HUMAN HEAD TOLERANCE TO IMPACT: INFLUENCE OF THE JERK (RATE OF ONSET OF LINEAR ACCELERATION) ON THE OCCURRENCE OF BRAIN INJURIES

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SUMMARY

Acceleration, S.I. and H.I.C. are parameters often considered in relation to head injuries produced by impact. This does not imply that any of these factors considered alone correlates very closely with the severity of the injuries. Do other parameters derived from a $\gamma(t)$ pulse, such as the acceleration jerk ($d\gamma/dt$) for the same type of impact loading to the head, have any influence on the extent of injuries ?

The first objective of this communication is to synthesize experimental data concerning any possible influence of linear acceleration jerk of the head on the extent of the cerebral injuries produced by frontal head impact to freshly perfused and instrumented cadavers.

Tha data obtained from these experiments, combined with that already obtained and published (2)(3)(4)(7) define the relationships between cerebral injuries and HIC values obtained by blows to the head without fracture of the skull.

I - THE INFLUENCE OF LINEAR ACCELERATION JERK OF THE HEAD ON THE EXTENT OF CEREBRAL INJURIES

1. METHODS - 1°) Description of the tests - All the tests reported below were performed according to the protocol already described (1)*.

- a fresh, unembalmed cadaver, with an aortic perfusion, was suspended horizontally, the head being in line with the rest of the body (Fig. 1-a).
- It was allowed to fall 3 meters, and the front of the head struck a flat, hard surface, covered with shock-absorbing materials which were selected according to the type of jerk desired.
- In side-view, the angle of the perpendicular to the surface struck was, at the time of impact, between 0° and 20° on the Frankfort plane (Fig. 1-a).
- The body was stopped so as to avoid extensive extension of the neck.

2°) - Calculation of the accelerations - So as to be able to calculate the linear and angular accelerations at the centre of gravity of the experimental subjects, we used a system of 9 acceleration channels, recorded by three tri-directional accelerometers: two of the accelerometers were attached to the right and left parieto-temporal areas, and the third to the back of the head. Their positions were defined by the usual methods, using the

* The numbers between parentheses designate references at the end of the paper.

Frankfort plane (5).

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 meant that the forces measured were very close to those actually experienced by the head.

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

All the tests were filmed at 1000 frames per second.

4°) Anthropometric data - Prior to each test, accurate anthropometric measurements were made of each subject. These measurements are given in the Table 1; aparts from the age and sex of the subject, the circumference and length of the head were measured around the lowest part of the frontal bone and the outer occipital protrusion. The width of the head was taken as the maximum distance between the right and left temporal areas.

After each test, the head and the neck were put on one side, according to the procedures already described (6) so that any cerebral, cranial or cervical injuries could be examined.

The mass of the head and neck, the head alone and the brain were noted for use in understanding the phenomena of equivalent masses and of the individual characteristics of the subjects, and also so that the influence of characteristics of the skull could be studied.

The available data are summarized in the Table 1.

5°) Calculation of the jerk - There is no standard procedure for the calculation of the jerk from the $\gamma(t)$ pulse. Several methods are described in the litterature (7)(8). They deal with the rising portion of the head deceleration curve: the time interval used in the calculation being, to a large extent, left to the author's intuition.

The method used here is as follows:

- two points, corresponding to 0.2 and 0.8 respectively of the γ R max. are determined from the rising portion of the γ (t) curve

- Then a straight plot of the mean jerk is obtained between these two points by the method of least squares. The curve was divided up for this purpose into 20 to 25 sections of equal curve length.

This method proved to be well suited to the graphs obtained; care had to be taken, however, concerning the scales employed. These must remain in a constant ratio whatever test is involved. In our own study, it was such that: 1 g corresponds to 25 x 10^{-5} seconds on the graph.

