# PROPOSITION OF A NEW DUMMY HEAD :
# THE BIMASS 150 PRINCIPLE

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## ABSTRACT

*Previous in vivo vibratory analysis of the human head showed that the first natural frequency of the head around 150 Hz was accompanied by a de-coupling of the cerebral mass with the skull. The theoretical models, complemented with the epidemiological and accidentological analysis showed that it concerned a phenomena which was fundamental in establishing the lesion mechanism in cases of head trauma.*

*The aim of this study is to transfer the biomechanical head study results to a physical model intended for "measuring" the shock severity. The chosen principle is that of two masses which model the brain and skull and whose mechanical liaison has a rigidity such that the systems natural frequency is at 150 Hz. The validation of the model relies on the superimposition of the physical model's mechanical impedance with the mechanical impedance of the human head in vivo.*

*In a real shock situation, this new "Dummy head" enables intracranial mechanical parameters to be recorded as a function of the shock's characteristics. In particular it is shown how it is possible to predict the relative brain-skull movement phenomena as a function of shock damping.*

## INTRODUCTION

To provide optimum protection of the human head when subjected to a shock requires a thorough knowledge of the "object to be protected". Biomechanic investigations of shocks applied to the head, carried out within the framework of a collaboration between the Biomechanical Systems Laboratory of Strasbourg University (URA CNRS 854) and INRETS Biomechanic and Shock Laboratory, have provided a better understanding of the in vivo dynamic behaviour of the cephalic segment and thus the lesion mechanisms involved in cases of cranio-cerebral traumatism.

Optimizing human head protection depends on the evaluation and preparation of a product or device aimed at protecting the human head, such as a crash helmet. It also involves evaluating and then improving existing products or devices which represent a danger to the human head, such as the dashboard. The work presented here is a first stage in this direction, since it concerns applying fundamental research results to experimental investigations. In spite of the appearance of more and more sophisticated theoretical models, shock tests will still have an important role, in view of the complexity of certain impacted structures and the need for certification test procedures.

The scientific community specialized in the field of head biomechanics has agreed to consider the head as a non-rigid structure made up of several components [1, 2, 3, 4, 5, 6]. However, despite this consensus, both European and North American standards recommend, for cephalic shocks severity tests, a dummy head which is nothing more than a rigid body on which it is also recommended to record the centre of gravity acceleration. It is this temporal acceleration function which is at the basis of the famous HIC (Head Injury Criteria) calculation. The criticisms of HIC are due to considering the head only as a rigid body and its simple kinematic analysis [3, 4, 5, 7].

Even though the HIC is representative of a certain shock severity level, and therefore a certain cerebral lesion risk, it is clearly not capable of distinguishing between the different possible lesion mechanisms. Knowing the sensitivity of the nerve cells to shear stresses and the importance of the brain-skull relative displacement phenomena, one can appreciate how difficult it is to assess these magnitudes just by the acceleration of a unique body.

The objective of our study is to improve the experimental evaluation methods of the severity of cephalic shocks by taking into account various lesion mechanisms and integrating the recording of certain intercranial mechanical parameters in real shock situations.The subject of this study concerns an alternative to the existing test dummy, by replacing this human head substitute by a structure made up of two masses, whose general dynamic characteristic comes close to those of the in vivo head.

The paper is set forth in five sections devoted respectively to a brief review of the previous studies which are the basis of the new principle, the methods used and prototype preparation, then in the third section the prototype validation phase. The two last sections deal with the prototype studies in a real shock situation, and the other gives an overall view of the study in the form of a discussion.

## ORIGINS OF THE NEW PRINCIPLE

The new experimental measurement principle of the severity of shocks applied to the cephalic segment comes directly from fundamental research which has been carried out within the framework of a collaboration between LSBM and LCB since 1990. With the aim of exposing the origin of the principle which is at the basis of the preparation of the new dummy's head, this section succinctly shows the steps and results of work which has previously been carried out.

