ROTATION - TRANSLATION DUALITY IN HEAD TRAUMA ?
PERCEPTIVE AND OBJECTIVE EVIDENCE

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ABSTRACT

Brain - skull displacement in case of head trauma has frequently been quoted in the literature. The common lesions linked with this relative movement mechanism are focal contusions and subdural hematomas (SDH). Specialists also agree that an angular acceleration of the head can cause intra-cerebral shearing and constitutes a lesion mechanism of the diffuse axonal injuries (DAI). The specific type of shock which releases one or the other of these mechanisms has not been studied in depth and has often been attributed to the angular or linear preponderance of the acceleration. In our earlier work we tried to describe the dynamic behaviour of the head. In vivo mechanical impedance recordings of the head revealed a de-coupling of the cerebral mass at about 100 Hz. In this study we have consolidated this result by low amplitude frequency by frequency vibration analysis of four voluntary subjects. The proposed analysis makes it possible to distinguish between the two lesion mechanisms, based on the temporal or frequency characteristics of the impact force. This position is illustrated by interpreting various observations given in the literature, which until now could not be explained.

INTRODUCTION

The preparation and evaluation of head protection systems under shock situations require a thorough knowledge of the "object to be protected". Biomechanical Research on shocks applied to the head, carried out within the biomechanical systems Laboratory of Strasbourg University (URA CNRS 854), have contributed to a better understanding of the in vivo dynamic behaviour of the head. It would seem that the optimisation of the protection systems require a comprehensive knowledge of lesion mechanisms and especially of lesion mechanism changes as a function of shock characteristics.

Although the lesion parameters to be considered for the various mechanisms are obviously not the same, this lesion mechanism change has not been taken into account in any test standard. To the best of our knowledge, no in-depth study has been proposed on lesion mechanism changes and the only generally accepted distinction is based on the "translation-rotation" duality of the nature of the applied shock.

The objective of this study is to reconsider the validity of this duality at a time when several laboratories are endeavouring to develop devices for measuring the angular acceleration of dummy heads. In general, a shock which causes a head rotation is assumed to create an intra-cerebral stress field which is at the origin of diffuse lesions known under the name DAI (Diffuse Axonal Injuries). Moreover, a pure translation shock is said to cause focal lesions such as cerebral contusions and sub-dural haematoma (SDH), this time due to the brain's mobility within the skull. Only these two lesion mechanisms will be considered in this study.

This mechanism change or this "translation-rotation" duality has already been described in the literature. Thus Stalnaker [1] focused on rectilinear shocks, but always of short duration, and Tarrière [2] studied the head rotation of a boxer subjected to a much longer impulsion. As the head rotation is only a cinematic consequence of a long shock and a pure translation is generally induced by a brief shock, it would seem interesting to imagine the consequences of a very brief head acceleration or a translation impulsion lasting several tens of milliseconds.

Epidemiological observation [3] informs us that in the case of a fall, DAI as well as SDH and contusions can be observed, whereas the main component in these cases is a translation and not a rotation. Here also, the influencing factor is the hardness of the impacted structure, thus the shock duration. The animal experiment published by Thibault [4] proposes an abrupt head rotation of a large number of monkeys. Here again the autopsy sometimes reveals SDH, contusions or DAI, thus showing that not only the preponderance of rotation does give DAI.

Through these examples, it would appear that the preponderance of the rotation or translation component of a shock is not enough in itself to predict the lesion mechanism which will be released. This study proposes to reconsider the "translation-rotation" duality in order to propose a lesion mechanism change criteria linked to the dynamic properties of the human head.

Firstly, the principles of modal analysis will be discussed, since these are the key of the method used. The following paragraph is devoted to the in vivo vibratory analysis of the human head under continuous excitation, in order to illustrate the brain-skull de-coupling. In the discussion, the results and lesion mechanism changes suggested by the latter will be analysed and compared with studies from the literature.

METHOD

Modal analysis is the technique used to describe the theoretical or experimental dynamic behaviour of the head. Its modal behaviour is characterized by the structure's modal properties. Each mode of vibration is defined by its natural frequency, mode shape and its damping. These intrinsic structure data are the base for calculating its dynamic behaviour under vibratory or shock conditions. From the experimental viewpoint, the method depends on studying the transfer function between the exciting force and the structure's response. This transfer function or mechanical signature, can be defined in terms of apparent mass, mechanical impedance or receptance, provided that the response recorded is respectively acceleration, velocity or displacement. The punctual mechanical impedance is then the ratio between the force and displacement velocity of the structure point considered, expressed in the frequency area by the Fourier transform.

