A NEW THEORY ON THE DYNAMICS OF BRAIN CONCUSSION AND BRAIN INJURY*

ARTHUR G. GROSS, B.S.
Gross Research Laboratories, Inc., Inglewood, California

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In the design and evaluation of protective headgear, there is need for the establishment of physical criteria upon which the performance of helmets subjected to impact can be determined. In the present state of the protective helmet art, there is little agreement regarding either the significant parameters to be measured or their critical threshold values. It is agreed, however, that the primary function of the helmet is to provide protection from brain concussion in case of accidental impact to the head. An extensive search of the literature has revealed theories relating to the mechanism of brain concussion and brain injury by Gama,6 Duret,5 Miles,10 Russell,12 Munro,11 Goglio,7 Denny-Brown and Russell,4 Courville,2 Gurdjian and Webster,8 Holbourn,9 Walker, Kollos and Case,13 Ward, Montgomery and Clark14 and others. None of these theories, however, was found to be sufficiently comprehensive to enable the establishment of the desired criteria. An excellent review of the development of the current knowledge of brain concussion has been presented by Denny-Brown.3

If it can be established that brain concussion is produced by, or occurs simultaneously with, a specific detectable physical phenomenon occurring within the head, it then may be possible to obtain considerable information on the threshold of concussion from research on impact on human cadavers. The data from such research could then be used to establish a standardized set of laboratory test conditions for the evaluation of helmets subjected to impact.

The subject of brain concussion is normally the exclusive concern of those in the medical profession. Research in the field of brain concussion has, in the past, accordingly been conducted mainly by those trained in the field of medicine. It must be recognized, however, that research dealing with impact to the head involves engineering dynamics, a highly specialized field that is normally foreign to the medical researcher. Lack of a clear understanding of the dynamics involved in impact to the head has served as a considerable handicap to these researchers.

The basic purpose of this research effort has been to investigate the dynamics of the head and its contents when subject to impact. The actual experimentation involved was limited to the study of the dynamics of fluid-filled glass flasks simulating the human head. Although the medical literature

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on brain concussion was carefully reviewed for guidance of this study, the actual research was of an engineering nature, conducted by engineering personnel.

**BASIC DYNAMIC CONSIDERATIONS**

Since this is a problem in dynamics let us start with Newton's first law of motion: Force equals mass times acceleration.

If we take the simple case of a bar being accelerated from one end by a tension force, as shown in Fig. 1, we shall find that the distribution of tensile force in the bar will be maximum at the end the tensile force is being applied, graduating to zero at the other end. The tension at any point along the bar will be proportional to the remaining mass being accelerated.

Let us now take a similar case in which tension is developed in a fluid, as shown in Fig. 2. If a glass tube partially filled with a fluid is struck on the top, the fluid will be accelerated downward by the tensile force developed in the fluid itself. The distribution of the tensile force in the column of fluid will be proportional to the mass of fluid above the level considered, being maximum at the bottom and zero at the surface of the fluid. If the tube is given a sufficiently hard blow so that the tensile force exceeds the tensile strength of the fluid, the fluid will tear apart, producing temporary cavities. Since the maximum tensile force is developed at the base of the fluid column, failure of tension or cavitation can be expected at this point. This phenomenon is demonstrated in Fig. 3.

Let us now take the case in which the glass tube is sealed at both ends and completely filled with a fluid as shown in Fig. 4. Neglecting radial expansion of the tube and assuming the compressibility of the fluid to be greater than the compressibility of glass, we can conclude that the fluid
FIG. 8. High-speed photographs (4,000 frames per second) of an ordinary glass test tube, partially filled with water, being impacted from the top. Failure of tension of the fluid occurs at the base of the tube in frame 2. Final collapse of the cavity formed occurs in frame 12. The impacting force produced by the collapse of the cavity then fractures the base of the tube.

FIG. 4 (left). Tensile stress gradient developed in the fluid contained in a closed tube because of acceleration produced by impact to one end.

FIG. 5 (right). Tensile stress gradient developed in the fluid of the brain because of acceleration produced by impact.
column will be accelerated by both pressure from the impacted end of the tube and tension from the opposite end of the tube.