In order to more accurately specify the dynamic behaviour of the human head, an in vivo recording of the dynamic vibrations of the head was made using a volunteer subjected to a moderate impact. This made it possible to calculate the mechanical impedance of the head which represents the signature of the structure in the frequency domain. This analysis revealed a natural frequency at about 150 Hz, accompanied by a "decoupling" of about 1.5 kg mass. These tests are at the origin of a new lumped model of the head which is able to distinguish the cerebral mass m2 from the other masses present [6, 8, 9] (see figure 1). This model was then completed by a finite element model validated in dynamic situation and in vivo, relative to brain-skull liaison conditions [10].

The use of these results and the analysis in the temporal domain of the theoretical models revealed four lesion mechanisms inducing deep diffuse lesions, peripheral cerebral lesions, sub-dural haematoma and contrecoup lesions [6, 10]. Validation of these lesion mechanisms depends on the accidentologic and epidemiologic analysis, taking into consideration the dynamic characteristics of the impacted structure carried out in collaboration with the Road Accident Research Unit at Adelaide University [11].

In summary, these studies resulted in proposing a change of lesion mechanism as a function of the energy distribution in the shock spectrum. For so called "long" shocks, lasting between about 15 $10^{-3}$ and 20 $10^{-3}$s, thus when the shock spectrum energy is distributed in a frequency range below 150 Hz, the brain follows the movement of the head, so the skull and the brain are subjected to the same acceleration field, resulting in intracerebral stresses directely proportional to the acceleration. For so called "short" impacts, lasting between about 5 $10^{-3}$ and 15 $10^{-3}$s, thus when the shock spectrum energy is distributed in a frequency range above 150 Hz, the brain no longer follows the skull movement and a relative displacement occurs. This then leads to the appearance of peripheral cerebral lesions such as sub-dural haematoma, crushing in the anterior part of the temporal lobes or damage of the frontal lobes at their contact with the orbital floor.

The main originality of these studies lies in the fact that the head is no longer considered as a rigid body, but as a non-rigid composite structure. In what follows, the principles resulting from the biomechanical study of the head will be transferred onto a physical model intended to estimate the aggressiveness of a shock during experimental simulations. This stage of our investigations concentrated on the first natural frequency of the head which was determined as being between 120 and 150 Hz and which is regulated by the mechanical liaisons of the brain with the skull. The mechanical phenomena related to this natural frequency seem to us to be the most important to be physically modelled, since they are at the origin of the most frequently encountered lesion mechanisms. This point will be described in more detail in the paragraph set apart for discussion.

To put these results in an international scientific context it is important to recall that the in vitro human head impedance curves, published by Hodgson (1967) [1] and Stalnaker (1985) [12] revealed a resonance around 100 Hz. This phenomena however was not stated in the above mentioned publications because the authors were primarily interested in the second natural frequency, which is due to skull bone deformations. More recently, in 1992, Trosseille and Tarrière [13] drew the same conclusions as us in 1990, namely that the human brain starts to resonate in the skull at about 120Hz.

## METHOD AND PROTOTYPE

The method is based on the theoretical and experimental methods of vibratory mechanics and was applied to the human head study as well as to the prototype's preparation and validation. Working out realistic physical and mathematical models inevitably proceeds via a non destructive analysis of the human head in vivo. The method used applied "black box" identification techniques