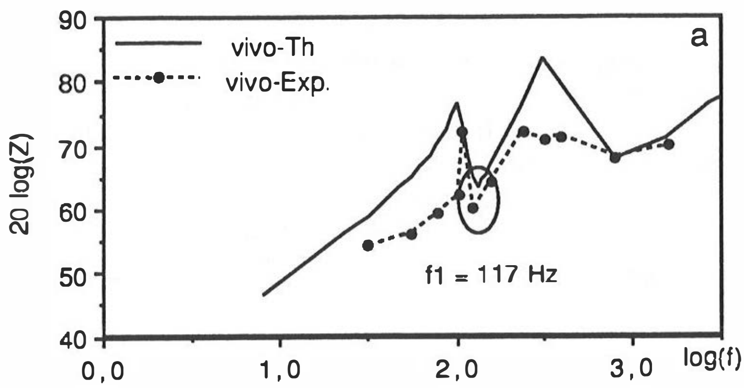
In the general case of a continuous deformable structure, the global description requires studying a large number of transfer functions between the impacted point and various points of the structure. For a given natural frequency, the amplitude and phase of these transfer functions make it possible to construct the corresponding mode shape. For a given degree of freedom, the structure can be characterized by its behaviour according to a particular direction. In this case, a single transfer function (or a single mechanical impedance) is sufficient to inform us about the natural frequencies, damping and de-coupled modal masse for this direction.

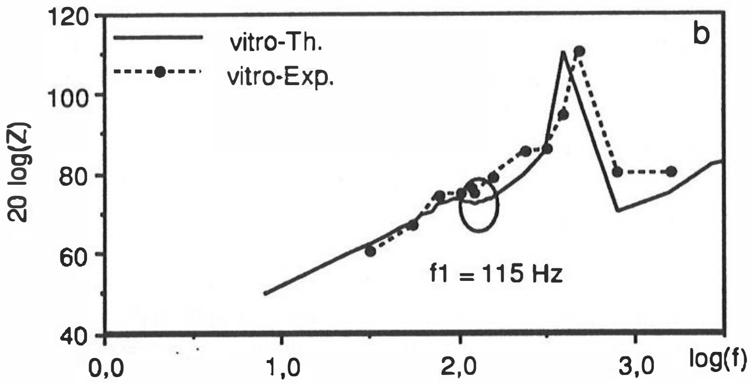
In practice, it is a matter of applying a moderate intensity impulse to the frontal bone by means of a hammer fitted with a force tranducer. The response is recorded by a piezo-electric accelerometer placed near the impact point. These two signals are expressed in the frequency area by their Fourier transform. The punctual mechanical impedance is calculated after integration of the acceleration signal. The frontal punctual impedance recorded on a human head in vivo serves as a reference base for validating the theoretical model. The natural frequency, damping, and de-coupled modal mass in accordance with the anteroposterior direction, serve as objective reference parameters in the validation process. The objective is then to prepare theoretical models able to reproduce the same modal behaviour as the human head.

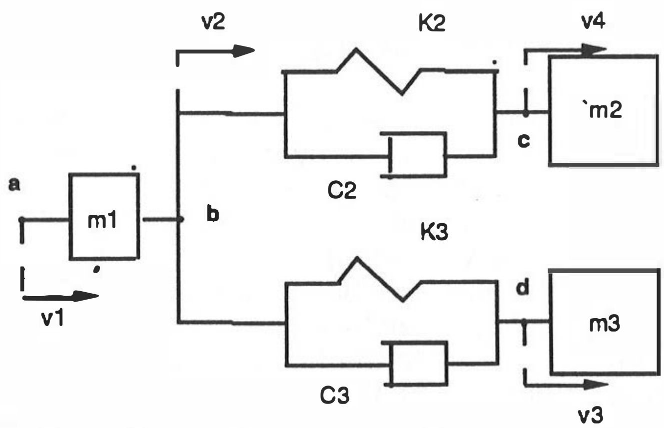
In this study the impulsion analysis is completed by a continuous vibratory one. Excitation by frequency scanning is provided by a shaker fitted with a transducer. The head response recording is always carried out by measuring the frontal acceleration, and the signal processing is identical to that used during the impulsion study.

VIBRATORY ANALYSIS OF THE HEAD

Vibratory analysis is the only non-destructive investigation method able to supply information about the head's dynamic behaviour. In their respective analysis, Hodgson in 1967 [5] and Stalnaker in 1971 [6] concerned themselves with the natural frequency due to skull deformation around 900 Hz and did not take into account the natural frequency recorded around 120 Hz. In an earlier study [7, 8, 9], the in vivo mechanical impedance of the head recorded by the impulsion method, made it possible to reveal the relative brain-skull movement once the shock duration was short enough to excite the head's first resonance frequency at about 120 Hz. These experiments were the basis for a spring mass model whose particularity is to distinguish the cerebral mass m_2 from the other masses present (see figure 1). More recently, in 1992, Troseille and Tarrière [10] proposed an analysis analogous to ours in 1990, and concluded that the human brain starts resonating in the skull at about 120 Hz.







head	m1 kg	m2 kg	m3 kg	K2 N/m	K3 N/m	C2 Nm/s	C3 Nm/s
vivo	0.4	1.6	2.2	0.7E6	10E6	200	1500
vitro	0.8	1.7	3.6	0.7E6	25E6	600	70

Figure 1 : Mechanical impedance curves and lumped parameter model of the brain and skull. Mass m1 simulates the frontal bone, m2 the brain mass and m3 the rest of the head.