Although the human skull is much more complex than the simple case stated above, there is reason to believe that distribution of pressure upon impact of the unrestrained head is of the same nature. For lack of substantiating evidence, let us assume that the distribution of pressure within the unrestrained skull upon blunt impact graduates from a positive pressure on the impacted side to a negative pressure on the opposite side, as shown in Fig. 5. This differs from the case in which the head is restrained and the forces are of a crushing nature.

**TENSION FAILURE OF FLUIDS**

If we are to assume that zones of negative pressure develop within the head upon impact, we then can conclude that cavities can develop within the fluid in the head, providing the negative pressure is sufficiently great to produce tension failure of the fluid.

The magnitude of the negative pressure required to produce tension failure is dependent on the following three factors: (1) Ambient pressure. (2) Vapor pressure of fluid. (3) Cohesive strength of the fluid.

Normal fluids, other than those specially treated in the laboratory, have little or no cohesive strength because of the presence of gas nuclei and other contaminants.

If we assume zero cohesive strength, we can then consider the fluid being held together by the external atmospheric pressure. If this pressure is removed (14.7 p.s.i. at sea level), cavities will immediately form because of the vapor pressure of the fluid.

**MECHANISM OF TISSUE DAMAGE**

In the various theories that are based on fluctuations of pressure it is generally concluded that it is the negative phase of the pressure cycle that is causing the tissue damage. It has been most difficult to visualize just how the application of a uniform field of negative pressure could produce brain damage of a focal nature. It is apparent that some significant factor is being overlooked.

If we assume formation of cavities within the brain caused by acceleration of the head, upon cessation of the accelerative force the cavities will collapse immediately because of the ambient pressure and the surface tension of the fluid.

The mechanical violence of collapsing cavities has long been known to the engineering profession. The first practical problems of cavitation came with the introduction of rotary hydraulic apparatus, such as ship's propellers and centrifugal pumps. If a propeller or pump rotor is driven too hard, cavities will form on the low pressure side of the blades because of tension failure of the fluid. The violent collapse of these cavities causes the metal to become spongy and wear away. This process is known as cavitation erosion.
and has been the subject of many investigations. It is generally agreed that
the erosion is caused by the impacting force of the collapsing cavity exceeding
the strength of the metal or at least the fatigue strength. The impacting pres-
sure produced by the collapsing cavities is believed to be in the order of
30,000 atmospheres. If the cavity were empty and the medium incompres-
sible the force of collapse would be infinite.

The mechanism of brain concussion being proposed is based on the prem-
ise that the various forms of focal brain damage are the result of the violent
collapse of cavities formed within the brain.

CONTRECoup CAVITATION

On the basis of the assumption made in relation to the distribution of
pressure, a plausible explanation for the phenomenon of contrecoup becomes
apparent. If the zone of negative pressure, which is opposite the point of im-
pact, exceeds the sum of the cohesive pressure and the ambient pressure,
cavitation will occur as shown in Fig. 6. The location of the cavities will be
dependent on the actual distribution of pressure and the location of the
gas nuclei. The maximum size of the cavities will be dependent on the magni-
tude of the negative pressure and its duration above the threshold of cavita-
tion. Once the negative pressure falls below the threshold necessary to sup-
port the cavities, the sequence of collapse begins.

It is this violent collapse of these cavities (Fig. 7) with the associated
impacting pressures that produce the physiological damage recognized as
contrecoup. If a large number of small cavities are formed, the damage will
show as a number of small petechial hemorrhages where the individual
cavities formed and collapsed; however, if the cavitation is localized at one
point on the surface of the brain, the characteristic conical contusion with the
apex extending into the brain will result. If the collapse of the cavity were
sufficiently intense, it is conceivable that contrecoup fracture could occur.

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**Fig. 6 (left).** Contrecoup cavitation occurring at a point opposite the impact because of tension
failure of the fluid.

**Fig. 7 (right).** Contrecoup brain injury of a focal nature resulting from the violent collapse of the
cavities formed during the interval of acceleration.
Some explanation is necessary for the relative resistance of the head to contrecoup injury from frontal blows. Cases reported involve a large percentage of fatal automobile accidents. In accidents of this nature, it is reasonable to assume (for the frontal impact) that the head is inclined somewhat forward as shown in Fig. 8. This position of impact places the foramen magnum adjacent to the area of negative pressure. It is possible that the feeding action of fluid through the foramen magnum is sufficient to attenuate the peaks of negative pressure, thereby tending to prevent contrecoup cavitation, for this particular type of impact.