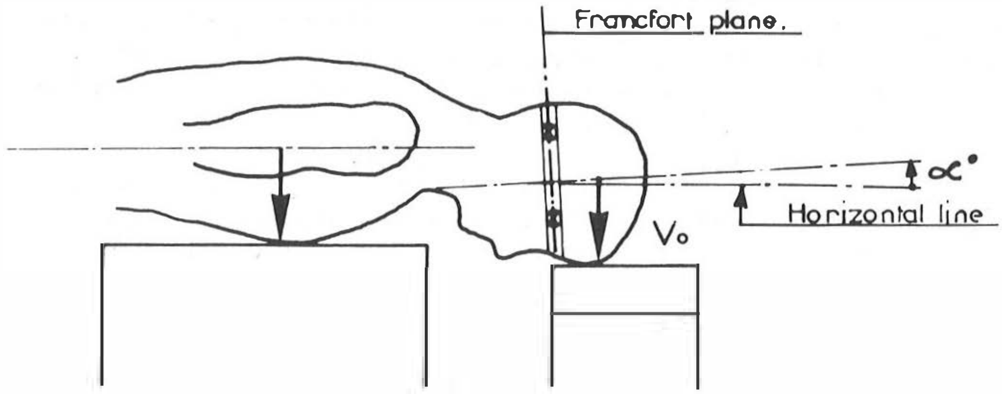
6°) Definition of the materials used to decelerate the heads of human subjects - The aim was to obtain different jerks whilst applying maximal accelerations (and HIC) as nearly equal as possible. The type of material used to decelerate the head was crushable phenolic foam with a density of 40 g/l. Two types of jerk were produced:

- high jerk values were produced with a parallelipipedic block 300x250x8 cm, covered with plywood of the same size and 2 cm thick, which was intended to distribute the impact pressures;
- moderate jerk values were produced by placing two liners of polystyrene foam, (density 15 g/l) and 1.5 cm thick over the plywood used for severe jerk. These polystyrene liners were of the same surface as the block.

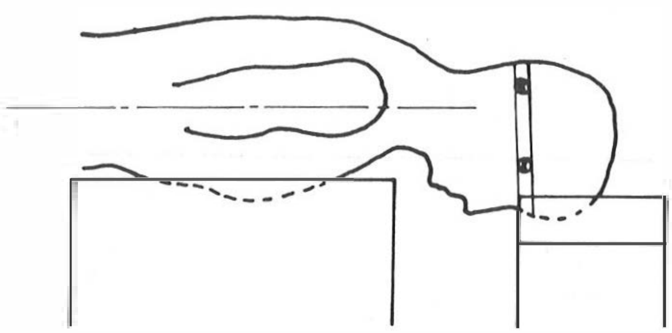
2. RESULTS - These are summarized in the Table 2.

1°) Kinematics of the head and neck - This is shown in Figure 1. In general, the kinematics of the head can be described in two phases as follows:

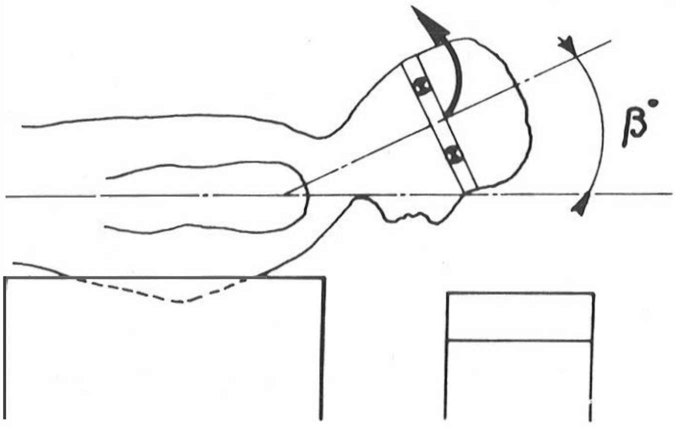
- a vertical descent of the head with no noticeable rotation from the original direction. It is during this phase, which last some 5 ms, that maximum acce-



a) Head contact



b) Maximum intrusion of the head in the padding (moderate jerk)