Our experimental impulsion analysis results proposed in 1990 [7] are completed in this report by a frequency by frequency vibratory analysis. The objective is to note down the sensations perceived during excitation and detect the excitation amplitude limits before causing any discomfort or unpleasantness to the volunteer.

The experimental procedure consists of asking the volunteer to stand up and put his forehead against the vibration exciter. The transducer is positioned between the forehead and the piston, and the accelerometer is fixed on the back of the piston. The subject deliberately applies a certain force on the piston to ensure a good piston-head contact. For a given sinusoidal vibration frequency, the volunteer himself then increases the amplitude of the piston movement until he experiences discomfort or unpleasantness. This operation is then repeated in steps of 10 Hz for frequencies between 30 Hz and 300 Hz and steps of 50 Hz between 300 Hz and 1000 Hz. The maximum force and acceleration at each frequency are shown and the subject describes the sensations perceived.

Before giving the results, it is important to point out that, due to the difficulties associated with in vivo tests, the head-piston contact is no longer assured at high frequencies. Moreover, at low frequencies, this contact is subjected to interactive forces in excess of the head's weight. These forces are due to the deliberate action of the subject who presses his head on the piston by contracting the neck muscles. These comments imply that the apparent mass curve of the head obtained by these tests will necessarily be erroneous. It should be remembered that these pre-tests are only intended to analyse the sensations perceived by the subject at each frequency and to estimate the limits above which the subject would experience discomfort or unpleasantness. This test was carried out on four volunteers and the results are given in table 1 and figure 2.

Figures 2a and 2b give respectively the maximum force and acceleration recorded at each frequency, for the 4 subjects. Concerning the maximum applied force (figure 2a), a dispersion between the subjects can be seen, but it appears that this maximum force does not change very much with the excitation frequency. In the case of continuous excitation, the order of magnitude of the maximum forces which should not be exceeded is about 10 N.

The maximum acceleration change, as a function of excitation frequency (figure 2b), shows much more perturbance. Dispersion between the different subjects is considerable, but it is quite clear that there is a continuous increase in "supported" acceleration with frequency and a very sudden increase between 100 and 150 Hz. Considering that the force is virtually constant, this result signifies that the masses put into motion diminish with frequency. This is illustrated by the apparent mass curve in figure 2c.

The sensations expressed by the subject during these tests are synthesised in table 1 with the order of magnitude of excitations that should not be exceeded. Three distinct types of sensations were experienced for three more or less clearly defined frequency ranges. At "low" frequencies (30 Hz to 120 Hz $\pm$ 30 Hz) the excitation is the most difficult to support. Maximum accelerations are about 30 ms^{-2} and displacement amplitudes of about a millimetre. Nausea type sensations are experienced in exactly the same way as when the head is volontarely and vigorously rotated. The subject also clearly feels that the vibration is transmitted to the gums and ocular muscles.

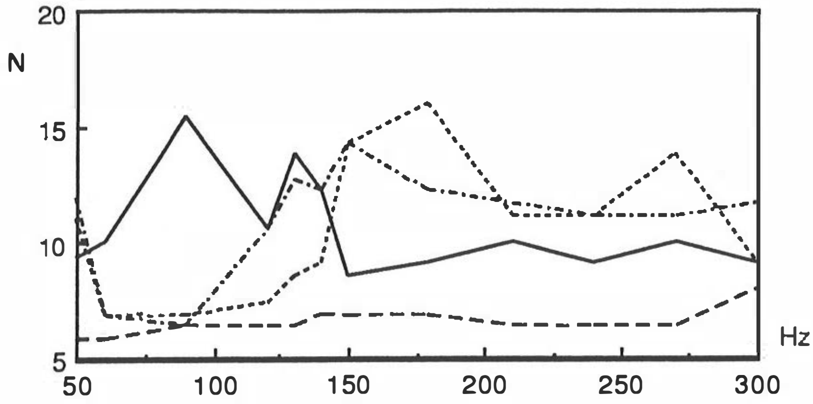


Figure 2 a : Maximum exciting force recorded at each frequency before causing any discomfort or unpleasantness to the volunteer.

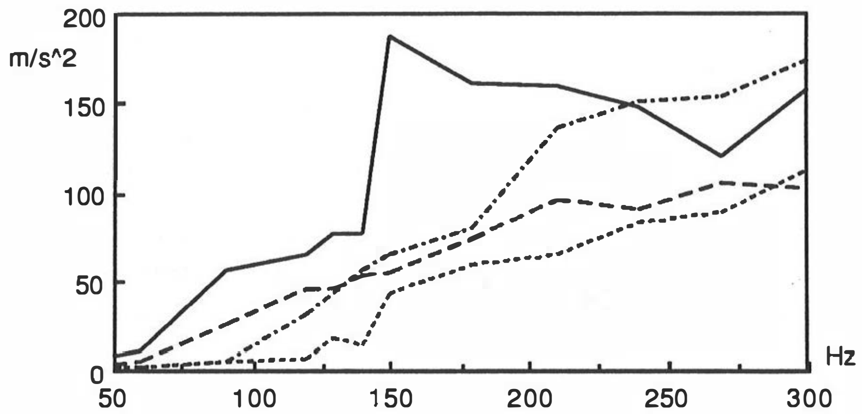


Figure 2b : Maximum acceleration recorded at each frequency before causing any discomfort or unpleasantness to the volunteer.

