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SCALING OF EXPERIMENTAL DATA ON CEREBRAL CONCUSSION IN SUB-HUMAN PRIMATES TO CONCUSSION THRESHOLD FOR MAN

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by

A.K. Ommaya, A.E. Hirsch, P. Yarnell
and E.H. Harris

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A method of extending the results of experiments on concussion-producing head rotations on lower primate subjects to predict the rotations required to produce concussions in man is presented. A rational scheme of development of the overall investigation is outlined. Theoretical scaling factors are derived and discussed and the results of concussion-producing tests on the Rhesus monkey are presented in chart form. A chart of angular acceleration required to produce concussion in the Rhesus monkey indicates that an acceleration of 40,000 radians per second² will have a >99 percent probability of producing concussion. The scaling factors presented herein tentatively indicate that an acceleration of 7,500 radians per second² will have the same probability of producing concussion in man.

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Scaling of Experimental Data on Cerebral Concussion in Sub-Human Primates to Concussion Threshold for Man

A. K. Ommaya and P. Yarnell

National Institute of Neurological Diseases and Blindness,
National Institutes of Health

A. E. Hirsch

Personnel Protection Branch,
Naval Ship Research and Development Center

E. H. Harris

Tulane University

A MAJOR PROBLEM WHICH concerns those working with experimental head injury is how to apply data obtained from a variety of animals to, what is after all our prime concern, man. As one lists the biological and structural variables that must be considered in obtaining such similitude, the task appears practically insoluble. Theoretically the problem is greatly simplified if we assume that for all practical purposes during and immediately after the injury producing blow, all factors other than the purely physical can be ignored. If we further assume that there is three-dimensional

geometric similarity between the brains of a series of sub-human primates and the human brain, then scaling between the species on the basis of size variation alone appears possible. In this paper, a more restricting set of assumptions is made in order to obtain tentative scaling factors.

One approach to the problem, which seems to have considerable merit involves four distinct steps; these are:

1. The development of theoretical scaling ratios, based upon the complete set of assumptions, relating forces required to produce concussion head injury in brains of different sizes.

ABSTRACT

A method of extending the results of experiments on concussion-producing head rotations on lower primate subjects to predict the rotations required to produce concussions in man is presented. A rational scheme of development of the overall investigation is outlined. Theoretical scaling factors are derived and discussed and the results of concussion-producing tests on the Rhesus monkey are presented in chart

form. A chart of angular acceleration required to produce concussion in the Rhesus monkey indicates that an acceleration of 40,000 radians per second² will have a >99% probability of producing concussion. The scaling factors presented herein tentatively indicate that an acceleration of 7,500 radians per second² will have the same probability of producing concussion in man.

This step establishes the shape of the curve.

2. The determination of points on the curve by experiments producing concussion in primates with different brain weights. This step quantifies the curve.

3. The extension of the curve to include brain weights as they exist in man. At this point the hypothesis is extremely tenuous.

4. The accumulation of data from actual accidental concussion in man. Conformation at this step would lend endorsement to the hypothesis.

Our present report is restricted to this type of approach to the problem and is concerned primarily with a presentation of a theoretical relationship for rotational accelerations and concussion; experimental data from a tolerance curve for cerebral concussion in the Rhesus monkey is introduced and charted along with theoretical concussion values for squirrel monkey, chimpanzee and man. The relationships developed seem to be valid for all sorts of strains including the shear strains due to angular acceleration which are regarded by many to be the immediate mechanical cause of cerebral concussion.

THEORETICAL ARGUMENT

The unique material and structural properties of the brain and its covering (an enclosed material with a low modulus of rigidity and a high bulk modulus encased within a shell having a very high modulus of rigidity) confer plausibility to Holbourn's theory that shear strain produced by rotational acceleration is quite likely the cause of brain damage in head injury produced by blows of long duration (1). This theory was developed on the basis of experiments with photoelastic stress analysis techniques using two-dimensional gelatin models of the head. In an unpublished letter, Holbourn had stated that the level of rotational acceleration required to produce injury in brains with similar properties and shapes is inversely proportional to the $2/3$ power of the masses of the brains (2). It is likely that this statement was made on the basis of physical reasoning alone, although some experimental verification may have been obtained with the gelatin models. It is possible to show from first principles via the theory of model similitude (3) that such an inverse $2/3$ power relationship between brain masses and required rotational accelerations is capable of theoretical support.