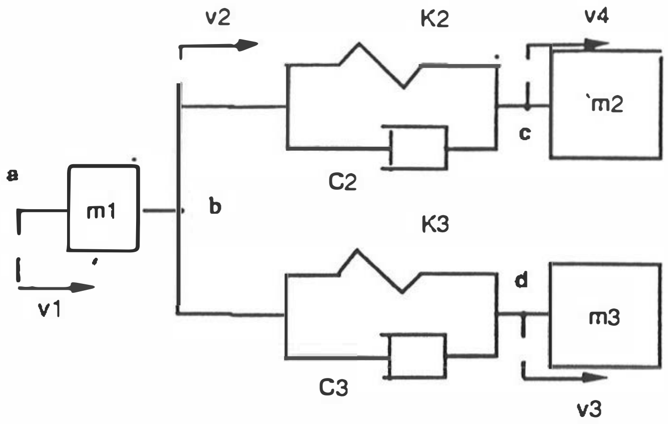


Figure 1 : The lumped head model

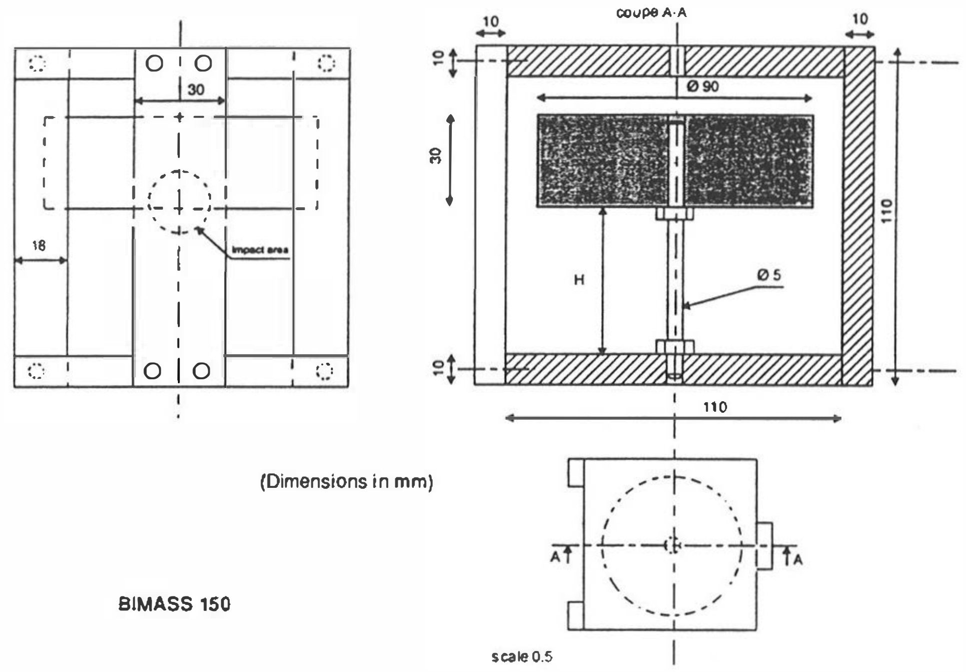
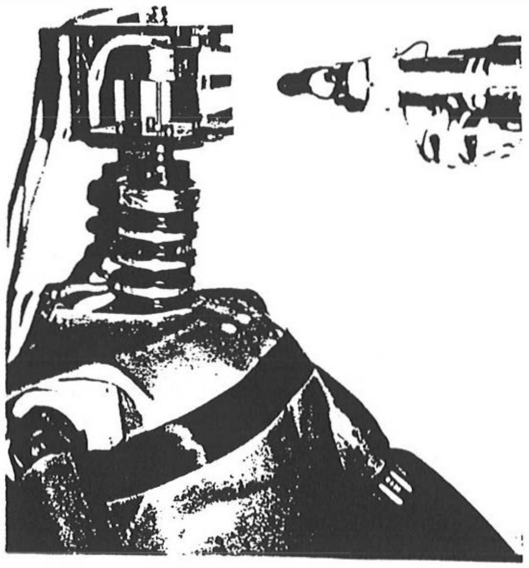


Figure 2 : Structure'sschema of the physical model. Parameter H conditions the first natural frequency. (f1 = 150 Hz for H = 50 mm).

Figure 3 :The Bimass 150 physical model, fixed on dummy Hybrid III in the impact test configuration.



via its frequency analysis.

The basis of the theoretical and physical models' construction and validation lies in the vibratory analysis of the volunteers' head subjected to a moderate impact. In the temporal area, the response of a structure to an impuls results in a more or less complex vibration which continues well beyond the shock duration. The Fourier transforms of excitation and response, respectively express the structures' excitation and behaviour in the frequency area. When the response is related to the excitation, this ratio makes it possible to characterize the system in the linear approximation. In the mechanical area, when the excitation force $F(\omega)$ is related to the structures speed $V(\omega)$, this signature is called mechanical impedance and enables the structures response to be calculated for no matter what excitation [14]. Mechanical Impedance is thus expressed by: $Z(\omega)=F(\omega)/V(\omega)$

A preliminary modelling stage therefore consist in impacting a human head in vivo using an impact hammer fitted with a force transducer, recording the structure's response by means of an accelerometer applied close to the impact area and then integrating this signal. In the second stage, a model is established. The simplest model is a mass-spring-damper type localized parameter model. The theoretical impedance has to be superimposed on the experimental impedance, in the frequency range which interests us.