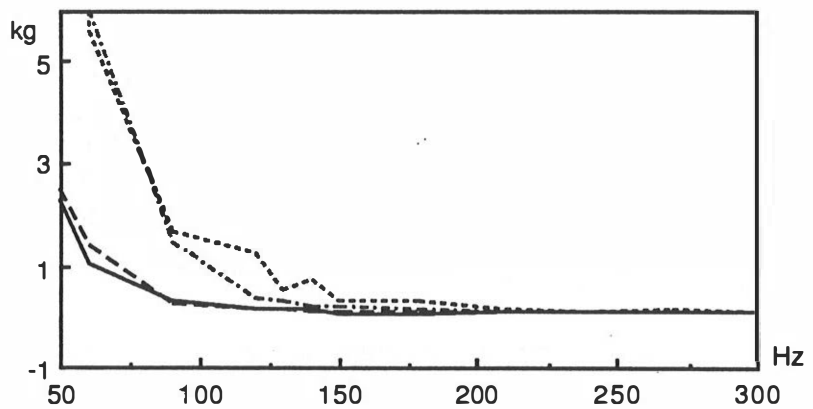


Figure 2c : Ratio between "supported" force and "supported" acceleration given as an apparent mass. Note that the mass put into mouvement diminish with frequency.

At "medium" frequencies (120 ± 30 Hz to 300 ± 50 Hz) the vibration gives a humming sound without any other sensation during the test. The maximum acceleration here, is limited to about 75 ms^{-2}. This limitation comes from the bearing point on the forehead, which because of its small size becomes uncomfortable. The displacements are only a few tens of millimetres. After the test, the subject feels a slight "instantaneous" dizziness lasting about one or two seconds.

At high frequencies above 300 Hz ± 50 the "supported" acceleration becomes important (up to 150 ms^{-2}) and apart from the noise that is heard but which does not cause any discomfort, no other sensation is felt. Displacements are less then a tenth of a millimetre.

The interpretation and significance of these results will be given during the discussion. In what follows, the vibratory analysis of the head is extended into the 30 - 300 Hz frequency range in order to focus on the brain-skull de-coupling phenomena. For this second tests procedure, the head is fastened to the piston with a rigid ring and the sinusoidal excitations are maintained at 50% of the maximum values given in table 1. The objective here is to record an apparent mass curve of the head at rest, by sinusoidal scanning. Only one volunteer has been tested up to now, and the only sensation expressed was a slight noise.

Table 1 : Sensations experienced by volunteers under continuous vibratory conditions and maximum excitation parameters before causing any discomfort or unpleasantness.

Frequency Range [Hz]	Sensations	Maximum Force [N]	Maximum Acceleration [ms^{-2}]
50 - 100	Nausea, vibration of gums and eyes	~ 10	~ 30
100 - 300	Noise ; 1 to 2 seconds post-test dizzines	~ 10	~ 75
300 - 1000	slight noise	~ 10	~ 150

The Fourier transform of the exciting force by sinusoidal scanning is given in figure 3. The result of this test is shown in figure 4 and represents the transfer function of the head in terms of apparent mass. In the same way as the impulsion test, it appears that a de-coupling of about a 1kg mass takes place between 100 and 150 Hz. At low frequencies the head mass represents 3.9 kg and after resonance frequency, only a 2.8 kg mass is still put in motion.

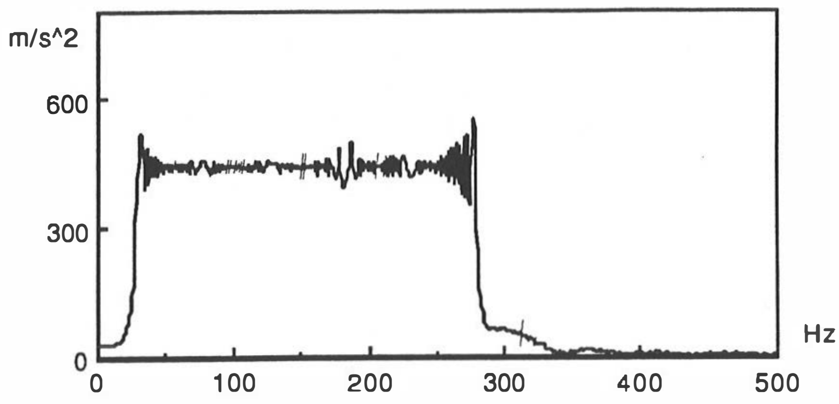


Figure 3 : Fourier transform of the exciting force in case of sinusoidal frequency scanning .

