Experimental intracranial pressure gradients in the human skull¹

L. M. THOMAS, V. L. ROBERTS, AND E. S. GURDJIAN

*From the Department of Neurosurgery and Biomechanics Research Center,
Wayne State University, Detroit, Michigan, U.S.A.*

Cerebral concussion, post-traumatic unconsciousness with associated vasomotor, cardiac, and respiratory changes, has been the subject of conjecture and investigation for many years. The mechanism by which this state is produced is not entirely clear, but many authors agree that the final common pathway of concussion must implicate the brain-stem, reticular formation, and medulla. The production of unconsciousness with associated cardiovascular and respiratory changes may result from the application of increased intracranial pressure over many time scales. A slowly expanding tumour or subdural haematoma will produce these changes over days to weeks. A rapidly expanding epidural haematoma will produce the syndrome in hours. Cerebral concussion produces similar changes, brought about rapidly by the great magnitude of acceleration and deformation of the skull resulting from impact. There seems little reason to doubt that all forms produce unconsciousness and vital function changes through a final common path, *i.e.*, the reticular formation and medulla.

Evidence continues to accumulate that the effect of a sudden increase in intracranial pressure at the time of an impact is related to the patho-physiology of concussion, and may be due to acceleration or deceleration forces or to deformations of the skull during impact. Presumably, a combination of these two effects occurs in most head injury, both experimental and clinical.

Since 1944, we have advocated the presence of a pressure gradient across the intracranial space following trauma (Gurdjian and Lissner, 1944). Many authors (Braquehay, 1895; Chipault and Braquehay, 1895; Goggio, 1941; Gurdjian and Lissner, 1944; Gross, 1958; Sellier and Unterharnscheidt, 1963; Lindgren, 1964; Roberts, Hodgson, and Thomas, 1966) have observed an increase in intracranial pressure on the side of the impact while the intracranial pressure of the opposite pole is decreased. Goggio and Unterharnscheidt have

suggested that many contrecoup lesions may be due to the effects of the negative pressure produced opposite the site of impact. Gross has recorded photographically cavitation due to negative pressure in a glass model filled with fluid. Gurdjian and Lissner (1961) reported high concentrations of shear stress in the craniospinal junction by studying a two-dimensional model of the sagittal section of the human skull filled with photoelastic fluid. Edberg, Rieker, and Angrist (1963) demonstrated similar stresses in a three-dimensional model. It is believed that the shear stresses are the results of pressure gradients set up by the impact with flows occurring towards the area of elastic deformation, the cranio-spinal junction.

Although such pressure gradients have been postulated and demonstrated on the basis of fluid mechanics, the shape of the gradients and location of the nodal point have not been previously recorded. In fact, at the time of writing, experimental data had consisted solely of measurement of the extremes: the greatly increased pressure at the point of impact and the markedly negative pressure in the contrecoup area. It is the purpose of this paper to present experimental data proving the existence of pressure gradients along three orthogonal axes, measured in a human skull preparation. Pressure magnitudes were obtained at discrete points within the closed container. The effect of the falx and tentorium upon such pressure gradients was also studied.

APPARATUS

Pressure pickups, described by Hodgson, Lissner, and Nakamura (1965), were mounted on a brass stem. These pickups were $\frac{1}{8}$ inch in diameter and utilized semiconductor strain gauges for the sensing element (Fig. 1). The brass stem, containing five pressure pickups, was attached to the skull. In the postero-anterior and vertical axes, the stem was attached at one point only and allowed to project across the cranial cavity. In the lateral axis, the stem was attached to the skull at both ends. The spacing of the pressure pickups across the cranium was controlled by the location of the pickups along the stem

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FIG. 1. Photographs of stem with pressure pickups.

as well as by the position of the entire assembly relative to the skull. The pressure pickups were individually calibrated both statically and dynamically, and as a unit with the stem. A 5 ft. long, four-point string suspension (Fig. 2) permitted the skull to swing freely when struck with the rotary striker. Magnetic proximity probes, which generate a voltage when a steel object traverses their electromagnetic field, were used to measure impact

velocity. The acceleration of the skull and of the striker were recorded by crystal accelerometers.

METHOD

A human skull was prepared by removing the external soft tissue and brain from a cadaver. In one series, the falx and tentorium were allowed to remain in place. In the second series these membranes were removed to determine their effect on intracranial pressure gradients. All skull orifices with the exception of the foramen magnum were filled with dental acrylic and the external surface of the skull was coated with glyptol. The foramen magnum was fitted with a threaded insert allowing the use of either a rigid or an elastic closure. Fluid which had leaked was continually replaced to prevent the formation of air pockets.

