HEAD AND SPINAL INJURY TOLERANCE WITH NO DIRECT HEAD IMPACT

By

A. K. Ommaya, M.D., F.R.C.S. and L. Thibault

This paper reviews the state of the art concerning tolerance for injury to the central nervous system when the head is not directly struck. Progress in this area of the biokinetics of impact has been hampered by the difficulty of sustained collaborative work in the three fields which must be coordinated in order to achieve adequate reliability of data; namely, mathematical models, experimental work with physical and animal models and predictive validation from human accident data.

After reviewing the four analytic models currently available, this paper will summarize the current knowledge concerning the other two areas mentioned with special reference to experimental work conducted by the author at the National Institutes of Health.

Mathematical Models

1. ADVANI. This model is of an elastic spherical shell with a low modulus elastic/visco-elastic core, subjected to three types of loading:

1. axisymmetric translational impact
2. symmetric torsional impact
3. whiplash type loading

The model drives numerical solutions for limiting desplacements, shear, and normal stresses.

2. HAYASHI. This is a two dimensional model, consisting of elastically connected concentric rigid body cylinders. The loading is in the sagittal plane symmetry with angular acceleration vs. time for the real

situation replaced by pulse wave $\ddot{\theta}_{MAX}$ for equivalent time duration t_D. The model derives resultant shear stress vs. $\ddot{\theta}_{MAX}$, t_D and uses the constitutive relations to determine the critical levels for injury. The data derived from this model was compared to our experimental data with reasonable correspondence.

3. JOSEPH AND CRISP. This model is of a spheroidal brain-skull body having the mathematical relationship $\frac{X^2}{a^2} + \frac{Y^2 + Z^2}{b^2} = 1$

The loading used in this model was a constant angular velocity i.e., a steady rotational motion about any of 3 mutually orthogonal axes. The model derives expressions for mechanical stresses, strains and displacements of the brain and uses the constitutive relations developed by the data from the work of Galford and McElhaney.

4. BYCROFT. This model is of the skull as a rigid spherical shell and of the brain as a simple elastic solid. The loading is a full sine and half-sine angular acceleration in the axisymmetric plane and it derives expressions for shear stress as a complex function of time and radial position in the model. Holburn's scaling law is used and compared to data obtained from some of this authors experimental work

Experimental Work in the Rhesus Animal Model.

Two hypotheses which have stimulated considerable research in the field of head injuries are associated with the name of Holbourn and Gurdjian. Based on experiments with gelatin models of the brain Holbourn believed that rotational components of inertial loading of the head was the most significant cause of diffuse effects on the brain (e.g. cerebral concussion and contrecoup lesions). He discounted translational components of inertial loading claiming that the resultant compression or rarefaction of the brain would not be significantly injurious.(1,2) Gurdjian correctly pointed out that this analysis neglected the effect of the foramen magnum and the work of this investigator and his colleagues over the past 25 years at Wayne State University has formed the basis of the current standard tolerance curve for head injury used by design engineers the world over.(3,4) Because this curve is expressed in terms of translational acceleration only it was important to determine experimentally the precise individual contribution of both translation and rotation to the injury potential of inertial loading of the brain. Both hypothesis accept that the contact phenomena of impact are the main cause of focal lesions at or near the site of impact but differ on the relative significance of the translational and rotational component of inertial loading caused by impact. Our earlier work had shown that pure inertial loading produced by experimental whiplash could produce cerebral concussion and surface haemorrhages of the brain (primarily subarachnoid and subdural bleeding).(5,6) Although the traumatic unconsciousness thus produced by a combination of head rotation and translation without direct impact was identical to that seen after head impact, the lesions found in the brain differed in the two types of injury. This difference was primarily due to the presence of cerebral contusions, not explicable solely by the contact phenomena of impact.(7)

This part of the paper presents our current data obtained by two new techniques; firstly the use of a special head holding device has allowed us to compare for the first time the injurious effects of pure translational acceleration of the head with head rotation at equivalent levels of input acceleration and without the complicating effect of impact contact phenomena. (See Figure 1) Secondly, we have developed the somatosensory evoked response (SER) as an in-vivo index of the onset and duration of traumatic unconsciousness and development of brain lesions. (See Figure 2) We have evidence that cerebral concussion and diffuse lesions in the brain are caused primarily by the rotational component of inertial loading while cortical contusions, intracerebral haematomas and similar focal lesions are primarily due to translation. (See Figure 3) At the levels of acceleration tested, cerebral concussion was invariably produced by rotation but not by translation of the head.(8,9) These data will be presented and discussed.