Holbourn's scaling law is based on several assumptions (all recognized by him) which may be stated as follows:

1. The brain, though incompressible much like water, acts as an elastic medium.

2. As a first step in a quantitative study it is convenient to assume that brain tissue is homogenous and isotropic in nature.

3. Density of this tissue in model and prototype is equal ($\rho_m = \rho_p$).

There is some evidence that this is true for macaque and human brain (4).

4. Model and prototype brains are geometrically similar, through one scale factor, i.e. $L_p = \lambda L_m$, $V_p = \lambda^3 V_m$, etc.

5. Injury is the result of shear strains exceeding a certain value.

6. The skull is very stiff, such that deformations of the skull do not contribute heavily to the strains in the enclosed brain.

7. Stiffness factors of the contained brains in model and in prototype are equal.

When a volume of a fluid-like material (such as a globe full of water or a brain in a skull) is translated or rotated at constant velocity there is no tendency for parts of the volume to move with respect to other parts, but when the angular velocity is changed there is a relative rotation of part of the enclosed material with regard to other parts. The rotation is in the direction opposite to the direction of the acceleration. The reason for the rotation is that differential elements further from the axis of rotation have higher inertial forces than those closer to the axis of rotation; the sum of these differences in forces produces a general rotation opposite in direction to the whole-body acceleration. A short motion picture taken by Professor Martinez (Tulane University), involving a half-skull filled with gelatin upon which grids have been imprinted, shows this opposite rotation very clearly when an angular acceleration is applied. Elements at various locations in the brain are, then, displaced by different amounts, and consequently shear strains are caused which, if large enough, cause injury. It has long been argued that large shear strains cause the injury and brain concussion. An analytic study such as the present one cannot, of course, show that shear strains are the cause of brain injury. The only possible yield of this analysis is a ratio of θ_p and θ_m for equal shear strains; it cannot provide a proof that an assumed cause is correct.

Cerebral Concussion in Sub-Human Primates

Holbourn's law may be formally written as:

$$\ddot{\theta}_p = \ddot{\theta}_m \left(\frac{M_m}{M_p} \right)^{2/3}$$

His example for man and rabbit brain, is:

Let $M_m = 1$ and $M_p = 64$; then

$$\ddot{\theta}_p = \ddot{\theta}_m \left(\frac{1}{64} \right)^{2/3}$$

$$\ddot{\theta}_p = \frac{1}{16} \ddot{\theta}_m$$

In words, it takes 16x the angular acceleration which will produce concussion in the prototype (man) to produce concussion in the smaller model (rabbit). Conversely, and more important, relatively smaller angular accelerations will be needed to concuss humans. In the Tulane whiplash studies, angular accelerations much higher than those expected by these workers were required to concuss rabbits and small monkeys. This has also been confirmed in our whiplash studies in the monkey at the David Taylor Model Basin.

Using the relationships

$$L_p = \lambda L_m$$

$$A_p = \lambda^2 A_m$$

$$V_p = \lambda^3 V_m$$

$$M_p = \lambda^3 M_m$$

$$S_p = S_m \text{ and}$$

$$\rho_p = \rho_m$$

Holbourn's inverse 2/3 power law for equal concussion probability reduces to:

$$\begin{aligned} \ddot{\theta}_p &= \ddot{\theta}_m \left(\frac{M_m}{M_p} \right)^{2/3} \\ &= \ddot{\theta}_m \left(\frac{M_m}{M_m \lambda^3} \right)^{2/3} \\ &= \frac{1}{\lambda^2} \ddot{\theta}_m \end{aligned}$$

Another viewpoint, resulting in the same scaling factor, is now presented. If shear strain (or, for that matter, any sort of strain) is the cause of injury, and equal strains cause equal concussion probability we may write

$$\begin{aligned} \text{Strain} &= \frac{\text{stress}}{\text{stiffness}} \\ &= \frac{\text{force/area}}{\text{stiffness}} \end{aligned}$$

