PERFORMANCE OF HELMETS AND CONTRIBUTION TO THE DEFINITION OF THE TOLERANCES OF THE HUMAN HEAD TO IMPACT (°)

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Tests of free fall of fresh cadavers, wearing helmets or not, onto a rigid flat surface are described here together with their results and compared with dropping of the heads of helmeted dummies falling in a similar way from the same heights, together with dropping of metallic headform.

The conclusions relate to human tolerance to lateral impacts of the head and the performances of the helmets.

METHODOLOGY

The series of tests carried out are all under conditions of free fall and come under three categories :

1) - free fall of helmeted or non-helmeted cadavers,
2) - free fall of Hybrid II anthropomorphic dummy head,
3) - free fall of light alloy metallic headform.

In all the cases reported here, the head, whether helmeted or not, strikes a flat rigid surface. The height of the fall and the helmet differ ; the desired point of impact of the head is invariably the same and would correspond on the human head to the lower part of the parietal bone near the temporal bone (see fig. 1). The impact thus brought about can be assimilated to a lateral impact where data concerning human tolerance is rare ; it is generally assumed that the tolerance to the lateral impact of the head is lower than the tolerance to impact on the frontal bone ; this has been verified with respect to the level of the efforts needed to obtain fracture.

The helmets used are available on the French market. The cross-section of these helmets is shown in fig. 1bis. They were selected in view of their wide diffusion on the market and in particular for the presence of shock absorbing material of relatively considerable thickness in the impact zone selected.

(°) - Study conducted in relation to a research contract (Thematic Action Programme) with the French Government.
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The "A" type helmet for instance has 20 mm of expanded polystyrene with a density of 22 g/l near to the point of impact. The polystyrene extends to the entire upper section of the helmet. The external shell is in A.B.S.

The"B" type helmet has a local thickness of 32 mm of polystyrene with a density of 40 g/l, but this material forms a crown which does not cover the upper part of the skull. The proximity of the point of impact and the edge of this lined zone, should such an impact occur, detracts from the shock absorbing capability. The external shell is in polycarbonate.

The "A" type helmet weighs 0.940 kg in size 58 and the "B" type helmet 1.5 kg. Size 58 was used for the heads of the Hybrid II and the light alloy head. The human subjects were given helmets adapted to suit the dimension of their head.

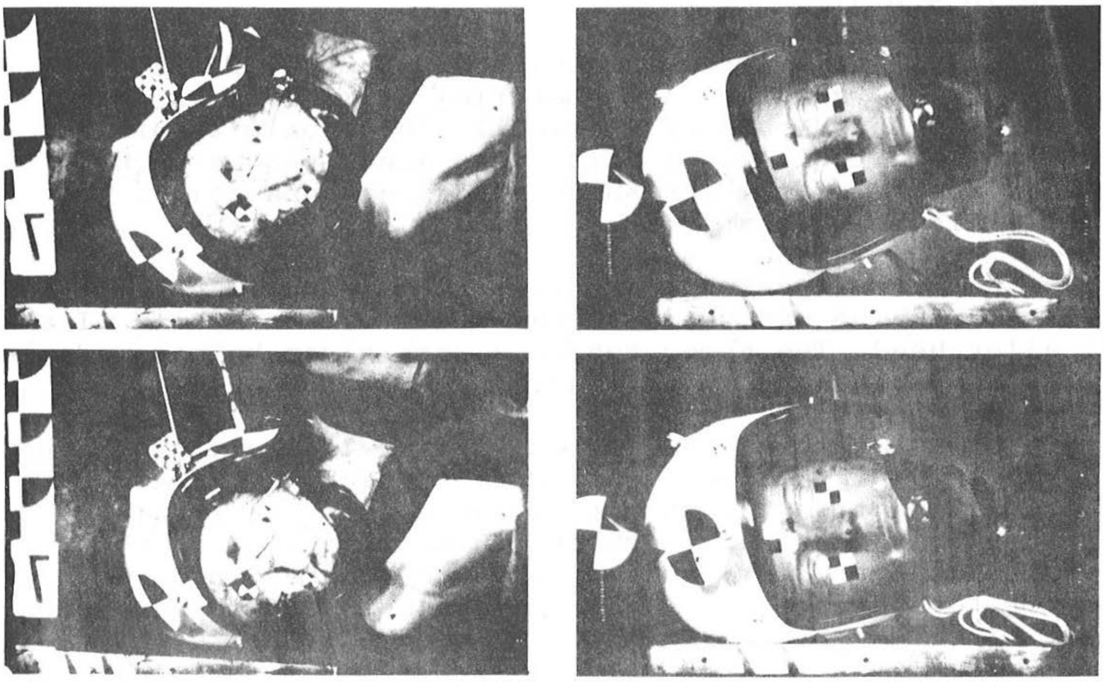
The "A" type helmet is equipped inside with a wide belt providing an additional dampening effect, this effect reaching a maximum in the case of an impact on the summit of the helmet. This belt had to be cut to enable the accelerometers to be installed on the skull of the cadavers. The result is that the performances recorded are lower for this helmet than were the belt not to have been cut .