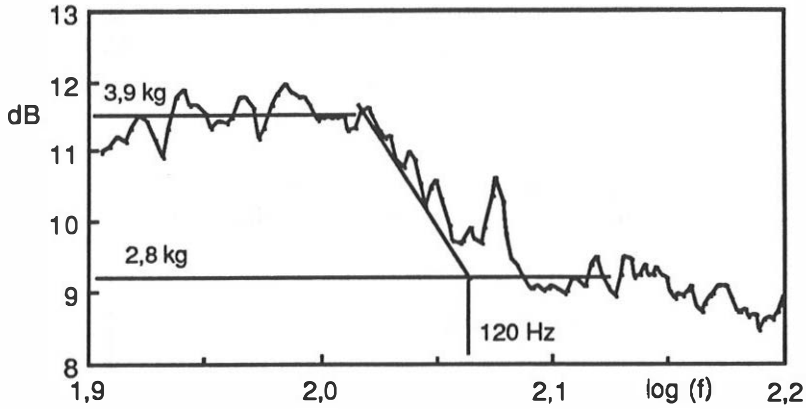


Figure 4 : Apparent mass of the head in vivo under exciting force by sinusoidal frequency scanning.

DISCUSSION

The discussion is centred around three axis. Firstly, it seems indispensable to reconsider the lesion mechanism changes suggested by figure 1 and the lumped model. This analysis will then be re-inforced in view of the vibratory study results of the head mentioned above. Finally, the third discussion point will be on the comparison of the proposed theory with the results from the literature.

Studies published since 1990 [7, 8, 9] have noted a change of lesion mechanism as a function of the energy distribution of the shock in the frequency area. When the energy of the shock spectrum is concentrated at low frequencies (less than 150 Hz), brain-skull de-coupling does not occur and the head as a whole is subjected to the same acceleration field (uniform or non uniform). This acceleration acts upon all the cerebral material in conformity with the equilibrium equation of a continuous medium subjected to an acceleration field.

$$\overrightarrow{\text{div}\,\Sigma} + \vec{f} = \vec{0} \qquad (1)$$

with:

Σ : the cerebral stress tensor

$\vec{f}$: the volume forces due to the acceleration $\vec{\gamma}$ $\quad \vec{f} = \rho \vec{\gamma}$ (2)

For this mechanism, the lesion parameter is the applied acceleration field (translation or rotation) and the lesions generated are intra-cerebral lesions distributed throughout the brain (DAI). In the case of a triangular impact, the energy remains concentrated below 100 Hz for shock durations exceeding 10 to 12 10^{-3}s. In case of no matter what impact shape is, the impulse duration by itself does not provide sufficient information and the Fourier transform of the impact must thus be analysed.

When the shock energy extends beyond the first resonance frequency (above 150 Hz), the brain-skull de-coupling appears, setting off the lesion mechanism related to the brain's movement within the skull, for both translation and sudden rotation cases. This mechanism is in conformity with the "rapid skull motion theory" given by Viano in 1989 [11]. Typically it causes SDH following bridge vein shearing, and focal cerebral contusions due to the contact forces of the brain against the skull. For this second mechanism, the head's acceleration is evidently not the lesion parameter. The displacement terms or brain-skull displacement speed terms would probably be more appropriate here. For triangular shock configurations, shock durations less than 10 to 12 10^{-3}s start this mechanism. Here again no matter what the shock shape is, the impulse duration does not give sufficient information and it will be necessary to have recourse to the Fourier transform of the impact force.

The proposed mechanism change has been validated in collaboration with the Road Accident Research Unit of Adelaide University [12]. These studies do not take account of impact energy or translation-rotation duality and very clearly show that the lesion type observed, depends above all on the nature of the impacted structure. In particular, this study has shown that the DAI are associated to soft shocks (below 150 Hz) and that focal lesions (SDH & contusions) come from hard shocks (above 150 Hz).

The validity of the "low frequency - high frequency" duality shown, is corroborated by the vibratory analysis on volunteers subjected to continuous vibrations. The results given above show that at low frequencies nausea is experienced when the brain is part of the masses put into movement. This proves that all the cerebral material was involved. In the case of high amplitude excitation, diffuse cerebral lesions could thus be caused. On the contrary, at high frequencies, when the brain is no longer in movement, the accelerations recorded only concern the skull. This explains why nausea is no longer felt. At these frequencies, it can easily be imagined that a high amplitude excitation could cause SDH type focal lesions or cerebral contusions. In this frequency range, the slight post test dizziness can be attributed to the excitation of the man's equilibrium organs, which are not mechanically linked to the brain, but to the otic bone, namely to the skull. In the third and highest frequency range, no information can be gleaned either because the head-piston contact is no longer ensured, or because the displacement amplitudes are too low (less than a tenth of a millimetre).

The last vibratory analysis stage of the head given in the previous paragraph shows that an excitation by focused frequency scanning between 50 and 300 Hz leads to the same result as the impulse analysis, namely brain de-coupling between 100 and 150 Hz. Lateral and occipital excitations have also shown up this resonance frequency at about 120 Hz, permitting confirmation that the brain-skull de-coupling phenomena can be initiated for all shock directions.

Before comparing the "low frequency - high frequency" duality with studies from the literature, it should be remembered that most of the authors are convinced of the validity of the brain-skull de-coupling phenomena, but the parameter initiating this process remained to be determined. Indeed the relative brain-skull displacement is often mentioned in the literature. For neuro-pathologists, it concerns evidence relative to the lesions observed. The bridge vein ruptures in the para-sagittal position which cause sub-dural haemorrhages, haemorrhage contusions of the frontal lobes in their interior part and at their contact point with the orbital floor are in evidence, to prove that this relative movement exists.