For equal strains in model and prototype of equal stiffness, $\text{Strain}_m = \text{Strain}_p$, and

$$\frac{F_m}{A_m} = \frac{F_p}{A_p}$$

Substituting for A_p , we obtain

$$\frac{F_m}{A_m} = \frac{F_p}{\lambda^2 A_m}$$

or

$$F_p = \lambda^2 F_m$$

In words, since λ^2 is a large positive number in the case of a small model (monkey) of a large prototype (man), the forces set up in the prototype are very large compared to forces set up in the model, both being acted upon so as to produce the same strain. From another viewpoint, small causes would produce stresses in a large prototype equal to stresses from large causes in a small model. This relationship is a sort of non-linear reciprocal law.

Another derivation of Holbourn's rule is given, possibly more restricted in that it is based on the assumption that angular acceleration is the cause of injury in model and prototype. Let us assume a uniform solid sphere approximating the head, which is rotated about any axis through its center. We may write,

$$I = (2/5) M r^2 \quad (1)$$

$$\text{Volume} = (4/3) \pi r^3 \quad (2)$$

$$\text{then } M = (4/3) \pi r^3 \rho \quad (3)$$

$$\text{now } T = I \ddot{\theta} \text{ or } T = (2/5) M r^2 \ddot{\theta} \quad (4)$$

Substituting for r from equation (3)

$$T = (2/5) M \left(\frac{3 M}{4 \pi \rho} \right)^{2/3} \ddot{\theta} \quad (5)$$

$$\text{or } T = (C) (M) (M)^{2/3} \ddot{\theta} \quad (6)$$

$$\text{so } \ddot{\theta} = \frac{T}{(C_1) (M) (M)^{2/3}} \quad (7)$$

However if $T < M$,

$$\text{then } \ddot{\theta} = C/M^{2/3} \quad (8)$$

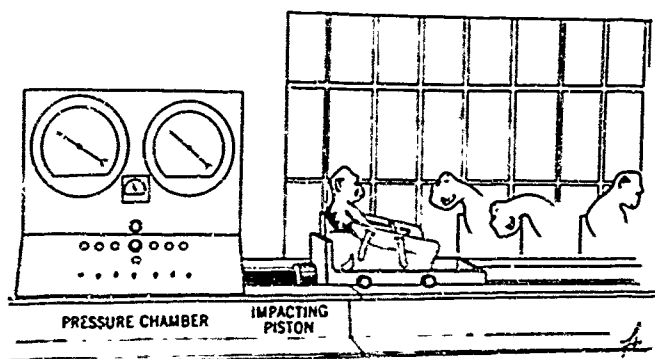


Fig. 1 - Experimental whiplash apparatus for sub-human primates

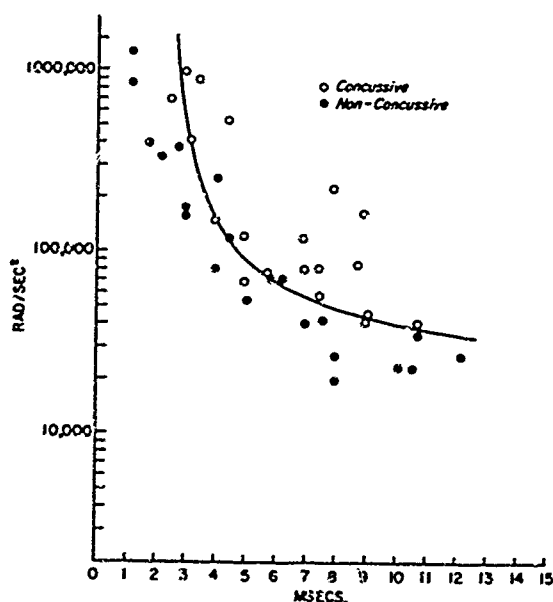


Fig. 2 - Whiplash injury and cerebral concussion: Tolerance curve for rotational acceleration amplitude versus duration for concussed and non-concussed monkeys