c) Head rebound

FIG.1. **Head kinematics**

leration is reached.
- Then, during the rebound, a slight backwards rotation of the head is observed. This never exceeds 10° from the horizontal. It is combined with movements of the head relative to the body which are well below the natural limit of hyperextension: the maximum value noted was slightly less than 30° (angle β, Figure 1-c) of movement between the head and thorax.
- Two special cases were observed from analysis of the films. These were subjects No. 163 and 165, the head of whom was slightly tipped forward during the descending phase. This tipping movement resulted from a shift of the shock-absorbing material, the back of which was not attached to the dynamometric balance firmly enough. This had the effect of increasing the stopping distance of the head and hence of reducing the levels of acceleration reached: this point will be taken up in our analysis of the results.

Variations of the speed of the heads of human subjects as determined from these films were of the order of 10 m/s for an impact velocity of 7.8m/s. During the rebound, the angular velocities remained mostly below 30 rd/s and the angular accelerations did not exceed 7000 rd/s (except 3 ms). From published data (11)(9)(10), one may suppose that the rotatory phase did not result in injuries. In the present series of tests, the cerebral lesions noted could be related to the linear accelerations measured. Besides, no brain injuries were recorded for the subjects which sustained the highest ω and ω' values.

2°) Analysis of the injuries - a) Lesions of the neck. No bone or medullary injuries were observed.

b) Injuries of the skull and face - Only one subject presented fractures. This was subject No. 166, part of whose nose was involved in the impact. Fractures of the nose bones, the eye sockets and the upper jaw-bone were noted, as was a slight linear fracture of the left parietal. The maximal force applied to the head, which was not out of the ordinary when compared with the other tests, did not explain these fractures. Use of the relationships:

$$\frac{\text{skull mass}}{(\text{circumference of head})^2} \quad \text{and} \quad \frac{\text{skull mass}}{(\text{circumference of head})^3}$$

which can be considered to be linked to the "mean" thickness, and the "relative mean thickness" of the skulls, did not shed any light either. Characterization tests of the skulls of the experimental subjects (mineralization, static flexion and shearing tests) delivered normal results. May be, the facial fractures weakened the skull.

c) Cerebral lesions - Further details concerning the injuries of each subject are given in Table 2. Out of the 11 subjects for whom a prognosis of injury had been established, 7 were uninjured, 3 presented injuries of degrees 2 or 3 of the AIS scale (12) and 1 presented an AIS of 4.

The injuries found were all localized in depth into the brain stem, especially around the pons, except for those of subject 175 (see Table 2). No injuries were found sub-jacent to the point of impact.

3°) Results of measurements - The main parameters used in the analysis are given in the Table 2.

a) the relationship between the injuries and the accelerations - The wide scatter of the results can be largely attributed to anthropometric differences between individuals. We did not find any close relationship between the maximum values of head accelerations (peak or 3 ms) and the severity of cerebral injuries expressed as AIS. This confirms the results obtained elsewhere and already published, concerning cerebral injuries in the absence of fractures of the skull (1). This does not imply that no conclusion can be reached from the

γ(t) pulse, but only that the maximum values obtained were not able to account fully for the severity of the injuries. The matter could be further investigated by using data relating to the dimensions and mechanics of the skull.

10 out of the 11 subjects taken into account by the analysis presented an AIS $\leq$ 3, 9 presented an AIS $<$ 3.

For all subjects with an AIS 3, the arithmetic mean of the maxima of the resultant acceleration was 205 g (139 g for 3 ms). These figures are 170 g (116 g for 3 ms) as regards AIS $<$ 3.

For the 7 subjects who escaped injury to the head, the maximum resultant acceleration fell between 180 g and 240 g (mean 217 g); the maximum level reached over 3 ms falling between 122 g and 165 g (mean 141 g).

b) The relationship between the injuries and the SI and HIC in the various tests - As we have already pointed out (1), no simple relationship was evident between these parameters, taken isolately, and the severity of the injuries expressed in terms of AIS.