Implications of these data.

1. The standard tolerance curve for head injury will have to be modified to take into account the role of rotation.
2. With this model for closed head injury it is possible to test hypotheses for head injury mechanisms with precision and ease.
3. It is now possible to analyse the clinical phenomena of head injury (coma, amnesia and post-traumatic sequelae) in a reproducible primate model.
4. Our work to date makes it possible to re-define cerebral concussion in a way such that the clinical and experimental data are reconciled. This hypothesis will be discussed.
5. The technique of SER recording is directly applicable to man for the development of an 'on-line' in-vivo index of severity of head injury as well as a research tool to unravel the mechanisms of neural trauma in the human.

Results With A Physical Model Using The Technique Of Moire Analysis Of Strain.

In collaboration with Dr. A. J. Durelli of Catholic University, we are currently performing experiments on four half skulls of the squirrel monkey, rhesus monkey, chimpanzee and the human. These half skulls are filled with a silicon material with physical properties approaching that of brain on which a grating has been printed and the entire surface is covered with a lexan plate. These models are subjected to linear and rotational accelerations and the Moire patterns of the resulant deformation are analyized to determine the relative displacement of points in the plane of symmetry of the brain model. This will be the first step in the determination of strains, velocities, and accelerations to which each point is subjected in the process of indirect impact. Preliminary results of these experiments shall also be reviewed in this paper. Finally the paper will attempt to correlate the available human injury data in this type of injury situation with the current available data from the models and possible directions for future work will be outlined.

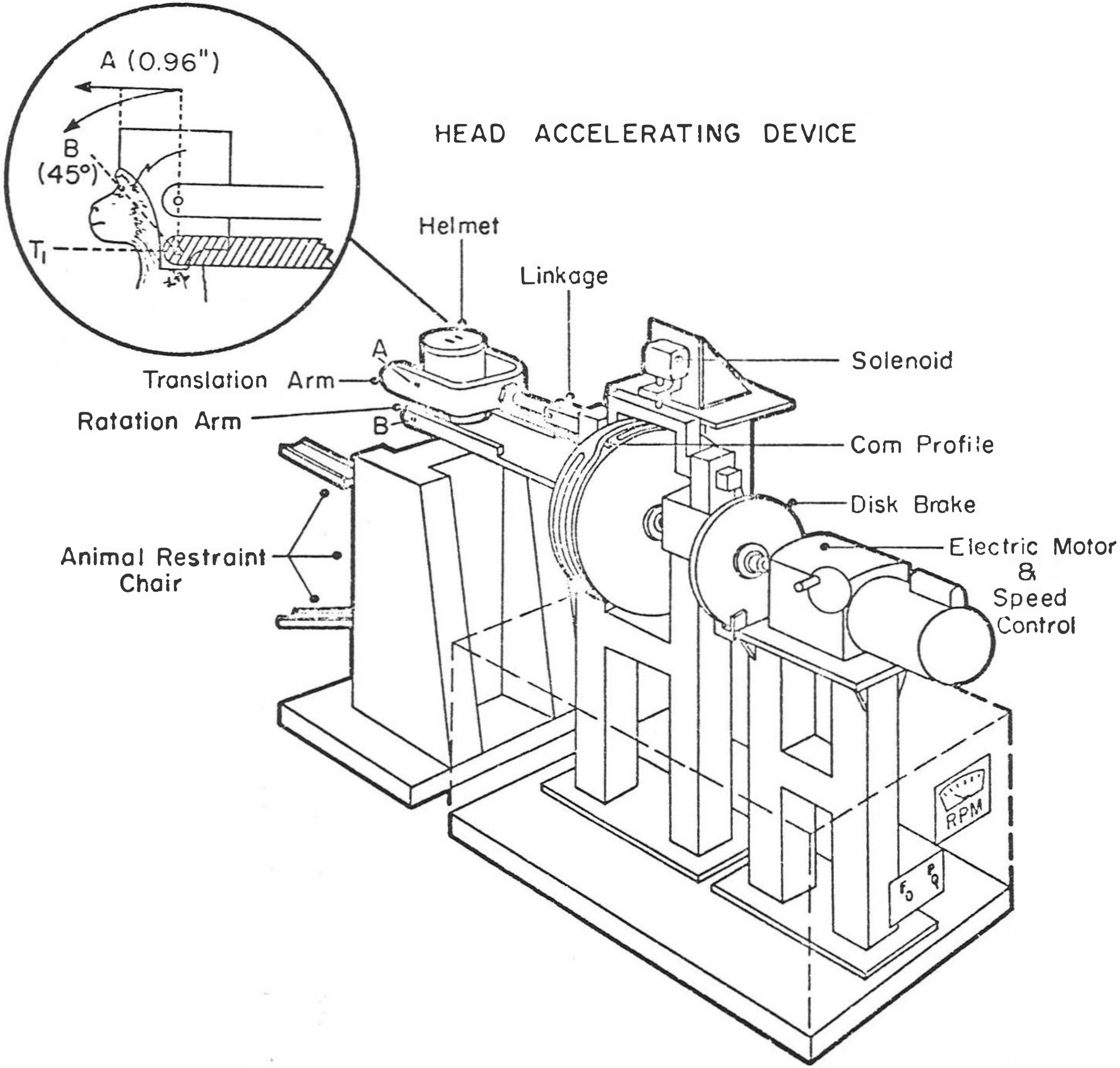
HEAD ACCELERATING DEVICE
A (0.96")
B
(45°)
T$_1$
Helmet
Linkage
Solenoid
A
Translation Arm
Rotation Arm
B
Com Profile
Disk Brake
Electric Motor
&
Speed
Control
Animal Restraint
Chair
RPM

