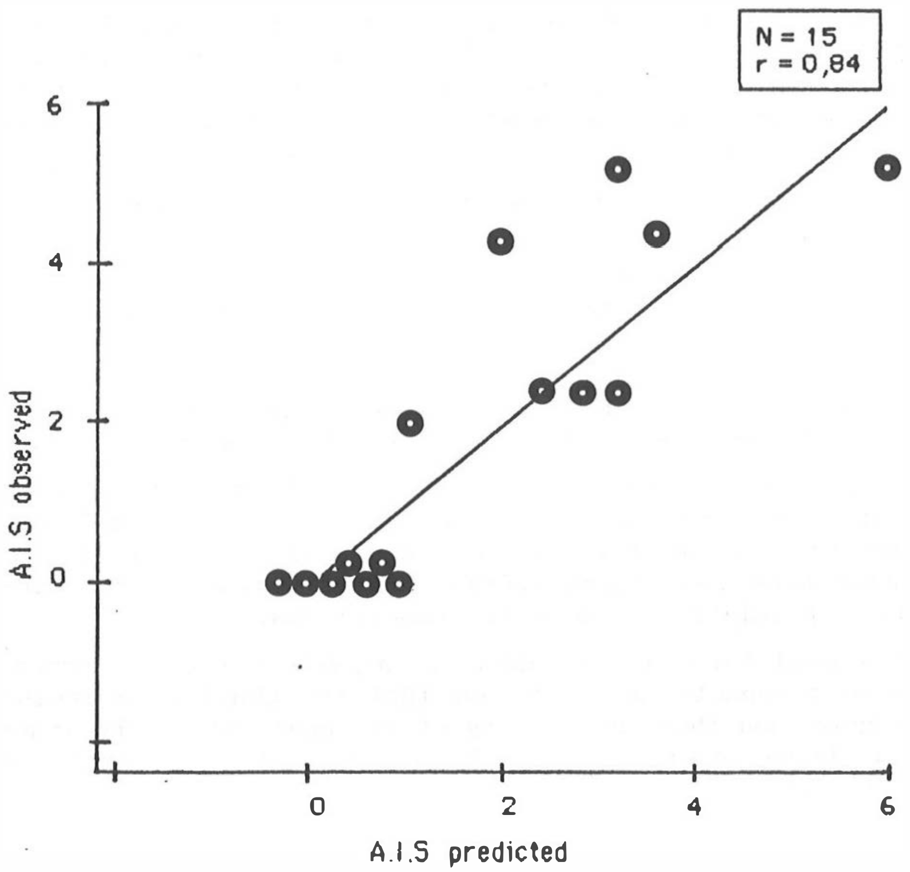
Such is also the case of test n° 195 obtained in reconstitution of lateral impact car against car reported a few years ago (12).

In the special case of the PEUGEOT 504/CITROEN LN lateral impact reconstruction (test n° 195) where the cadaver was unbelted, it is the extensive rotation of the head (by partial ejection of the drivers struck vehicle) without any significant head impact occuring (HIC = 100), which was responsible as well as the two injuries to the brain stem (AIS = 4).

	coef	stand _ err	dgdf	F _ ratio	sig
constant	-3.859	1.336	12.000	8.338	0.014
HIC	0.005	0.001	12.000	20.757	0.001
SBCF	-2.527	0.655	12.000	14.898	0.002

	rsquare	adj _ rsquare
total _ rsq	0.711	0.663
HIC	0.353	0.303
SBCF	0.359	0.360

	sum _ of _ squares	dgf	mean _ square	f _ ratio	sig
total	58.476	14.000	4.177	*	*
regression	41.589	2.000	20.795	14.777	0.001
error	16.887	12.000	1.407	*	*



RELATIONSHIP BETWEEN A.I.S OBSERVED AND A.I.S VALUE PREDICTED BY THE FUNCTION

Fig 9 Predictive function of brain injury risk in side impact.

The analysis of the respective influences of the physical parameters (head/trunk angle, angular acceleration and angular velocities) linked to this type of lesionnal mechanical is under study.

9. CONCLUSIONS

- In damped free fall head impact (helmeted head or head against a padded obstacle) skull fractures are rare in parieto-temporal impacts.

- The subjects' skull bone characterization (mineralization, average thickness and SBCF) enable us to delete within the sample some exceptional cases with very weak bone strength.

- Skull characteristics determining the skull stiffness have an important influence on the force or acceleration values (HIC) obtained with cadavers for no damped impacts.

- For SBCF or average thickness values corresponding to the average values of the population of cadavers (**N** = 146) it may be claimed that the probability of occurrence of injuries is very small (nil in our sample) when the HIC is inferior or equal to 1100 ; in addition it was observed in the case of the cadavers used that, generally speaking, they represent only an under-estimate of the tolerance of live human beings exposed to accident risks (14) (15).

  This suggests a much higher tolerance value for the population exposed to risks.

  Such differences, i.e between living and experimental subjects in terms of average skull bone characteristics, has to be precised. This work is now proceeding.

- A multiple linear regression analysis taking into account HIC and the skull bone resistance index of the subjects (SBCF) was performed.

  The predictive function obtained is statistically significant. It shows, on the basis of the few available points, that a 1300 HIC value is a tolerable one (that is to say a predicted AIS value of 2.6) for a subject having a skull bone resistance (SBCF) representative of the average for the 146 cadaver population used in the experiments.

  For the human head tolerance to impact, cadavers are good surrogates for living vehicle occupants on condition that the skull bone resistance of cadavers is known and that the quality of the brain after the inquest upon the cause of death permits a good injection ; this is essential in the data analysis stage.

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