Four series of experiments were performed. The first two series had the falx and tentorium intact and the pressures were recorded along three axes during successively higher energy blows. The cover over the foramen magnum was rigid in the first series and elastic in the second. The elastic cover was provided by the tip of a surgical glove.

The three axes were oriented as follows: (1) the stem was inserted in the inion and extended forward toward the frontal bone (postero-anterior); (2) the stem was inserted in the parietal bone and directed toward the opposite side in the vertical plane of the foramen magnum (transverse); (3) the stem was inserted in the mid-sagittal line at the junction of the middle and posterior thirds and extended inferiorly through the foramen magnum (vertical) as in Figure 3. These axes intersected to the rear of the midpoint of the skull in the anterior posterior direction, above the foramen magnum. This point of intersection was chosen because of interest in the pressure gradients along the axis perpendicular to the foramen magnum and in the region of the brain-stem. The third and fourth series of experiments were identical except for the absence of the falx and tentorium.

After each series of blows, the pickups were removed from the skull and recalibrated. Due to limitation in the amount of recording equipment, only two axes were measured simultaneously. Four sets of information were thus recorded for each series; e.g., postero-anterior,

FIG. 2. Photograph of experimental model with rigid closure.

FIG. 3. Schema of axes for measured pressure gradients.

transverse, vertical, postero-anterior. The redundant set of findings allowed for a check against the values previously recorded for that axis for repeatability of the data. The data were recorded on instrumentation tape recorders and played back at slower speeds in order to expand the time base and allow a more thorough examination of the pressure phenomenon.

RESULTS

Figure 4 shows the pressure distribution existing in the postero-anterior axis of the skull with the falx and tentorium intact and a rigid closure over the foramen magnum. The pressure gradients are linear and progressively steeper with increasing levels of acceleration. Force was held below that necessary to produce a negative one atmosphere of pressure contrecoup for the purpose of preserving the same skull throughout the entire series of experiments.

Figure 5 shows the results achieved in the postero-anterior axis with the falx and tentorium intact and an elastic closure over the foramen magnum. Again the linearity of the results indicates that the skull was not deformed appreciably and acted much as a rigid container. The magnitude of the recorded pressures correlates well with that seen in the case of a rigid closure. The site of the nodal point has shifted toward the rear of the skull, approximately over the foramen magnum. The elastic closure thus has the same effect as a free surface in shifting the nodal point.

Figure 6 shows the recorded pressures with the stem in the vertical axis extending through the foramen magnum. The falx and tentorium were intact and a rigid closure was present. The magnitude of the recorded pressures is low. Superimposing Figure 6 on Figure 4 indicates that the pressures recorded on the middle pickup on Figure 6 are quite reasonable when compared with the corresponding point of the postero-anterior axis.

Figure 7 shows the pressures recorded in the vertical axis with the falx and tentorium intact and an elastic closure over the foramen magnum. Again, recorded pressures were low because the axis was lying almost at the zero pressure plane of the postero-anterior distribution curve. The shape of the curves in Figure 7 is slightly different from that in Figure 6. However, with recorded pressures less than one-half psi negative, no significance can be attached to the shape of the curve except to note its essential linearity and that it shows no marked change along the axis.

Figure 8 records the pressures measured in the transverse axis of the skull with the falx and tentorium intact and a rigid closure over the foramen magnum. Curves are symmetrical about the midline of the skull and the magnitude of the recorded pressures increases with increasing levels of acceleration. The recorded values of pressure are quite low again because the axis is in a frame slightly to the rear of the nodal point.

Figure 9 shows the pressure recorded in the transverse axis of the skull with the falx and tentorium intact and an elastic closure over the foramen magnum. It is consistent with the other results recorded for this series inasmuch as the pressures with the elastic closure are smaller than those recorded with the rigid cover. Again, this can be attributed to the shift in the nodal point found with the elastic closure and the results are consistent when compared with those recorded at the midpoint of the skull with the stem in the vertical position.

Figures 10-15 show the results achieved in the third and fourth series of experiments utilizing the same skull, but with the falx and tentorium removed. Figure 10 demonstrates the pressure gradients observed at the stem in the postero-anterior position and a rigid closure of the foramen magnum. The pressure magnitudes are consistent with those

FIG. 4.