Figure 1

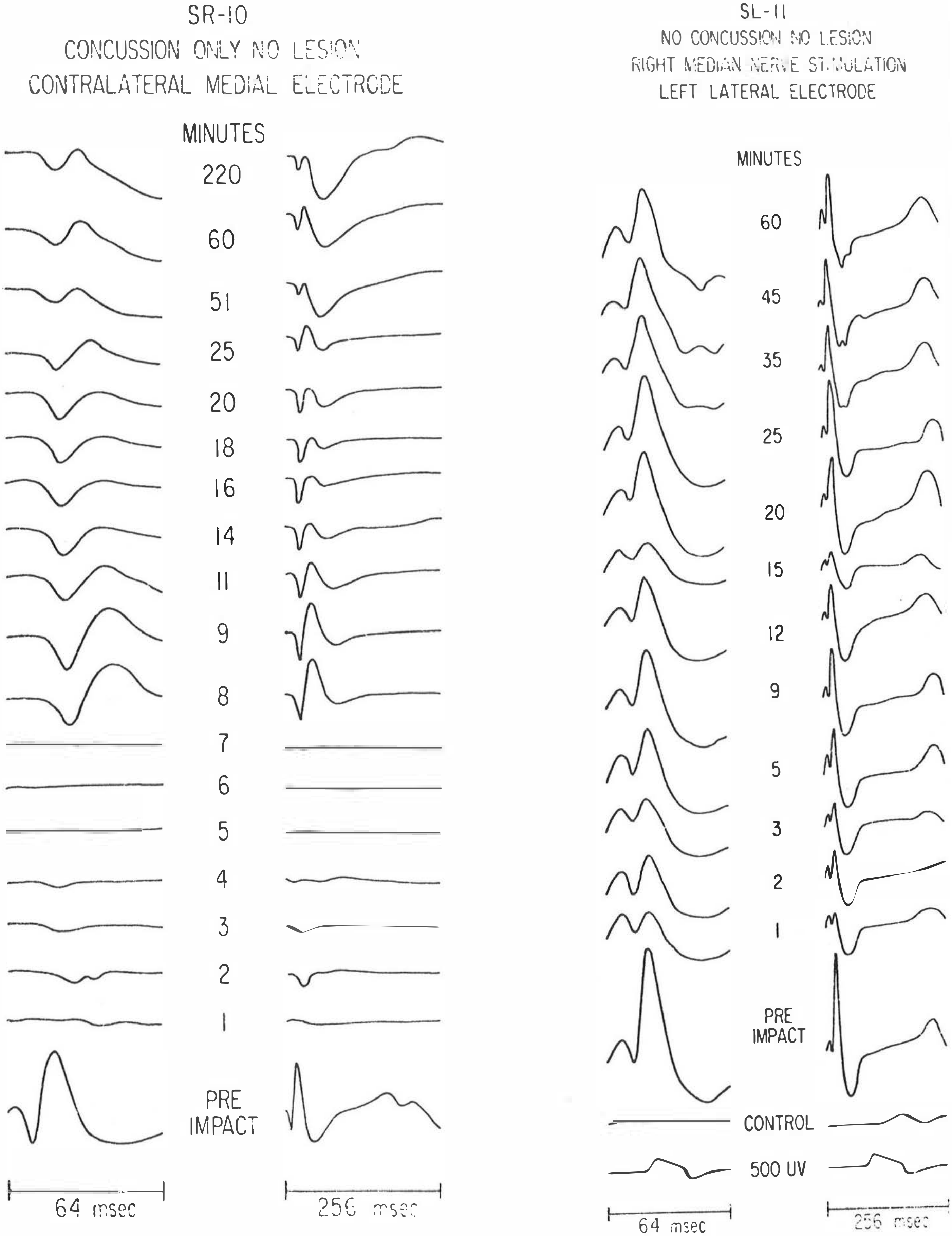
SR-10
CONCUSSION ONLY NO LESION
CONTRALATERAL MEDIAL ELECTRODE
MINUTES
220
60
51
25
20
18
16
14
11
9
8
7
6
5
4
3
2
1
PRE IMPACT
64 msec
256 msec
SL-11
NO CONCUSSION NO LESION
RIGHT MEDIAN NERVE STIMULATION
LEFT LATERAL ELECTRODE
MINUTES
60
45
35
25
20
15
12
9
5
3
2
1
PRE IMPACT
CONTROL
500 UV
64 msec
256 msec