However, the sum of the results published does show that the absence of any correlation between the AIS and the HIC does not preclude the use of the HIC in the prediction of the likelihood of noticeable cerebral lesion. This point will be gone into later.

A single case of AIS = 4 (subject 174) was noted with an HIC of 1620.

The HIC value 1500 was exceeded or reached in two other cases by subjects 176 and 177 who incurred no injury and for whom the HICs were respectively 1500 and 2138.

These results confirm that in case of impact, if the HIC is below 1500 (2)(4), there is very little likelihood of injuries. However, one subject (No. 163) presented both a low HIC (750) and slight injuries, of AIS degree 2 or 3. These results are taken up in the discussion of the possible influence of the jerk on the extent of lesions.

c) The influence of jerk - General remarks:

- The Figure 2 shows the general outline of the γ (t) pulses corresponding to jerks described as "moderate" and "high" below.

- The slower rise of the moderate jerk curve can be explained by the fact that the very high jerk padding had a less stiff material placed over it.

- The jerk referred to as "moderate" corresponds to values of about 0.5 x 10^5 g/s. In a series of experiments previously described (1), this level was reached during tests of frontal impacts on human subjects wearing a helmet of which the front part contained 3 cm of polystyrene foam liner.

- Levels of 10^5 g/s and over were obtained with the "high" jerk. In the above-mentioned series of tests, these levels were attained by subjects wearing a helmet, performances of which had been shown to be insufficient or deteriorated by the effect of nearness of the shell edge.

- The time intervals taken into account in the calculation of the jerk (of the Δ T type shown in the Figure 2) lay between 2.2 ms and 5.4 ms for the "moderate jerk", and between 0.5 and 1.1 ms for the "high" jerk. These values obviously diminished as the jerk level rose.

- 2 series of jerks were performed for γ and HIC values as close as possible. Here then, we obtained independence of the jerk from the other parameters usually taken into account in the estimates of tolerable levels.

The jerk, then, is not considered in terms of these parameters. Furthermore if we have no found any relationship between the jerk versus the severity of the cerebral injuries in terms of AIS, then some observable phenomena should be discussed:

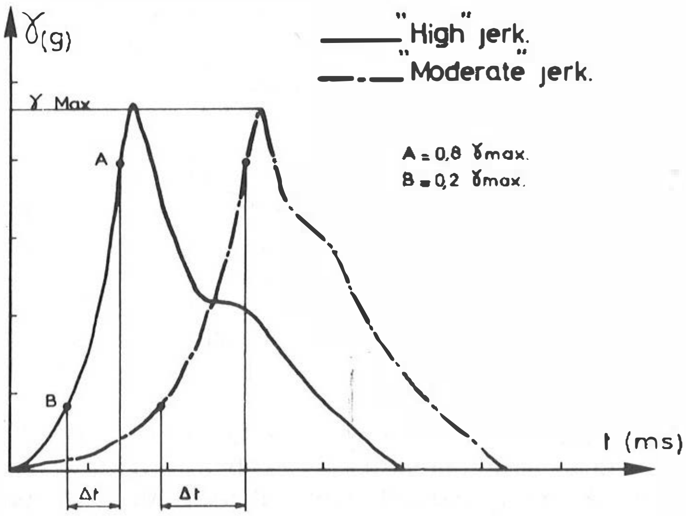


FIG.2 Typical head deceleration pulses for an high value and a moderate value of the jerk.