FIG. 5.

FIG. 4. Distribution of pressure (lb./sq. in.) along the antero-posterior axis due to a blow, with increasing magnitudes of acceleration, to the front of the skull with the falx and tentorium intact and a rigid closure over the foramen magnum.

FIG. 5. Pressure distribution along the antero-posterior axis with a frontal blow, with increasing magnitudes of acceleration, to the skull with the falx and tentorium intact and an elastic closure over the foramen magnum.

FIG. 6.

FIG. 7.

FIG. 6. Pressure distribution in the vertical axis with a blow, with increasing magnitudes of acceleration, to the forehead with the falx and tentorium intact and a rigid closure over the foramen magnum.

FIG. 7. Pressure distribution, with increasing magnitudes of acceleration, in the vertical axis with the falx and tentorium intact and an elastic closure over the foramen magnum.

FIG. 8. Pressure distribution, with increasing magnitudes of acceleration, in the transverse axis with the falx and tentorium intact and a rigid closure over the foramen magnum.

FIG. 9. Pressure distribution, with increasing magnitudes of acceleration, in the transverse axis with the falx and tentorium in place and an elastic closure over the foramen magnum.

FIG. 10. Pressure distribution, with increasing magnitudes of acceleration, in the antero-posterior axis with the tentorium and falx removed and a rigid closure over the foramen magnum.

FIG. 11. Pressure distribution, with increasing magnitudes of acceleration, in the antero-posterior axis with the falx and tentorium removed and an elastic closure over the foramen magnum.

FIG. 12. Pressure distribution, with increasing magnitudes of acceleration, in the vertical axis with the falx and tentorium removed and the rigid closure over the foramen magnum.

FIG. 13. Pressure distribution, with increasing magnitudes of acceleration, in the vertical axis with falx and tentorium removed and an elastic closure over the foramen magnum.

FIG. 14. Pressure distribution, with increasing magnitudes of acceleration, in the transverse axis with the falx and tentorium removed and a rigid closure over the foramen magnum.

FIG. 15. Pressure distribution, with increasing magnitudes of acceleration, in the transverse axis with falx and tentorium removed and an elastic closure over the foremen magnum.

recorded previously with the falx and tentorium intact and the position of the nodal point is approximately the same. Again, the pressure gradients exhibited a high degree of linearity indicating that the skull was not appreciably deformed. (The mathematical derivation in the Appendix predicts a linear distribution for a rigid container.)

Figure 11 shows the results for the postero-anterior position of the stem with an elastic closure over the foramen magnum. Similar to the first series of experiments, the nodal point shifts toward the rear when an elastic closure over the foramen magnum is used.

Figure 12 shows the pressures of the stem in the vertical position. The magnitudes of the recorded pressures are in close agreement with those recorded in the first series of tests. The shape of the curve, however, is changed slightly.

Figure 13 shows the results achieved with the stem placed in the vertical position but with an elastic closure over the foramen magnum. The magnitudes of the recorded pressures dropped once again from those recorded from a rigid closure. This drop is attributed to the shift of the nodal point toward the origin of the three axes.

Figure 14 shows the pressure distribution along the transverse axis. The rigid closure is present over the foramen magnum and the falx and tentorium are removed. Results are similar to those found in Figure 8. The distribution of pressure and the magnitude of the pressure in the side-to-side orientation does not seem to have been affected by the removal of the membranes.

Figure 15 records the stem in the transverse position with an elastic closure over the foramen magnum. Once again the magnitude of the pressures has dropped, correlating well with those studied in Figure 9.

DISCUSSION

The pressure gradients obtained in these experiments are consistent and, within the limits of experimental variation, repeat well when similar blows are applied subsequently. The gradients permit an excellent correlation between theoretical (see Appendix A) and experimental results. Obvious changes appear when the rigid closure of the foramen magnum is substituted by a more natural elastic closure.

The small pressure gradients recorded across the transverse and vertical axes are in good correlation with the predicted theoretical changes. The falx and tentorium do not play a major role in influencing the shape or magnitude of the pressure gradients existing in the skull due to an accelerative blow. Although the skull, prepared as described, is not

identical to the living, it is a model having the same geometric configuration and it is expected to respond particularly at acceleration less than 80 *g*, in the same fashion as the living. As impact velocity rises the skull will become deformed. At this point the pressure gradients in the postero-anterior axis would assume a configuration other than a straight line. This has been studied in a limited series of tests. At the higher levels of acceleration, the curvilinear pattern of pressure gradients indicates that flow and deformation are occurring. It is reasonable to assume that, in the presence of such deformation below the level to produce skull fracture but high enough to produce accompanying flow within the container, such a flow of cerebrospinal fluid could well produce the shear stresses demonstrated by Gurdjian and Lissner (1961) and by Edberg *et al.* (1963).