Figure 2

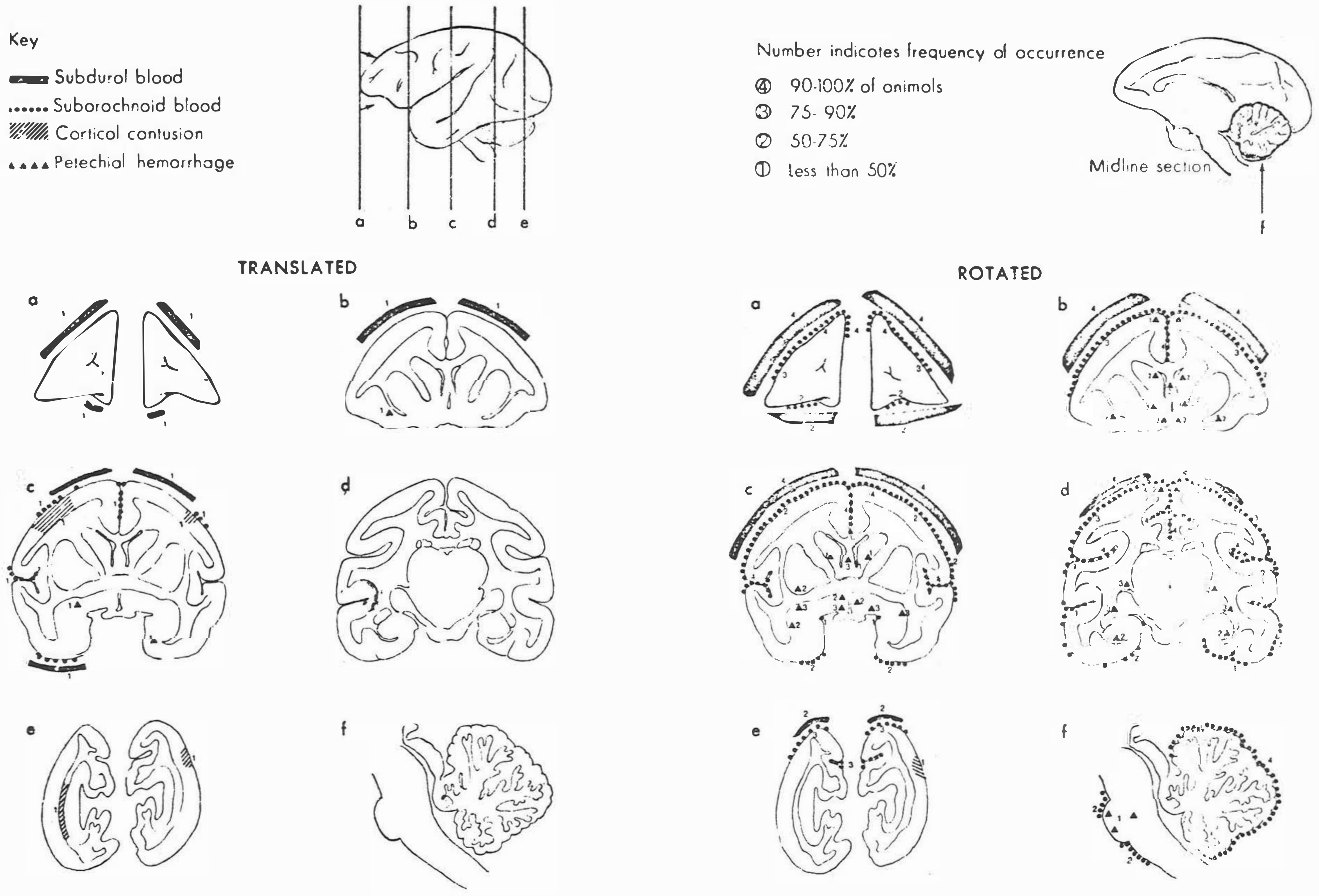
Key
Subdurol blood
Suborochnoid blood
Corticol contusion
Petechiol hemorrhage
a
b
c
d
e
Number indicotes frequency of occurrence
④ 90-100% of onimols
③ 75- 90%
② 50-75%
① less than 50%
Midline section
f
TRANSLATED
ROTATED
a
b
c
d
e
f
a
b
c
d
e
f