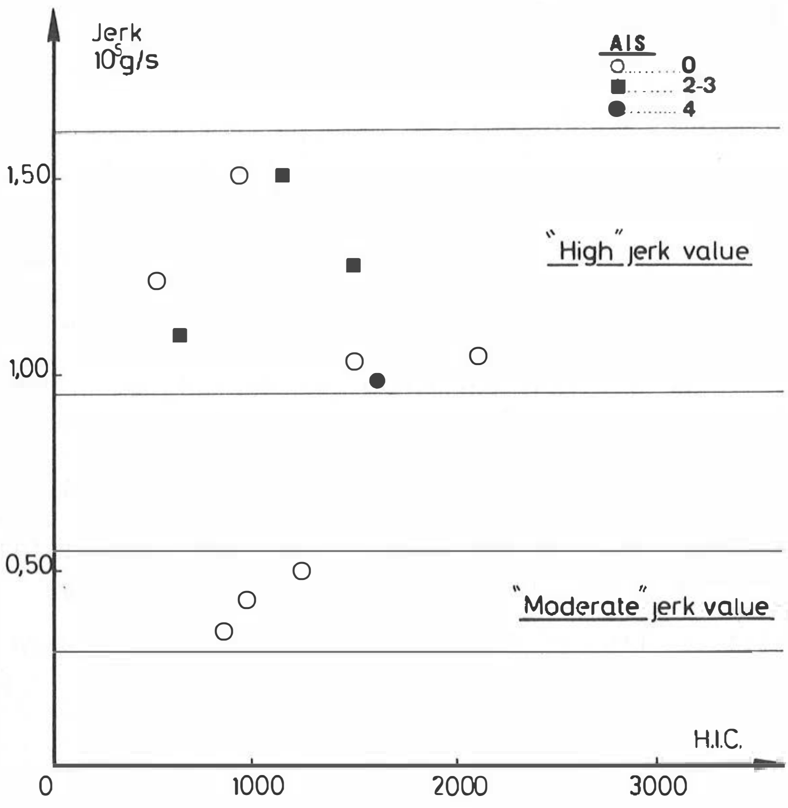


FIG.3 Cerebral injuries shown in a(HIC, Jerk) plane.

- the highest jerk found in the absence of injury was around 1.5 x 10^5g/s (subject 172).

- Inversely, the lowest level of jerk associated with injury was around 10^5g/s (for subject 174) who had had to undergo the highest γ 3 ms (170 g).

If all the tests in which there were injuries of an AIS below 3, and in which the jerk had been greater than 10^5 g/s are taken into consideration, then the arithmetic mean of the jerks became 1.2x10^5g/s.

The influence of the jerk cannot be interpreted independently of the other physical parameters used to assess the severity of cranial impact. If we look at the HIC and the severity of injuries in the Figure 3 in which the jerks are given, then there does not seem to be any simple relationship between the jerk and the severity of injuries for any one class of HIC.

This is not surprising because jerk is only one of the many parameters which describe the state of loading experienced by the head in the impact. Our intention is to determine in which conditions the jerk is a parameter capable of increasing the severity of injuries. In this light, the following remarks can be made:

- In the case of the "high" jerk, or 10^5g/s to 1.5 x 10^5g/s and with the HICs sustained, 1 subject out of 2 presented cerebral injury (Figure 3). These injuries were slight (AIS 2 or 3) except for subject No. 174 whose injuries were classed as AIS 4.

In this range of jerk level, subject 163 alone combined a relatively low HIC (750) with injuries classified between 2 and 3 on the AIS scale. Several hypotheses can be advanced to explain the lower tolerance of this subject:

- a skull with less favourable bone characteristics; characterization tests of the skull did not confirm that up.

- Some influence of the jerk, which was relatively high (1.17 x 10^5g/s) for these values of HIC.

Only a large number of tests would permit one to conclude.

3. DISCUSSION - The results obtained made it possible to precise human tolerances of which the transposition to dummies and headforms should be envisaged.

In general, the conclusions presented concerning the influence of a parameter on the head injuries give only an underestimate of the tolerance towards this parameter, because they are obtained with cadavers which are, a priori, more vulnerable than living persons.

Besides, whatever the physical parameter considered, we attached particular importance to the observation of uninjured subjects, whenever their number was not negligible in comparison with the number of tests performed.

This decision is explained by the frequent impossibility of using a rigorous definition of tolerance such that to a given value of the parameter, there corresponds an AIS $<$ n (or $>$ n) for p% of subjects sustaining this value ("n" and "p" demand a consensus, generally n = 3 or 4 and p = 50 % are taken).