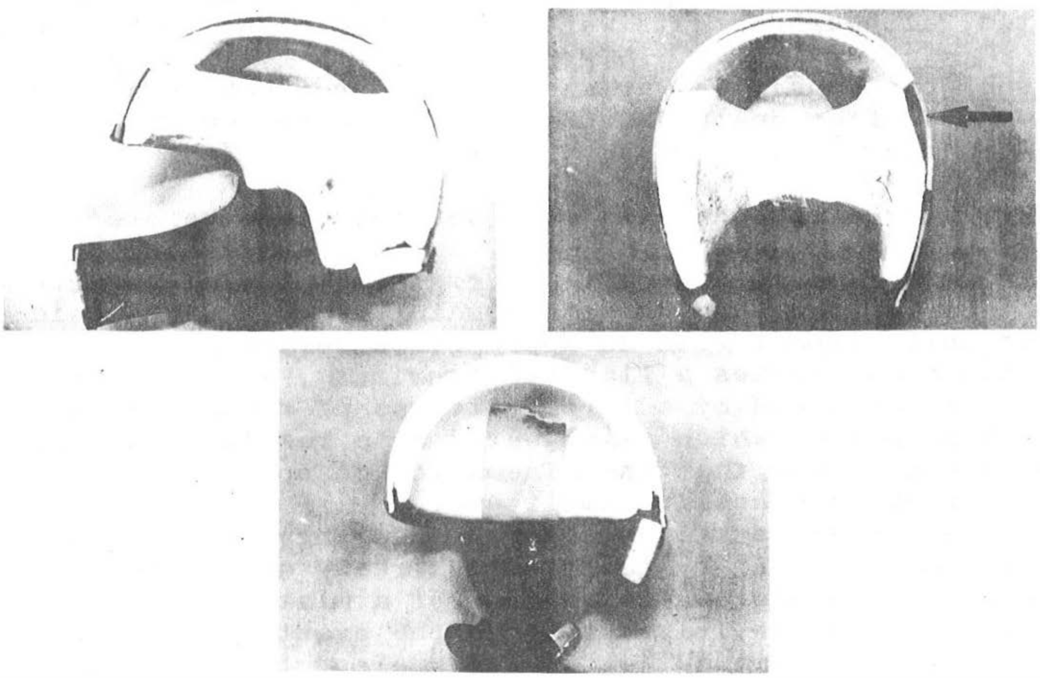
Local cuts in the helmets had to be made to enable accelerometers to be mounted, although no cuts were ever made in the impact zone.

<u>The human subjects</u> consist of fresh cadavers, not embalmed, tested less than 4 days after death, having been preserved in the meantime in a cold room between 0 and 2° C.

They were withdrawn from the cold room several hours before the tests.
The subjects were installed prone in a rigid metal cradle, with the head and top of the shoulders protruding. The head was held in alignment until impact with an appropriate device.
On impact, the head strikes a flat rigidsurface , while the motion of the cradle is dampened by a thick mattress of shock-absorbent material, the height of which is adjusted as a result of preliminary tests in such a way that the kinematics do not result in motion of the neck of excessive amplitude.
The circulatory system is kept pressurized during the tests and for a few seconds after it by the method already described in (1) and (2). The liquid injected, consisting of a mixture of formol water and china ink makes it possible in the event of bursting of a blood vessel even of minimum extent, to detect the spreading of the "blood" under microscopic examination of the brain fixed by the formol. In this way, a fine "read out" of the cerebral legions that may occur is obtained, supplementing the conventional autopsy.