Figure 3

Bibliography

1. Advani, S.H., Owings, R.P. and Schuck, L.Z.: Response Evaluation of Translational and Rotational Head Injury Models. Shock and Vibration Digest. October, 1972

2. Hayashi, Tsuyoshi. Brain Shear Theory of Head Injury due to Rotational Impact. Journal of the Faculty of Engineering. U. Tokyo. (B). Vol. 30, No. 4. 1970.

3. Joseph, P.D. and Crisp, J.D.C.: On the evaluation of Mechanical Stresses in the Human Brain while in motion. Brain Research. Vol. 26 15-35, 1972.

4. Bycroft, G.N.: Mathematical Model of a Head subjected to Angular Acceleration. In press (Journal of Biomechanics).

5. Holbourn, A.H.S.: Mechanics of Head Injuries. Lancet 2: 438. 1943.

6. Holbourn, A.H.S.: Mechanics of Brain Injuries. British Medical Bulletin 3: 147, 1945.

7. Gurdjian, E.S., Lissner, H.R., Hodgson, V.R. et al: Mechanisms of Head Injury. Clinical Neurosurgery 12: 112, 1966.

8. Gurdjian, E.S., Roberts, V.L. and Thomas, L.M.: Tolerance curves of acceleration and intracranial pressure and protective index in experimental head injury. Journal Trauma 6: 600-604, 1966.

9. Ommaya, A.K., Hirsch, A.E. and Martinez, J.: The role of "whiplash" in cerebral concussion. Proceedings of 10th Stapp Car Crash Conference, 197-203, 1966.

10. Ommaya, A.K., Faas, F. and Yarnell, P.: Whiplash injury and brain damage: An experimental study. JAMA 204: 285-289, 1968.

11. Ommaya, A.K., Brugg, R.L. and Naumann, R.A.: Coup and contre-coup injury: observations on the mechanics of visible brain injuries in the rhesus monkey. J. Neurosurgery 35: 503-516, 1971.

12. Gennarelli, T., Thibault, L. and Ommaya, A.K.: Comparison of translational and rotational head motions in experimental cerebral concussion. Proceedings of 15th Stapp Car Crash Conference, 797-803, 1971.

13. Gennarelli, T., Thibault, L. and Ommaya, A.K.: Pathophysiologic responses to rotational and translational acceleration of the head. Proceedings of 16th Stapp Car Crash Conference, 296-308, 1972.

14. Ommaya, A.K. et al: Traumatic unconsciousness: Mechanisms of Brain Injury in violent shaking of the head. Proceedings American Assoc. Neurological Surgeons. Paper No. 36, 1973.