Biomechanics have had more difficulty in proving or measuring this relative movement for determining its importance under shock conditions. In the 1960's the important studies by Hodgson involved these phenomena by means of high speed X ray cinematography and were able to demonstrate this phenomena on live monkeys [13]. Löwenhielm [14] focused on this phenomena with the aim of setting the tolerance limits of this lesion mechanism. More recently, Viano [11] postulated the relative brain skull displacement as a possible lesion mechanism and called it the "Rapid Skull Motion Theory". This postulate which at the time seamed reasonable however lacked the theoretical and experimental basis to be able to estimate the importance of these phenomena and the conditions under which they appeared. In the past, certain studies either directly or indirectly, referred to a phenomena observed in the region of 100 Hz or for briefer shocks of less than 10 milliseconds. Let us firstly review the analysis done in the frequency area.

Hodgson in 1966 [5] and Stalnaker in 1971 [6] published mechanical impedance curves of human corpse heads showing a highly damped first natural frequency towards 100-150 Hz without giving details of this observation. Stalnaker [5] also published impedance curves of a head and then of a skull of a monkey. These curves clearly showed that a natural frequency at 100 Hz disappeared when only the skull was considered, thus proving that the cerebral mass is the origin of the phenomena. Both authors were interested in the crushing of the brain by bony matter deformation and not in the brain-skull de-coupling.

In the 1970's an original approach was proposed by Slattenschek [15] and Brinn [16]. The idea was to imagine a mass (the cerebral mass), excited by means of a spring and a damper. Then calculate the system's natural frequency so that under the shock limit given by the WSU curve, the mass displacement would not exceed a certain value x_{tol}. No information is required about the mass, spring, dumper parameters and the model is thus characterised by its only natural frequency f_o and its critical damping ξ. For a displacement limit x_{tol} of about 3.10^{-3}m, the WSU tolerance curve is respected with a simple mass-spring system whose natural frequency f_o is 101 Hz for Slattenschek and 76 Hz for Brinn.

In the early 1990's, the frequency characteristics of the head were the subject of more in-depth studies. In 1990, Willinger et al. [7] published in vivo mechanical impedance curves of the head with a lumped model distinguishing the cerebral mass from the other masses present. The brain-skull de-coupling phenomena was raised as well as the lesion mechanism change linked to this phenomena. In 1992, the mode shape of a finite element model of the head in its sagittal plane showed the same phenomena around 150 Hz (Willinger et al. [17]).

In 1991, Ruan and King [18] proposed a finite element model of the head in the frontal plane; the calculated natural frequency was about 80 Hz.

In 1992, Tarrière et al [10] expressed the fact that the brain has a resonance frequency at 120 Hz and their work on the General Motors' bi-dimensional finite element model gave a natural frequency of about 98 Hz.

The latest study to be classified under the frequency analysis heading is the one relating to the "Bimass 150" dummy head and which deals with the preparations and validation of a physical model of the head whose first natural frequency is established at 150 Hz (Willinger et al 1993 [19]).

The brain-skull de-coupling at 100 Hz can also be shown by considering temporal shock studies applied to the heads of human corpses or monkeys. The oldest illustration of the phenomena is most likely the WSU curve. On these curves resulting from "limit" shocks applied to human corpse heads, everybody could see that the "tolerated acceleration" suddenly increases for shock durations less than 8 ms. The explanation of this observation is that for these brief shocks, the energy spreads out above 120 Hz and the acceleration recorded is then only relative to the skull itself.

In 1977, Stalnaker [20] made a very interesting observation which can be explained by the brain-skull de-coupling phenomena for short duration shocks. He studied the temporal response of the head to an impact and noted a non-linearity in the relation linking the maximum impact force to the maximum acceleration of the head. The non-linearity is shown by two lines which depict the mass put into movement. This non linearity is observed at shock duration times in the region of 10 ms. In conclusion, the author points out that the head "does not have a constant mass" or that the head behaves like a group of masses which when subjected to a shock start vibrating relative to each other. To these more qualitative than quantitative analysis from the literature can be added a temporal study of monkey heads which particularly illustrate the proposed "low frequency - high frequency" duality.