Fig. 1. Compared falls of dummy head and cadavers





Type B

Type A

Fig. 1bis. Cross-section of tested helmets: note the local déformation of the polystyrene

In contrast to the procedure of (1), the perfusion liquid is injected directly into the aorta.
After the test, the heads and necks are weighed ; the sections retained are those used by L.B. Walker (4).
The anthropometric characteristics are grouped together in table 1.

Accelerometers were mounted on the heads of the subjects (fig. 2). These accelerometers were secured to metal plates screwed into the skull. On the right temple, on the side of the skull opposite the impact, a triaxial accelerometer was mounted. A biaxial accelerometer was mounted on the forehead, giving a transverse component with relation to the head and a vertical component. On the occiput, a biaxial accelerometer was mounted resulting in a transverse component to the head and a longitudinal component.

It was not possible to mount the accelerometers in strictly the same position for each test with relation to conventional anatomical reference points (Ewing - 5) which situate the centre of gravity. The reasons for this can be ascribed to the extension of the frontal sinuses, anthropometrical differences in the heads, etc...

The position of the accelerometers was recorded for each test for subsequent use of the data.
The measuring systems as a whole comply with the requirements of FMVSS 208/SAE J 211 b for the head.

Free falls of the head of the anthropomorphic dummy were induced in conjunction with tests of the human subjects wearing the same helmets and falling through the same height.

The head was that of a Hybrid II dummy equipped with instruments in accordance with the specifications of FMVSS 208/SAE J 211 b. The neck of the dummy is present and the unit weighs 5,304 kg without the helmet.

The purpose of these tests was to obtain values of the protection criteria derived from the measured acceleration such as the severity index SI (3) and the Head Injury Criterion (HIC) for head impacts of the dummy commonly used today, comparable to those undergone by human subjects.

We considered that the impacts of the head of the human subjects would be better reproduced by dropping the dummy's head alone than by dropping the complete dummy, owing to the considerable rigidity of the dummy's neck, compared to the neck of subjects under the test conditions. This point will be specified by subsequent tests.

Free fall of light alloy headforms supplement the previous tests. Light alloy headforms with low resonance are in fact commonly used in testing helmets ; they have no surfacing as does a Hybrid II head and consequently have higher accelerations for the same impact, although having the same weight.

Furthermore, by adjusting the distribution of the ballast, we have caused the centre of gravity of the unit to coincide with the position of the triaxial accelerometer used ; the point of impact and the centre of gravity lie on the same vertical line.

The kinematic obtained therefore approximate more closely to simple transverse motion ; the offset of the sensor is small and the acceleration measured is exempt from causes of attenuation.

The dropping heights used were 1.83 m in the first series and then 2.50 m in the second.
1.83 m corresponds to the falling height required for helmet tests under American legislation.
2.50 m corresponds to a higher severity which appeared necessary following the satisfactory results of the first series.
All the tests of human subjects and most of the other tests were filmed by STALEX cameras at 1000 frames per second.

R E S U L T S

1. Tests on human subjects

The results consist of the autopsies and the analysis of the measurements made. One can only be absolutely certain that no lesions have occurred provided the vascular injection technique has succeeded perfectly, which does not occur on every subject.
The results of the autopsies are shown in table 2.

It can be concluded that with the helmets tested, dropped up to height of 2.50 m, serious lesions were only revealed in a single case n° 74, out of the 9 subjects wearing helmets.
A dropping height of 2.50 m only corresponds to an impact speed of about 25 km/h, but the variation in the speed of the head is higher in view of "bounce", which varies depending on the test. One can estimate the mean value at the head of ΔV as 30 km/h, in the vertical direction.
The results of the measurements are shown in table 3.

The period during which speed variation is undergone is about 15 ms, the HIC values have been calculated for durations of from 4 to 6.5 ms. The SI & HIC values must be considered in function of the measuring point used to calculate them, which was indicated previously. The head rotations during impact change the accelerations measured on its periphery ; this phenomenon is distinct for Gz accelerations (parallel to the vertical axis of the head) which are increased considerably when passing from the measuring point on the forehead to the measuring point on the right temple.