The objective of this study is to apply the same method to the physical model by developing a prototype whose experimental mechanical impedance superimposes on the mechanical impedance of the in vivo head even if the similarity with the external anatomy of the human head is not respected. Applying these methods leads directly to the preparation of a prototype since it is a question of envisaging a structure composed of two masses, one representing the brain and the other the rest of the head. The liaison system between the two masses is such that the system's natural frequency is established at 150 Hz, from which the proposed designation "Bimass 150".

Figure 2 represents the structure's schema. The first mass, the brain, is made up of a 1.5 kg steel cylinder and the second mass, modelling the rest of the head, is a rigid metallic frame with a total weight of 2.4 kg. The "brain" is fixed in the frame using an adjustable flexible system made by using a 5mm diameter steel rod. The "brain" position, given by parameter H, conditions the stiffener of the liaison, thus the system's natural frequency value. Finally, an accelerometer is put on each mass to study the dynamic behaviour of the "Bimass 150" head thus obtained. Figure 3 shows the model fixed on dummy Hybrid III in the impact test configuration.

## PHYSICAL MODEL VALIDATION

As indicated in the previous section, the model validation is based on superimposing its mechanical impedance onto that recorded on the voluntary live subjects. The in vivo tests carried out on the human subjects were given in a previous study [8] and the results are reproduced in figure 4. In order to show the "single mass" behaviour of the existing model heads we have superimposed the mechanical impedance of the Wayne State Headform on these curves. This curve does not show any natural frequency in the frequency range 10-500 Hz.

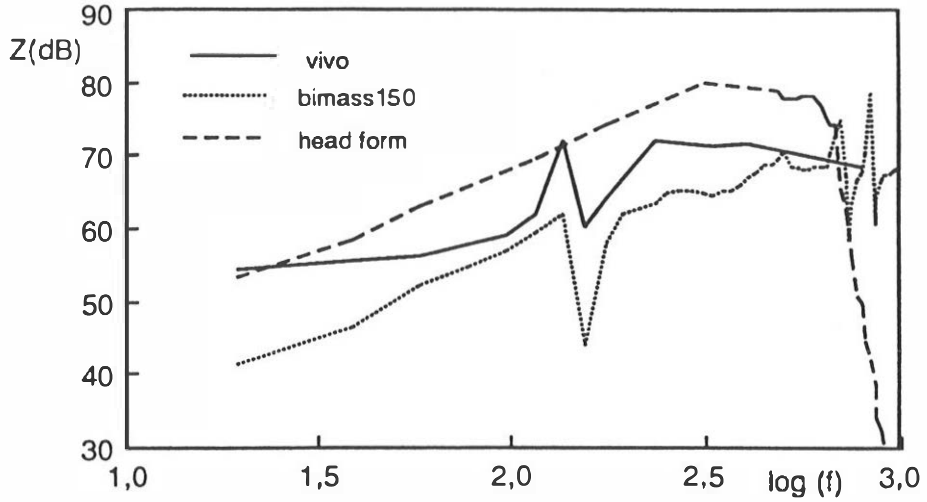


Figure 4 : Superimposition of three mechanical impedance curves : the in vivo curve, our physical model signature and the Wayne State headform response.