It concerns a recent publication in which Thibault and Genarelli [4] propose a synthesis of their very extensive experimental work in which 165 monkeys were subjected to a rotary impulsion. Three loading systems were used during these experiments which were spread over a period of several years. The published table of results gives the number of the experiment, type of monkey, shock orientation, maximum angular acceleration, shock duration, and especially the type of lesion caused. In this table it appears that the monkeys killed by system 1 were subjected to focal lesions (contusions and / or SDH), whereas those impacted by systems 2 and 3 succumbed to DAIs. In figure 5, we have presented the evolutions of the maximum angular acceleration and the impulsion duration, as a function of the experiment number. The very low variations of these parameters show that neither of these two parameters can explain the sudden lesion change after monkey No. 103. Further, as all the impacts having a rotary preponderance, these experiments show that a rotation can cause contusions and SDH as well as DAI. The explanation of this mechanism change is found in the in-depth analysis of the temporal and frequency characteristics of the loading machines or systems. The

Fourier transform of the first system presents energy up to 300 Hz. This system thus results in a brain-skull de-coupling and produces the SDH and contusions observed. On the contrary, systems 2 and 3 show both energies concentrated below 150 Hz, which excludes any de-coupling and subjects the complete skull-brain to an acceleration field systematically resulting in DAI. In figure 5, the maximum frequency excited by the system used is superimposed onto the acceleration and impact duration parameters thus illustrating the "low frequency shock - high frequency shock" duality for distinguishing the two lesion mechanisms.

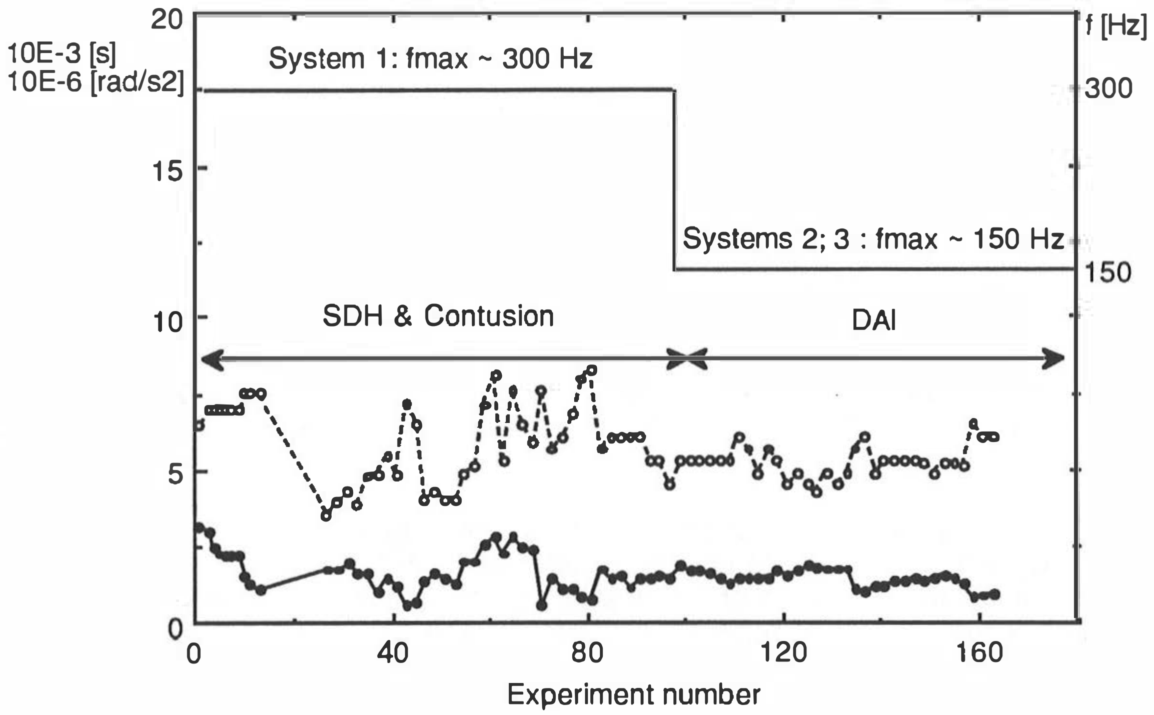


Figure 5 : Value of the maximum angular acceleration (dashed line) and impulse duration (solid line) as a function of the experiment number (origin : Thibault [4] ; shock applied to monkey heads). Maximum frequency excited by the loading system is the objective parameter to explain the lesion mechanism change after experience N° 103.

CONCLUSION

While all the specialists agree that a relative brain-skull movement exists, none of the studies investigated the parameter which would enable the intra-cerebral acceleration lesion mechanism to be separated from the relative brain-skull displacement lesion mechanism. This study gives some examples, which show that the rotation-translation duality is unable to explain the preferential creation of diffuse lesions or focal lesions (HSD and contusions) in case of shock. The proposed in vivo vibratory analysis of the head further develops the previously published results. Based on the sensations experienced under low amplitude continuous sinusoidal excitation, this analysis confirms the brain-skull de-coupling between 100 and 150 Hz. The "rotation translation" duality is superseded by the "low frequency - high frequency" duality and the lesion mechanism change is thus found to be linked to the dynamic mechanical properties of the head. In one case, the shock excites the head's resonance frequency at 120 Hz and the de-coupling phenomena occurs. In the other case, the shock shows a concentrated energy at low frequencies and the acceleration is fully transmitted to the total cerebral mass.

In the general case of an impulse excitation of any sort, neither the amplitude nor the shock duration is sufficient to predict the type of lesion which is to be feared. Only the Fourier transform or power spectral density constitutes a characteristic or signature of the shock. This information, added to the mechanical properties of the head thus make it possible to come to a conclusion on the lesion mechanism which is going to be initiated.