Having said this, a relatively low Gx-acceleration results in a relatively small rotation around the vertical axis of the head. For such tests, the SI & HIC values calculated are close to those which would have been attained from a measuring point coinciding with the centre of gravity of the head and close to those obtained on the

head of a dummy subjected to the same kinematics. Except for subject 74, which we shall consider later, the heads of the helmeted subjects revealed SI values of about 1,000 to 2,500, accompanied with HIC values of 800 to 2,100.
The highest values are for subject 66, the head and neck combination of which was the lightest of all.
Subject 74 underwent exceptional values (HIC $>$ 2300). This is the only subject among our sample suffering notable lesions after the autopsy (AIS $\geq$ 3). The interpretation must allow for one particularity of the test : this is the subject the head of whom was inclined the most to the horizontal at the moment of impact (40°). Allowing for the technology of the helmet used (type B), the dampening of the impact in the vertical direction of the head has been insufficient. This explains the very high vertical accelerations values recorded and their importance compared to the transverse accelerations.
According to the method used to detect cerebral lesions, one has to consider that the head impact tolerance has been exceeded in this case, which differs from other cases of the sample by the paramount magnitude of Gz acceleration (370 g and 450 g measured by 2 transducers at different locations).
In this series of fairly lengthy lateral impacts (thanks to the dampening materials in the helmets) high SI & HIC values could be reached without noticing lesions ; an HIC of 1,500 was exceeded twice.
Without a helmet, fractures of the skull occurred in the two tests carried out, together with very high HIC values.

2. Tests with the head of a dummy

These have enabled us to draw up the following table :

		Peak acceleration					
		Longitudinal	Transverse	Vertical	Resultant	S.I.	HIC
HELMET A	1.83 m	12	132	63	135	800	700
(modified)	2.50 m	31	196	53	211	1873	1590
Helmet B	1.83 m	0	118	71	138	791	681
	2.50 m	9	140	97	170	1453	1247

These results express lower accelerations than during comparable tests with human subjects. The kinematics of the sensors is however not exactly the same. For example, if we consider the previous test n° 66 with its counterpart above (helmet B, 1.83 m), the vertical rebound velocity observed on the films in the alignment of the accelerometers is about 2.5 m/s. for subject 66 (frontal sensors) and 1.5 m/s. for the Hybrid II head. One should allow for the difference in the weights in order to explain this lower rebound speed.

These results therefore do not reveal a lower tolerance as measured on the dummy, but the fact that the test imposed on this dummy head was less severe for the cases reported here. For all other types of test imposed on a human subject and an anthropomorphical dummy under identical conditions, the conclusions concerning the hierarchy of severities might be different.

3. Tests with the metal heads

Comparable falls give the following results for the "B" helmet.

		Peak acceleration					
		Longitudinal	Transverse	Vertical	Resultant	S.I.	H.I.C.
Helmet	1.83 m	17.5	150	40	150	1200	1000
B	2.50 m	12	187	25	190	1953	1724

Changing from the head of Hybrid II to the metal head results in an increase in the acceleration levels measured. This evidence is confirmed by the results of tests made with other types of helmet, not published here.

NOTE : These 3 types of impacts leave a lasting print on the dampening material of the helmet, evidencing the violence of the impact. An example of this can be seen on the section of "B" helmet shown on figure 1a.

DISCUSSION

It has been showed in the foregoing that SI & HIC values going over 2100 could be supported without indication of notable lesions even microscopic ones. This has been established for impacts on the side of the head with a helmet which avoids excessive pressions.

These impacts last about 15 ms and the corresponding HIC have been calculated on a 4 to 6.5 ms time interval.
Validity and range of application must be pointed out.

On concern of lesions detection, one can be certain of absence of fracture and of gross trauma. There is either no microscopic injuries when injection was able to include the entire cranial territory and that there was no lesion before.
The study of Table II shows that few risks are taken when supposing the absence of lesions other than minor ones.
The results of the range of application can be discussed in terms of role of the helmet on the impact duration and the impacted area on the head.