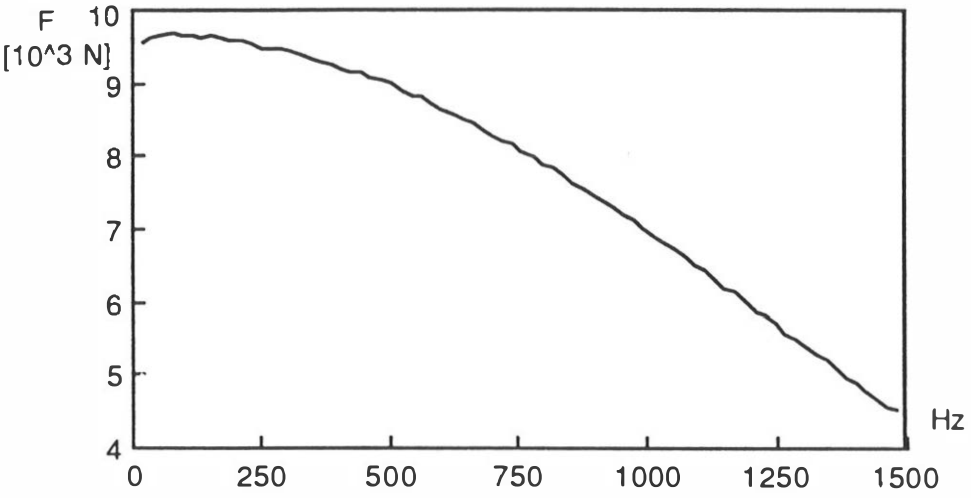


Figure 5 : Fourier transform of the impact force in the validation process. (shock duration $5.10^{-4}$s)

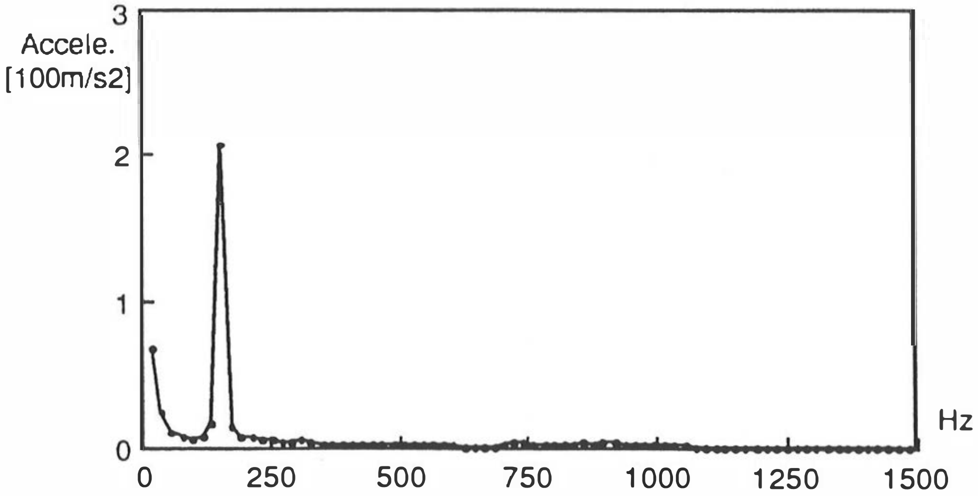


Figure 6 : Fourier transform of the "brain" acceleration. (No energy above 150 Hz).

Validation tests of the "Bimass 150" physical model are carried out under free-free limit conditions, with an impact applied in the "impact area". The recording of the applied force and acceleration of the "box" is at the origin of the impedance calculation of the "Bimass 150" model. This mechanical signature of the model is plotted in figure 4 along with the in vivo impedance curve.

To obtain a resonance frequency at 150 Hz, the length of the rod was set at $5\ 10^{-2}$m. In this configuration, the impedance curve clearly shows a resonance at 150 Hz due to the de-coupling of the two masses. Beyond this critical frequency, only the box continues to vibrate and for this type of excitation there are important relative brain-skull displacements.

The fact of no "brain" vibration at high frequencies was verified by putting an accelerometer on the "cerebral mass" and calculating the Fourier transform of the signal obtained after the impact. This impact duration was particularly short (about $5.10^{-4}$s) to also excite the high frequencies. The Fourier transform of the force is given in figure 5 and shows that the energy introduced into the system is distributed over a very wide frequency range. The brain acceleration result is given in figure 6 : There is some energy below 120 Hz, a maximum energy around the natural frequency of 150 Hz and no energy at all above this "de-coupling frequency".

It should be pointed out that in this validation phase, we are attempting to reproduce the de-coupling phenomena in this stage of the study without taking the damping problem into account. The objective here is to show the de-coupling risks as a function of the shock characteristics and not to determine tolerance limits. The results of figure 4 validate the model in the 20-700 Hz frequency range and it is now a question of studying its behaviour in a real shock situation.