This impossibility is true of the jerk tests for which we have only one case of AIS = 4 and no AIS = 5, and so no statistical analysis is possible. In such circumstances, the uninjured subjects are to be examined to determine the thresholds at which significant injury appears; this step is complementary to the definition of the probable tolerance, which is inevitably higher.

4. CONCLUSION CONCERNING THE INFLUENCE OF THE LINEAR ACCELERATION JERK ON THE HUMAN HEAD ON THE EXTENT OF INJURY - On the basis of the small number of tests performed, it seems to be neither necessary nor possible to define a supplementary criterion of tolerance linked to this other function of γ(t), as

long as the condition HIC $\leq$ 1500 is satisfied, because of the slight severity of cerebral injuries observed, even with an HIC value close to 2000, and maximum associated accelerations of 230-240 g (150-160 g for 3 ms). However, in the context of protection of the head from direct impact, and to avoid the possibility of error in the selection of paddings, it could be checked that the human head does not have to undergo a jerk of more than about 1.2×10^5 g/s. This value corresponds to the arithmetic mean of jerks $\geq 10^5$ g/s with an AIS$\neq$0, but here $<$ 3.

In the absence of skull fracture, these conclusions are applicable under the following conditions: moderate angular accelerations and angular velocities, HIC calculation times of between 4 and 8.5 ms. Furthermore, the variation of head speed associated with the impact is of the order of 10 m/s. As a reminder, the acceleration sustained by the head in these tests is due to the impact alone. The case is different for the car passengers, restrained by seat-belts in frontal collisions (neck action). Results of this study are not applicable to them.

II - CONTRIBUTION OF THIS STUDY INTO THE RELATIONSHIP HIC/CEREBRAL AIS

1. Reminder of litterature data: let us refer to the data summarized by NEWMAN at the 24th Stapp Conference (2). If we eliminate from this analysis [(2), fig. 1] all results not directly related to the tolerance of human brain in case of impacts, i.e:

- -results obtained from mathematical models,
- -results obtained by accident simulation with dummies (Sierra adult or child),
- -results obtained with facial impact to the human head,
- -and results relating to one exceptionnally thin-skulled subject [(1), test 107] because of his poor representativity, we find the following result:

apart from one exception (AIS=4, HIC=1400), a very localized impact in which the human head, equipped with helmet, fell 2.5 meters onto a hard hemisphere, 10 cm in diameter (1), there was no cerebral injury of AIS $>$ 3 with an HIC $\leq$ 1500 (fig. 4).

Note: there were two cases of AIS = 3 associated with HICs of 600 and 1000 respectively. In the former case [(1), HIC = 600] which was not one of our own sample, more information is needed to explain the results (notably concerning the skull characteristics, etc.) In the latter case (HIC = 1000), hyperextension of the head was noted, and this may have aggravated the injuries [(1), test 143].

2. Results from this study or from other recent publications - Taking into account not only the data obtained in the jerk tests described above, but also those recently published and not included in NEWMAN's analysis (3)(4), the same conclusions are reached (Fig. 5) on the basis of a sample of 53 tests carried out on fresh, perfused cadavers equipped with instruments.

3. Conclusions concerning the HIC/Cerebral AIS relationship - Summarizing the above data, and whilst awaiting further data to get enabled to distinguish the influence of each parameter and to define a function derived from the $\gamma(t)$ pulse sufficiently correlated with cerebral injuries, we can see that for HIC $\leq$ 1500, there is very little probability of cerebral injury (in any case less than 50 %), and that higher HIC values may often be sustained by the human head from frontal or lateral impact without any serious injury.