A padded helmet protects against fracture like a padded steering wheel hub, like a padding for B-pillar, like a laminated windshield and any device which increases the impact duration. One can use the indicated tolerance levels in case of head impact against each of such pieces, against dashboards, in case of a pedestrian head hitting a hood, so far as impact duration exceeds a sufficient value, such as 12 ms e.g. (as a matter of fact, the impact of a head which hits at 22 km/h a B-pillar covered by a 40 mm padding exceeds 20 ms; the impact of a pedestrian head at 32 km/h against a hood may be 15 ms long).

It could be more practical to use a minimum HIC computation duration, such as 4 ms from our tests.

At the present state of hypothesis on the ranking of head impact tolerances according to the impacted area (6), a supplementary and rarely restraining condition is the head being hit on its frontal or lateral part.

CONCLUSION

On the basis of these first results obtained from human subjects, it appears that certain current helmets protect against skull fracture and cerebral lesions in impact on the lateral head face up to at least 2.50 m of drop height.

The main fact lies in the level of probable head tolerances in terms of SI & HIC. In fact, for HIC above 2100 on human subjects, the following statements have been allowed.:

- absence of fractures and severe cerebral lesions and, more generally, of any macroscopic lesions.
- absence of microscopic lesions such as arteriole or cerebral capillaries ruptures in all correctly injected territories.

The test conditions are applicable in any situation when the impact duration is over 12 ms approximately, which in fact covers the impact conditions most frequently observed in real crash conditions.

These results, which confirm those obtained in belt restraint tests with or without head impact (2) (7) lead us to propose a HIC of 1500 as a protection criterionin case of frontal or lateral head impact during tests conducted with Hybrid II dummies.

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TABLE 1 - DATA ON CADAVERS

Test No	Age/Sex	HEAD Circum-ference mm	HEAD Breadth mm	HEAD Length mm	Head and Neck Mass Kg	Head Mass Kg
63	78/F	541	150	182	4,020	3,280
64	59/M	548	145	192	4,860	3,920
65	57/M	571	155	194	5,020	4,230
66	82/F	539	145	182	3,560	2,920
67	82/F	554	141	182	4,430	3,340
68	49/F	556	145	184	5,160	3,820
69	71/H	585	156	202	4,700	3,810
70	68/M	548	141	192	4,580	3,560
73	55/F	560	140	175	4,780	3,680
74	74/H	565	135	180	5,220	3,640
76	75/H	550	140	192	4,290	3,450