## PHYSICAL MODEL UNDER SHOCK CONDITIONS

The first real impact tests on the "Bimass 150" model were intended to show the possibilities of recording certain intra crania parameters in a shock situation, then analyzing their evolution as a function of the temporal and frequency characteristics of the shock. Evidently the HIC value for these tests is pointless, since the acceleration of the model's centre of gravity is no longer of interest.

The tests were carried out on an impacting device setting a 16.6 kg mass in motion. The model was fixed on the neck of a Hybrid III dummy placed in front of the impacter as illustrated in figure 3. The impact surface is a $2.5.10^{-3}$m radius disk. The speed of the impacting mass was kept constant at 11 +/- 0.1 km/h, for all the tests. The energy involved is therefore about 77 Joules, which represents severe shocks. Three impacts were applied at three different damping levels, characterized by the interstitial material's thickness : damping 0 m, $23.10^{-3}$m and $48.10^{-3}$m.

Before analyzing the model's responses, it is interesting to study in more depth the damping notion by detailing the appearance of the loading curves given by the force transducer placed on the impacting device. If we call these three damping levels respectively D0, D23 and D48, it is seen on the force as function of time curves (figure 7) that for D0 the shock duration is about $7.10^{-3}$s, for shock D23 about $15.10^{-3}$s and that shock duration D48 extends to about $25.10^{-3}$s. As the shock energy is constant, the maximum force values reduce when damping

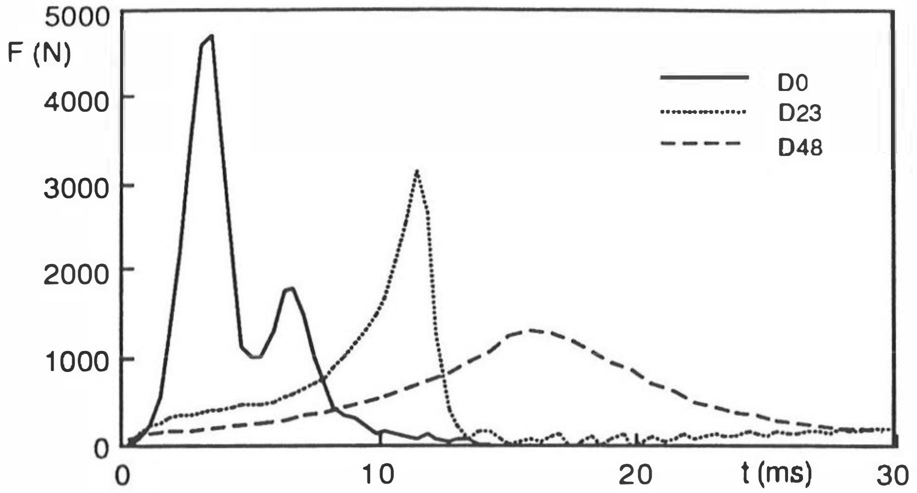


Figure 7 : Impact forces in the time domain. D0, D23, D48 are respectively relative to damping material thickness 0 mm, 23 mm and 48 mm.

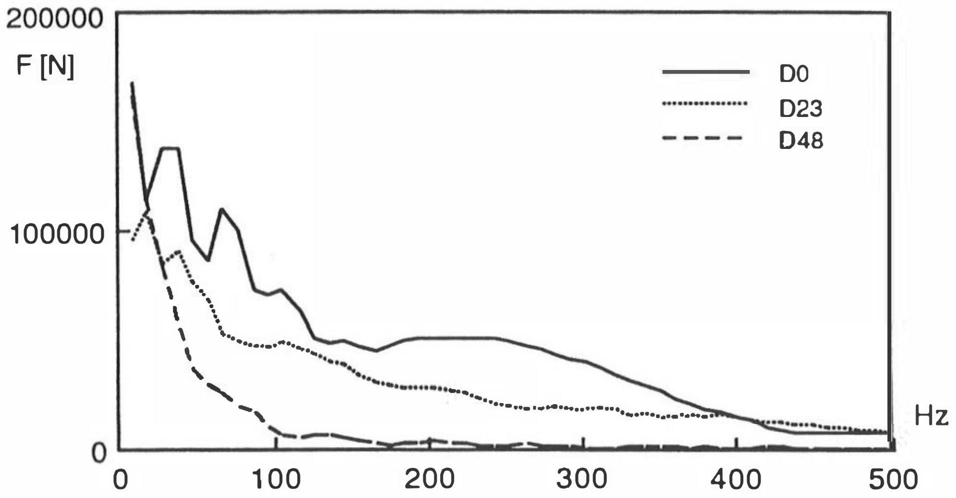


Figure 8 : Fourier transforms of the impact forces. (See also figure 7).