**COUP CAVITATION**

Damage of a focal nature occurring in the area immediately adjacent to the blow can be explained in the following manner: A sharp nonpenetrating blow to the skull (Fig. 9) will produce the distribution of negative-positive pressure discussed above as long as the force of impact and acceleration of the head are maintained. Upon cessation of the impacting force there is no longer the acceleration of the head essential to support this distribution of pressure.

At the instant of the collapse of the field of pressure because of cessation of the acceleration, the skull is left locally depressed as a result of the force of the blow. If fracture does not occur, the elasticity of the skull will cause a very rapid recovery of shape at the point of depression. The elastic forces in the skull returning the depression to its original shape can be sufficiently high to cause localized negative pressure sufficient to cause tension failure, within the fluid. Coup injury, therefore, frequently shows not only the contusions associated with direct impact but also shows the petechial hemorrhages caused by subsequent coup cavitation.

**DIFFUSE BRAIN DAMAGE**

The above mechanisms of coup cavitation and contrecoup cavitation relate to damage of a focal nature found near the surface of the brain. These mechanisms fail to explain the cause of diffuse contusions found throughout the brain. It is apparent that an additional mechanism is required to extend the damage into the central portion of the brain.

**RESONANCE CAVITATION**

After many months of futile experimentation on the dynamics of fluids, the author observed the unusual occurrence shown in Fig. 10. The photo-
FIG. 9. Mechanism of coup cavitation. (a) Impact to top of skull causes local deformation of the skull inward. (b) Cessation of the impacting force leaves the skull locally deformed in a highly stressed condition. (c) Snap-back of the deformed skull to its normal position results in localized cavitation. (d) Collapse of the cavities formed produces the punctate contusions associated with coup injury.

graphs, taken at approximately 4,000 frames per second, are of a simple glass test tube partially filled with water. The tube is being impacted from the top with a hammer.

Normally the photographs of this experiment had shown the cavities to form at the bottom of the tube and then collapse without any subsequent formation of cavities.

In the particular experiment shown, however, there was apparently a small bubble of gas adhering to the side of the tube. As the negative pressure developed because of the impacting force, this bubble expanded and cavity formation at the base of the tube did not occur. Upon collapse of this cavity, however, the tube was apparently driven into radial oscillation resulting in subsequent spontaneous cavitation of a disperse nature.

Radial oscillation of such a tube will cause a corresponding fluctuation of the internal volume of the tube. Such a radial oscillation at low frequencies will merely result in an oscillation of the height of the fluid column. If the amplitude and frequency of the oscillation are sufficiently high, negative pressures will be developed on the expanding phase of the cycle that will produce cavitation.

To extend this experiment to one more closely simulating a human skull,
FIG. 10. High-speed photographs (4,000 frames per second) of an ordinary glass test tube, partially filled with water, being impacted from the top. Frame 12 shows the growth of a gas bubble on the side of the tube, precluding the normal formation of the cavity at the base of the tube. Collapse of this cavity in frame 20 then drives the tube into radial oscillation resulting in the resonance cavitation shown.

a common 2,000 ml. glass flask filled with water was used as shown in Fig. 11. The stopper was grooved at the sides to vent the space above liquid to atmosphere. The flask was impacted by striking the rubber stopper a sharp blow with a rubber mallet. The results of this experiment are shown in Fig. 12.

If you will observe the photographs carefully, you can see the formation of the contrecoup cavities with their subsequent collapse followed by several cycles of resonance cavitation. You can also observe that in resonance cavitation there is the recurrence of the cavities at the same distinct points, resulting in multiple impacts at these points. Not only does the collapse of the initial cavity produce extremely high force of impact, but in resonance cavitation this impact is repeated at the same points.