EXPERIMENTAL WORK

At the 10th Stapp Conference we described our apparatus and technique for simulating whiplash injury in monkeys (5) (Fig. 1). In further experiments we have confirmed that the rotational acceleration of the head thus induced can, indeed, produce experimental cerebral concussion as previously defined (6). In addition, we have been able consistently to produce surface hemorrhage on the brains of monkeys subjected to the higher concussive level of experimental whiplash (7). The amplitudes and durations of the peak rotational acceleration produced during concussive and non-concussive experiments are plotted in the form of a tolerance curve (Fig. 2) after the technique of Kornhauser (8). From these data we may obtain the level of rotational acceleration for durations greater than 6.5 milliseconds at which cerebral concussion will occur in >99% of the Rhesus monkeys subjected to whiplash injury. This is equal to 40,000 radian/second approximately. This experimental value for the Rhesus monkey was then used to

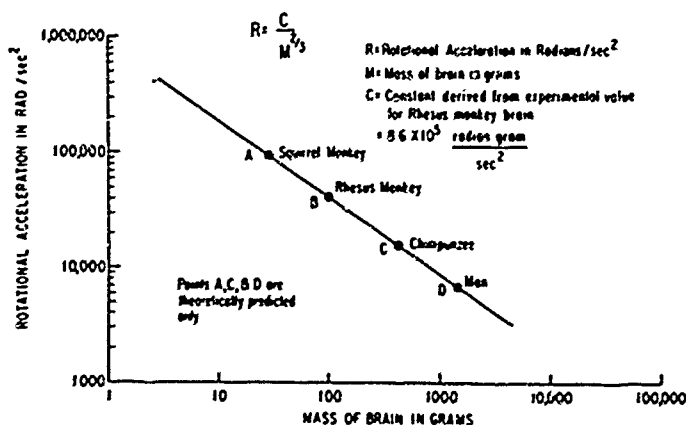


Fig. 3 - Scaling relationship between sub-human primates and man for concussive levels of rotational acceleration

derive the value of the constant C in the equation $\dot{\theta} = C/M^{2/3}$ and in this case $C = 8.6 \times 10^5$ (radian) (gram)/second² in the Mass System. Knowing the masses of the brains of various lower primate species and that of man we are thus able to plot a curve relating concussive rotational acceleration to brain mass (Fig. 3). This plot shows that if the inverse $2/3$ power relationship is true, then the squirrel monkey with a 26 gm. brain will have a >99% probability of concussion at about 100,000 radian/second² and man with a 1,300 gm. brain should have a >99% chance of concussion at about 7,500 radian/second² (all for accelerations with durations exceeding 6.5 milliseconds).

DISCUSSION

We would like to emphasize very strongly that this plot (Fig. 3) is our working theory and not a factual demonstration. Only when further experiments have actually demonstrated the levels of rotational acceleration required for cerebral concussion in the squirrel monkey and in the chimpanzee and only if such experimentally demonstrated levels fit acceptably with our theoretical derivation can we suggest what the actual concussion threshold for man may be. Further, confidence in the prognostication relative to concussion in man can only come from conformation of actual accidental concussions in man.

We are currently planning some experiments on the squirrel monkey and chimpanzee and hope to have some preliminary data ready, at least for the squirrel monkey, in time for the Stapp Conference this year. If the experimental data on these other primate species do not fit the present theory, then both the data and the assumptions made in the scaling law derivations will be closely examined to determine the nature of the fault. Evidently, the most difficult of the four steps outlined in our investigation procedure will be the obtaining of extensive, reliable and analyzable data from human accidents, but an orderly program of data gathering should produce what is needed. This item of work will be time consuming and may be several years in the doing.

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NOTATION

Dimensions shown are in the Force System. Subscripts m and p refer to model and to prototype, respectively.

λ A geometric scale factor, which is a real positive number, greater than 1 for prototypes larger than their models.

C, C_1 Constants

I Moment of inertia of a mass, $[FLT^2]$

T Torque, $[FL]$

$\ddot{\theta}$ Angular acceleration, $[T^{-2}]$

L Length, $[L]$

A Area, $[L^2]$

V Volume, $[L^3]$

M Mass, $[FL^{-1}T^2]$

r Radius, $[L]$

ρ Unit density, $[FL^{-4}T^2]$

S An undefined stiffness factor, $[FL^{-2}]$

F Force, $[F]$

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