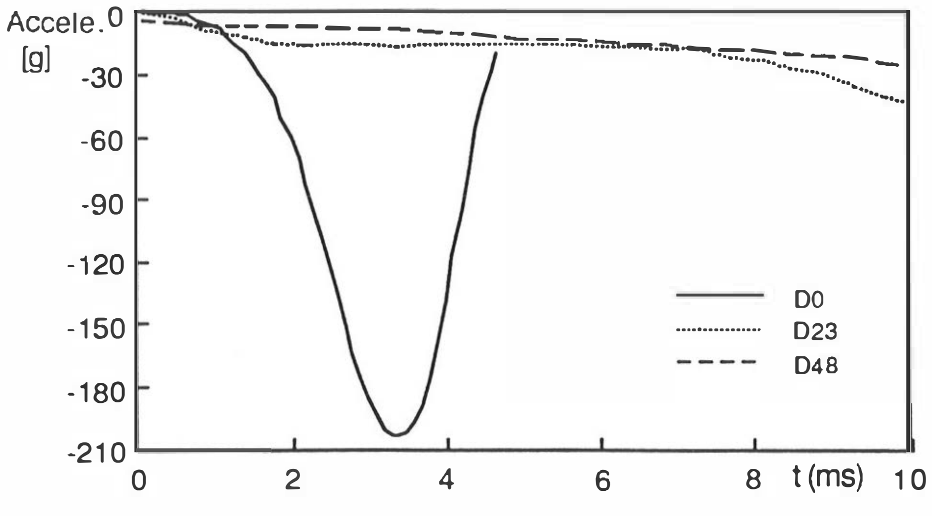


Figure 9 : "Brain" - "skull" differential accelerations recorded on the physical model under D0, D23 and D48 impact conditions.

increases.

When these load signals are expressed in the frequency area by their respective Fourier transforms (figure 8), it seems that the D0 shock is quite short to present energy at frequencies up to 400 Hz, that D23 presents less energy between 100 Hz and 400 Hz and that the D48 shock spectrum does not exceed the 100 Hz value. This figure 8 therefore makes it possible to confirm that the D0 shock starts the "Bimass 150" structure resonating, the D23 will excite this resonance frequency with a much lower energy and that finally, the D48 shock will not be able to make the structure to resonate.

The "Bimass 150" model response is given by the difference in acceleration between the "brain" and the "skull" which is a vital factor in the lesion mechanism changes previously mentioned. This "intracrania" mechanical parameter directly modulates the stresses of the "skull-brain" liaison system as well as the global acceleration of the cerebral mass itself.

The results of the three test conditions are superimposed in figure 9. For shock D0, the differential acceleration increases very sharply up to 2100 m $s^{-2}$ in the first 3 milliseconds after the impact. The D23 impact, generates a differential acceleration having the largest variations at the beginning of the shock. D48, which is the most dampened impact, results in very low differential accelerations between the brain and the skull.

At figure 9, the small difference between the curves for D23 and D48 were predictable to the extent that the two shocks excite the resonance frequency with a negligible or zero energy in view of their Fourier transforms at figure 8. According to the proposed classification in a previous study [11] and integrating both the characteristics of the head and the shock spectrum, these two shocks are to be classified as soft. The D0 impact will be classified among the hard shocks. These experiments show that the "severity" of the shock at the brain-skull displacment point of view, is not fundamentally changed when the 23 mm damping material is replaced by 48 mm thickness in the same material.

## DISCUSSION

Even though the "Bimass 150" model does not have the external appearance of a human head and is made from "rigid" metallic masses, it nevertheless gives useful information about the lesion mechanisms likely to be set off as a function of the shock characteristics. The first natural frequency of the head plays a major role in the head's dynamic behaviour. This is why we were particularly interested in this frequency. Bone deformations which are the type of lesion which can occur as the result of a very hard shock, were not taken into consideration in this development stage of a new dummy head.