The proposed concept is compared to the results from the literature. In certain cases, analogous results are encountered, and in others, the new mechanism change concept, enables the observed results to be explained.

The consequences of this research are evident in relation to homologation tests for head protection systems and dummy heads. The specifications relative to the false head do not allow any natural frequencies below 3000 Hz [21]. The hybrid III head gives access to accelerations at the centre of gravity of a single mass. Current tests are based on the HIC which is a function of a classical rigid body acceleration. According to our studies, the validity area of the classical "mono-mass" approach is limited to "low frequency" shocks. The moment the shock excites the head's firsts resonance frequency, only a "bi-mass" physical model whose natural frequency lies between 100 and 150 Hz can show the reality. It is the accelerations of the two masses as well as their differential acceleration which constitute the lesion criteria for this type of shock. Future research will have to be directed for the determination of distinct tolerance limits for these two lesion mechanisms.

REFERENCES

[1] Stalnaker RL., Rojanavanich V. : A practical application of the translational energy criteria. IRCOBI conf. 225-243, 1990.

[2] Chamouard F., Troseille X., Pincemaille Y., Tarrière C. : Methodological aspect of an experimental research on cerebral tolerance on the basis of boxer's training fights. Proceed. of the 31st Stapp Car Crash Conf. 1987.

[3] Manavis J, Blumbergs PC, Scott G. Brain injury patterns in falls causing death. In : Proceedings of International IRCOBI Conference on the Biomechanics of Impacts. Bron : International Research Council on Biokinetics of Impacts, 1991: 77-88.

[4] Thibault LE., Gennarelli TA. : Brain injury : An analysis of neural and neurovascular trauma in the non human primate. Proceed of the 34th AAAM Conf, 337-351, 1990.

[5] Hodgson V.R., Gurdjican E.S. : The response characteristics of the head with emphasis on mechanical impedance. 11 th. Stapp Car Crash Conf., 79-83, 1967.

[6] Stalnaker R.L., Fagel J.L. : Driving point impedance characteristics of the head. J. of Biomec.1971,vol. 4, 127-139.

[7] Willinger R., Cesari D. : Evidence of cerebral movement at impact through mechanical impedance methods. Conf. Proceed. of the International Research Council on Biokinetics of Impacts (IRCOBI)., 203-213, 1990.

[8] Willinger R., Kopp CM., Cesari D. : Cerebral motion and head tolerance. 35 th proceed. of the Association for the Advencement of Automotive Medicine (ISSN), Toronto, 387-404, 1991.

[9] Willinger R., Kopp CM., Cesari D. : Head tolerance curves in the frequency domain. Experimental Safety Vehicles conf. paper 91-S8-w-16, 1991.

[10] Trosseille X., Tarriére C., Lavaste F., Guillon F., Domont A. : Development of a F.E.M. of the human head according to a specific test protocol. 36 th. Stapp Car Crash Conf., 235-253,1992.

[11] Viano D.C., King A.I., Melvin J.W., Weber K. : Injury biomechanics research : an essential element in the prevention of trauma. J. of Biomec. 1989, vol 22, 403-417.

[12] Willinger R., Ryan GA., McLean AJ., Kopp CM.: Mechanisms of brain injury derived from mathematical modelling and epidemiological data. Proceed. of the International Research Council on Biokinetics of Impacts, 179, 192 - 1992.

[13] Hodgson V.R., Gurdjian ES., Thomas LM. : Experimental skull deformation and brain displacement demonstrated by flash x-ray technic. J. of Neurosurg. 25, 549-552, 1966.

[14] Lowenheilm P. Dynamic properties of the parasagittal bridging veins. Zentralblatt Rechtsmedizin , 74 ; 55-62, 1974.

[15] Slattenschek A., Tauffkirchen W. : Critical evaluation of assessment methods for head impact applied in appraisal of brain injury hazard. Int. Auto. Safety Conf. 1970, Paper 700426, NY ; Society of Automotive Engineers, Inc. 1968.

[16] Brinn J., Staffeld SE. : Evaluation of impact test acceleration : A damade index for the head and torso. 14 th. Stapp Car Crash Conf. 1970, Paper 700902 ; NY, SAE, Inc. 1970.

[17] Willinger R., Kopp CM., Cesari D. : New concept of contrecoup lesions ; Modal analysis of a finite element head model. Proceed. of the International Research Council on Biokinetics of Impacts, 283 - 297, 1992.

[18] King A.I., Ruan J.S., Khalil T. : Human head dynamic response to side impact by finite element modeling. J of Biomec.,113, 276-283, 1991.

[19] Willinger R., Kopp CM., Ramet M., Bouquet R., Caire Y. : Proposition of a new dummy head : The bimass 150 principle. Proceed. of the International Research Council on Biokinetics of Impacts , 229 - 240,.1993.

[20] Stalnaker R.L., Melvin J.W., Nusholtz G.S. : Head impact response. Stapp conf. 21, 305-335, 1977.

[21] Normes Françaises : Casque de protection pour usagers de motocycles, vélomoteur et cyclomoteur. NF S 72-305, 1984.