In consequence, although HIC is neither rigorously defined, nor sufficiently correlated with cerebral injuries, we do believe that it can be used

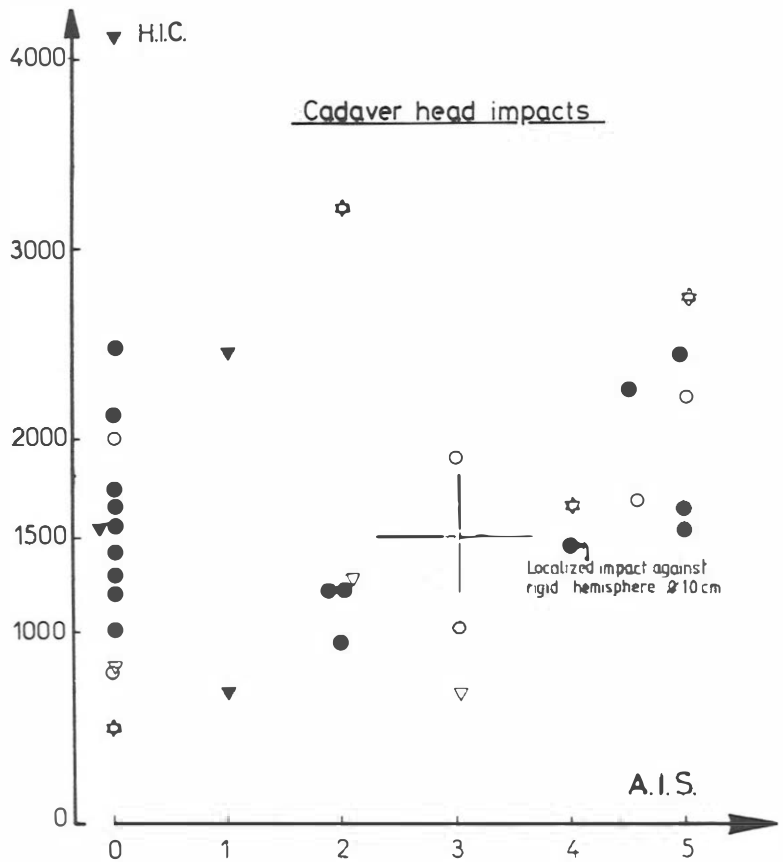


FIG.4. HIC versus AIS . Reference: Newman 24th stapp

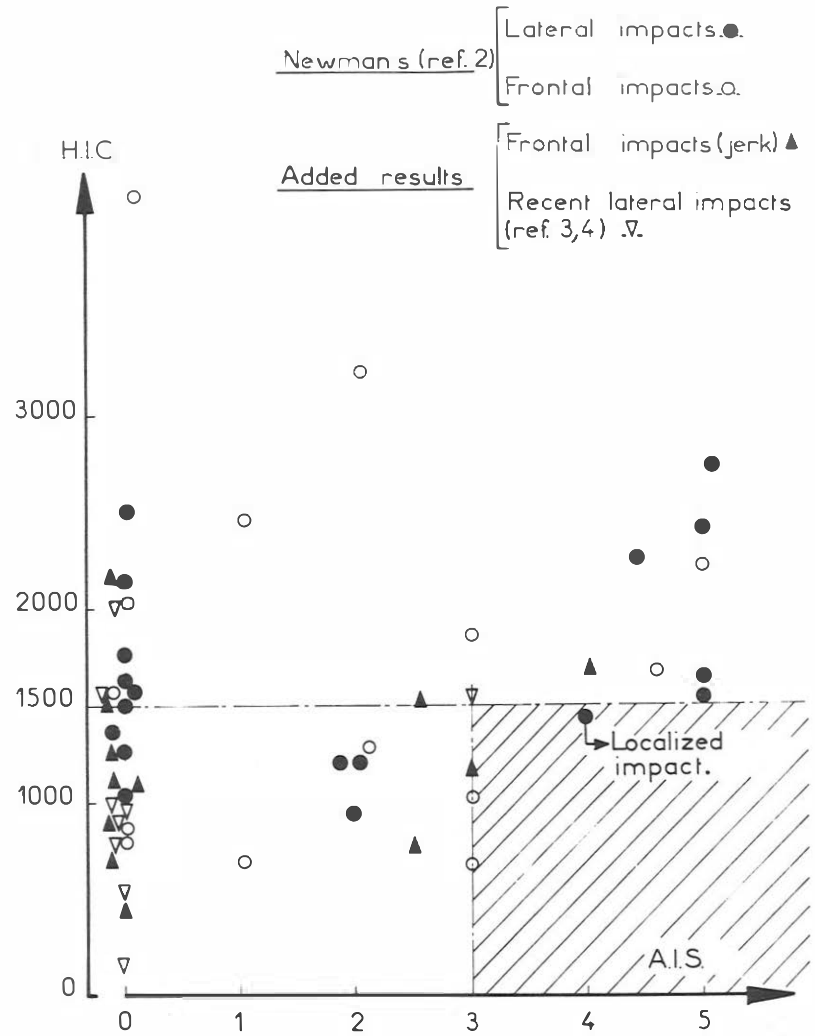


FIG. 5 Like fig 4 with supplementary tests reported

as a limit for human tolerance, and that a level of 1500 is acceptable since it has been obtained from human subjects who generally provide only an underestimate of the tolerance of living human subjects exposed to the dangers of accident.

This conclusion is related to the human head tolerance when impacted, when the main cause of measured acceleration consists of the external contacts.

Acknowledgements

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TABLE 1 - CADAVER ANTHROPOMETRIC DATA

Test No	Age	Sex	SKULL DIMENSIONS (cm) Length	Breadth	Circumference	WEIGHTS (kg) Head + Neck	Head	Skull	Brain
159	60	M	20.5	16	60.6	5.61	4.41	0.995	1.54
160	56	M	20.6	16.2	57.2	5.45	4.25	0.975	1.48
162	64	M	19.2	15	54.4	4.86	3.62	0.636	1.19
163	63	M	20	17	59.4	6.56	4.59	0.785	1.45
165	66	M	20.5	15	57.5	5.95	4.31	0.93	1.36
166	59	F	18	15.2	56.4	5.14	4.10	0.688	1.6