From the point of view of its dynamic validation, this model is more bio-faithful than existing models. Since its dynamic behaviour is very similar to that of the human head the recordings can be expected to be close to reality. The mechanical parameters thus accessible are, of course, the accelerations of the two masses present. These two parameters regulate the relative brain-skull movement which leads to peripheral focal lesions of the brain, stresses of the liaison systems which cause sub-dural haematoma and inertial brain loading which result in diffuse cerebral lesions. The totality of these parameters or these risks can be analyzed as a function of the shock type.

In addition to the model's intrinsic behaviour, the correct superimposition of its mechanical impedance with that of the living one, assures that at the moment of the shock, the impacted structure responds as if it had been struck by a human head.

In the validation phase, the mechanical impedance curve of the Wayne State Headform did not show a resonance frequency at 150 Hz, and behaved like a rigid body up to 500 Hz. If this result leads to the conclusion that a low bio-fidelity exists, it is important to mention that this model is nevertheless adapted when the shock spectrum is below 150 Hz, or when the shock duration exceeds about $20.10^{-3}$s. In consequence this restriction defines an HIC validity area beyond which the acceleration of the head's centre of gravity is no longer valid, since several masses are in movement.

In the "Bimass 150" model response under real shock conditions, it appeared that for a hard shock, the acceleration difference between the brain and skull was large, which implies there is a risk of internal contact between the two bodies. Further, in this configuration, the liaison system is very quickly stressed. For a dampened shock, the acceleration difference is considerably reduced, indicating that the "brain" follows the skull and this cerebral movement presents a certain degree of intra-cerebral stresses. In this case the liaison system is also stressed but with a much lower amplitude and loading speed.

In this analysis, we have not mentioned the translation shock - rotation shock duality, because we feel that the hard shock - soft shock duality, is more fundamental in the release of lesion mechanisms. Head rotation is either the kinematic consequence of a short duration shock, or it occurs in the case of a very long impulse. This general head rotation could possibly result in cervical lesions which are not part of this study.

This remark does not mean that the brain cannot be animated by a rotational movement within the skull. On the contrary, our theoretical studies [10] have shown that because of the skull's internal geometry, the brain is subjected to a rotational movement even in a translation situation caused by a pure anterior-posterior impact. Thus, in the physical model, the measured relative movement can be attributed to the relative brain - skull movement for which there is a rotary component.

The axial symmetry of the "cerebral mass" and liaison system proposed in "Bimass 150" makes it possible to analyze any direction shock but staying in the horizontal plane. A similar device but with a spherical symmetry can be imagined if it is felt necessary.

Even if the proposed device makes it possible to express an opinion on the appearance or not of the relative movement phenomena as a function of the shock characteristics, it is not able, in its current state, to propose new shock tolerance limits. To achieve this ultimate aim, it is necessary to deepen and refine the epidemiological analysis then endeavour to reproduce on the physical model, the damping characteristics of the skull-brain liaison.

## CONCLUSIONS

This study presents the use of theoretical models of the human head developed in previous studies to physical modeling. The physical model designated "Bimass 150" comprises two masses, one representing the brain and the other the rest of the head. The flexible liaison between the two masses was chosen in such a way that the systems first natural frequency occurred at 150 Hz. The physical model is validated in vivo and under dynamic conditions by superimposing the mechanical impedance curves.

The model analysis under real shock conditions gave results in accordance with expected behaviour. The hard shock or slightly dampened shock excited the natural frequency at 150 Hz and resulted in important relative displacements between the "brain" and the "skull". The soft or dampened shock did not excite this frequency and therefore the "skull" and "brain" accelerations were very close.

This first development stage of a new dummy head, has thus shown the possibility of predicting the lesion mechanisms involved as a function of the damping characteristics of the shocks.

The main originality of these studies is that the head is no longer seen as a rigid body but as a non rigid composite structure. These results show that protecting the human head against a shock is not just a matter of dampening at any price, but "dampening" intelligently, by avoiding certain frequency ranges or certain temporal forms of the loading function. By this bias it will be possible to reduce the risk of a given lesion without increasing the risk of another type of lesion.

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