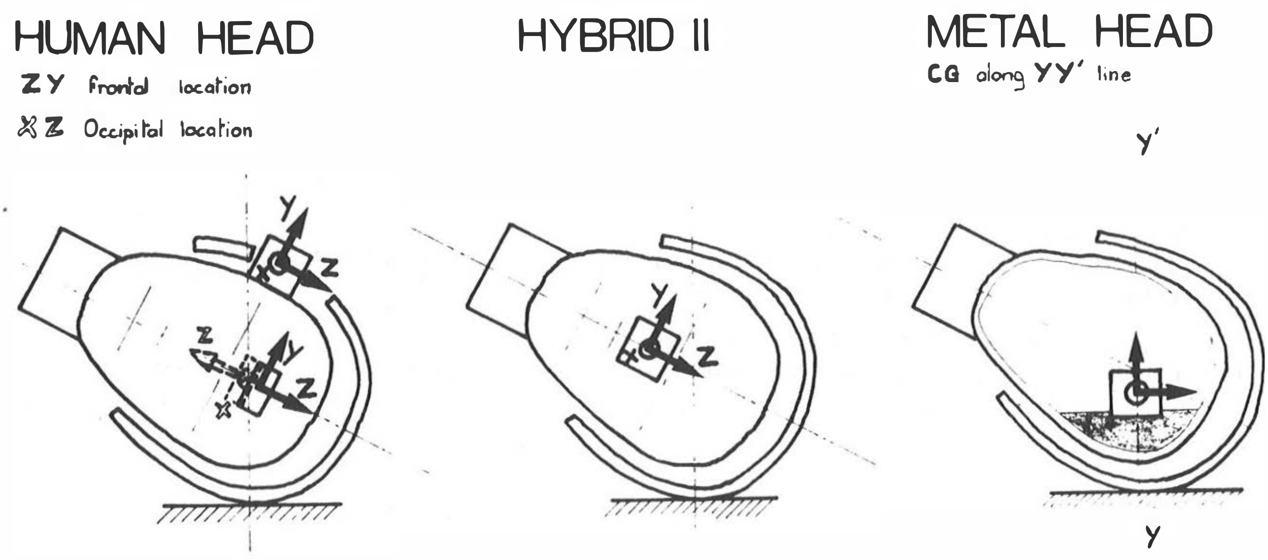

Fig. 2 - LOCATION OF ACCELEROMETERS

TABLE 2 - SUMMARY OF CEREBRAL EXAMINATIONS

Test No	Dropping Height	
63	1.83	NO APPARENT LESION IN THE VERTEBRO-BASILIAR AREA, ALTHOUGH THE INJECTION WAS NOT PERFECT.
64	"	MINOR LESIONS - AIS 2 PROBABLE FOR A LIVING SUBJECT.
65	"	THE FORMER STATE OF THE BRAIN IS THE CAUSE OF THE MINOR DAMAGE OBSERVED.
66	"	NO LESION.
67	"	PROBABLY NO LESION, BUT THE INJECTION WAS NOT PERFECT IN THE PERIPHERIC CAROTIDIAN AREA.
69	2.50	NO LESION.
70	"	NO LESION.
73	"	NO APPARENT LESION, ALTHOUGH THE INJECTION WAS NOT PERFECT IN THE RIGHT ANTELO-CEREBRAL AREA
74	"	LESIONS OF MINOR EXTENT BY VOLUME, BUT SEVERE DUE TO THEIR LOCATION AT CEREBRAL TRUNK LEVEL (PROBABLE COMA).
68	NO HELMET 1.83 M	MINOR FRACTURE OF THE SKULL (THE FAILURE OF THE INJECTION INTO THE DEEP BRAIN STRUCTURES DOES NOT ALLOW THE DETECTION OF POSSIBLE CEREBRAL LESIONS).
76	NO HELMET 2.50 M	VERY CONSIDERABLE FRACTURE OF THE SKULL AND FATAL LESIONS (RUPTURE OF THE CALLOUS CORPUS AND CEREBRAL TRUNK LESION).

SOME SUBJECTS BEING QUITE OLD, ONE MIGHT THINK THAT THEIR CEREBRAL TOLERANCE TO IMPACT HAS DIMINISHED THOUGH NO OBJECTIVE DATA IS AVAILABLE CONCERNING ARTERIOLARY AND CAPILLARY WEAKNESS CAUSED BY AGE.

TABLE 3 - SUMMARY OF MEASUREMENTS ON HUMAN SUBJECTS

Test No	Height of Fall m	Helmet	PEAK ACCELERATIONS (g)								COMPUTED GADD SI. AND HIC.					
			Right Side of Head			Frontal Bone			Occipital Bone		2 frontal components		2 frontal components + AP component from occiput		2 occipital compo. + SI component from frontal bone	
			AP.	SI.	RL.	SI.	RL.	R*	AP.	RL.	GSI.	HIC.	GSI.	HIC.	GSI.	HIC.
			Gx	Gz	Gy	Gz	Gy		Gx	Gy						
63	1.83	A	50	380	215	-	150	-	-	150	-	-	-	-	-	-
64	-	-	35	190	125	120	136	165	48	150	1050	833	1120	926	1750	1541
65	-	-	88	200	150	125	126	175	28	155	1350	1204	1400	1253	1720	1560
66	1.83	B	58	240	175	225	170	~240	28	200	2450	2122	2500	2133	3000	2547
67	-	-	90	400	170	165	160	~210	20	180	1750	1451	1800	1458	2300	1882
69	2.50	A	-	-	-	-		-	-	-	-	-	-	-	-	-
70	-	-	33	160	130	110	120	160	30	132	1400	1207	1450	1239	1400	1224
73	2.50	B	65	290	240	105	220	240	30	220	2000	1713	2050	1729	2500	2286
74	-	-	(40)	(370)	(160)	(450)	(275)	(-)	(52)	(145)	(4350)	(2579)	(4467)	(2678)	(4125)	(2322)
68	1.83	NO			> 500		> 500					> 7000				
76	2.50	NO			> 500		> 500					> 5000				

R* : Max. Resultant