172	50	M	19	17	57.5	5.4	4.17	0.69	1.34
174	65	M	18.5	16	55.3	4.78	3.96	0.76	1.05
175	73	M	20.5	15.5	53.6	4.27	3.22	0.785	1.22
176	53	M	20	16.5	57.4	5.69	4.26	0.80	1.6
177	64	F	19	15.5	53.6	4.24	3.30	0.67	1.28

TABLE 2 - RESULTS OF FRONTAL IMPACTS ON CADAVER HEADS - FREE FALL HEIGHT: 3 METERS

Test No	JERK Type of jerk	Value 10^5 g/s	Duration of calculation	HEAD RESULTANT ACCELERATION γ max (g)	γ 3 ms (g)	HIC Value	Duration of calculation	CEREBRAL INJURIES	AIS
159	moderate	0.415	3.3 ms	214	117	1078	4.5 ms	no injury	0
160	moderate	0.32	5.4 ms	180	135	1378	5.7 ms	no injury	0
162	moderate	0.518	2.2 ms	192	132	1334	5.5 ms	no injury	0
163	high	1.17	0.7 ms	150	102	750	6.2 ms	very little hemorrhage in the brain stem	2 or 3
165	high	1.25	0.5 ms	163	109	691	6. ms	no injury	0
166	high	1.588	1.1 ms	212	132	1270	5.9 ms	little extravasation in the pons	3
172	high	1.523	0.9 ms	201	101	1042	4.3 ms	no injury	0
174	high	0.996	1.4 ms	230	170	1620	5.7 ms	some extravasations in the pons	4
175	high	1.30	0.9 ms	190	130	1500	5.3 ms	little hemorrhages: right anterior hypocampus + left posterior quadrigeminal tuberculum	2 or 3
176	high	1.00	0.9 ms	240	140	1500	5.5 ms	no injury	0
177	high	1.14	0.9 ms	255	168	2138	4.8 ms	no injury	0