The results of this experiment prove the existence of a pressure gradient across the skull, developed as the result of an impact without appreciable deformation. The presence of such a pressure gradient permits the ready inference that flow may occur toward the elastic craniospinal junction under the influence of such pressures. This flow causes shear stresses to develop in the area of the brain-stem and medulla, providing a means to invoke the final common pathway of experimental concussion. The experimental information as described supports the theory that intracranial damage may be mechanical, with injury to tissues due to dynamic stresses set up in the brain by the pressure gradients produced (Gurdjian and Lissner, 1944).

Blows from only one direction have been studied. A continuing programme is under way to determine the effects of blows to other areas of the skull, and it is planned to utilize the same stems placed in the brain of a fresh cadaver 11-12 hours after death. The results of this improved model of the intact cranio-cervical junction will allow final conclusive evidence of the existence of pressure changes within the skull during impact.

This experiment was designed to prove a point by fluid mechanics applied to acceleration impact in the human skull. It is difficult to correlate directly such a study with clinical findings. It is important to realize that the clinical effects of an impact, whether it produces acceleration, deformation, or a combination of the two, will be dependent upon many variables. These include the magnitude and the rate of change of acceleration; the magnitudes of the positive and negative pressures as well as their rate of change (gradient); and possibly most important, the time during which the acceleration and pressure forces act. It is possible to withstand high acceleration changes with resulting high pressure gradients if they last for only the briefest of instants. Much

lower values for pressure may produce concussion or death if they are permitted to act over a longer period of time.

We believe that the application of basic engineering principles to each of the factors involved in head injury will permit a final clear understanding of this problem. This paper is presented to demonstrate the effects of acceleration, at low values to be sure, in the production of intracranial pressure gradients without requiring the skull to be deformed.

APPENDIX A

ANALYSIS The linearity of the pressure gradients produced in the front to rear direction allows a relatively simple mathematical analysis to be performed. Referring

FIG. 16 Site and direction of axes and model used to demonstrate the analysis.

to Figure 16, if we choose x parallel to A , dynamic equilibrium in the x direction requires

$$P dy dz - (P + \frac{\partial P}{\partial x} dx) dy dz - \rho A dv = 0 \quad (1)$$

$$\text{then } \frac{\partial P}{\partial x} = \rho A \quad (2)$$

Integrating with respect to x yields

$$P = -\rho Ax + C \quad (3)$$

when $x = 0$, $P = P_1 = C$

$$P = -\rho Ax + P_1 \quad (4)$$

Thus when $x = -h$

$$P = \rho Ah + P_1$$

However, P_1 is an unknown which cannot be evaluated in the general case due to insufficient boundary conditions. Similarly, dynamic equilibrium in the y and z directions requires that

$$\frac{\partial P}{\partial y} = 0 \quad (5)$$

$$\text{and } \frac{\partial P}{\partial z} = 0 \quad (6)$$

Therefore, P is constant in those planes parallel to the yz plane for any x . When A reaches the level necessary to produce the maximum possible (vapour) pressure at $x = 0$, $P_1 = -P_a$

From this level of acceleration upwards:

$$P = -\rho Ax - P_a \quad A \geq A_a$$

from equation 4 we can locate the plane of zero pressure.

$$P = -\rho Ax + P_1 = 0 \quad (7)$$

$$\text{Then } x = \frac{P_1}{\rho A}$$

Thus $x \rightarrow 0$ as A increases since P_1 approaches P_a and then remains constant for $A \geq A_a$.

GLOSSARY OF TERMS This glossary explains the terms used in the equations.

A	= Acceleration
A_a	= Acceleration required to produce P_a
C	= A constant
V	= Volume
dV	= Differential volume
P	= Pressure
P_1	= Pressure at the boundary
P_a	= Atmospheric pressure
h	= Length of container in the x -direction
x, y, z	= Coordinate axes
ρ	= Mass density
∂	= Indicates a partial derivative
$\geq$	= greater than
$\rightarrow$	= approaches

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