Evidence obtained by strain-gage instrumentation of the flask indicates
that the significant oscillatory mode in this phenomenon is radial in nature, producing large fluctuations in internal volume of the flask. Knowledge of the exact nature of the oscillatory mode is not essential to this theory as various modes of oscillation could produce volumetric pulsations. Considering a cycle of resonance of the human skull, the pressure within the skull would increase as the volume of the skull decreases, and, conversely, the pressure within the skull would decrease as the volume of the skull increases. Because of this fluctuation of volume, there would be a pumping action through the foramen magnum and other cranial cavities, but their effect on the overall pattern of pressure would be limited because of the inertial properties of the fluid. If the magnitude of the oscillation were sufficiently great, disperse cavitation would occur on the expanding phase of the cycle (Fig. 13). As the distribution of pressure under this oscillatory condition would be relatively uniform within the skull, the location of the point or points of cavitation would be dependent on localized reduction of pressure because of the flow of fluid and the location of gas nuclei.

High-energy resonance in an elastic shell first requires structural continuity of the shell itself. Just as a crack in a bell destroys its properties of resonance, a fracture of the skull tends to prevent resonance cavitation. This is in accord with the literature reporting that in many cases in which the skull is fractured, the symptoms of concussion are less profound.

The second requisite for high-energy resonance in an elastic shell has to do with the means of exciting the resonance. The ringing of a bell requires a sharp blow from a relatively hard object. If the rate of rise of the exciting force is not sufficiently steep, high-energy resonance will not occur. In the experiments to date it has been found that it is most difficult to produce resonance cavitation directly from a sharp external blow, but resonance cavitation is most easily produced from the collapse of a contrecoup cavity (Fig. 14). The fact that the internal impact caused by the collapsing cavities drives the shell directly into the expanding phase of the oscillation is probably of significance. More significant, however, is the extreme sharpness of the impact caused by the collapsing cavities.

METHODS OF PRODUCTION OF CAVITATION

The three types of cavitation that we have considered so far are:

1. Coup cavitation
Fig. 12. High-speed photographs (4,000 frames per second) of a 2,000 ml. spherical glass flask being impacted from the top with a rubber mallet. The flask is filled with water half way up its neck. The stopper used was grooved along the sides to vent the interior of the flask. These photographs show the formation of the initial contrecoup cavities (frame 7) with subsequent cycles of resonance cavitation (frames 34, 37 and 49).
FIG. 13. Mechanism of brain injury caused by a blow to the back of the head. (a) Head is accelerated forward causing tension failure of the fluid at the front of the brain. (b) Upon cessation of acceleration of the head, the cavities at the front of the skull collapse with great violence, driving the skull into an expanding phase. (c) The expansion of the skull drops the internal pressure until cavitation occurs throughout the mass of brain. (d) As the skull then contracts, the cavities formed collapse with great violence, causing dispersed damage throughout the brain. It is possible for several cycles of resonance cavitation to occur for a single impact.

2. Contrecoup cavitation
3. Resonance cavitation

In the experiments with the 2,000 ml. water-filled flask, one or more of the above types of cavitation were excited by the following methods:

1. Direct impact.
2. The glancing of a .22 bullet from the surface of the flask.
3. Impact of a loose-fitting wooden dowel floating in the neck of the flask.
4. A shock wave propagated in water with only the neck of the flask submerged into the shock medium.
5. A shock wave propagated in water with the unstoppered flask completely immersed in water.

EXPLANATION OF CHARACTERISTIC CONTUSIONS

The satellite petechial hemorrhages surrounding a focal hemorrhage may be explained on the basis of this theory in the following manner. As a cluster of cavities starts to collapse, the impacting force of those cavities collapsing initially is somewhat absorbed by the proximity of the adjacent cavities. As
the last cavity collapses, however, the cushioning effect of the adjacent cavities is no longer there and the full intensity of collapse caused by the inertia of the fluid is developed, resulting in the focal hemorrhage surrounded by the smaller satellite hemorrhages.

The characteristic conical contusion can be explained by the formation and collapse of a large hemispherical cavity against the rigid skull.

**PUNCH-DRUNK SYNDROME**

The well-known “punch-drunk” effect suffered frequently by boxers who have taken too many hard blows to the head indicates that the damage to the brain from these successive blows is cumulative in nature. The sectioned brain of a punch-drunk fighter shows small areas of damage dispersed throughout the brain. Such progressive damage may well be caused by minute cavities produced by sub-concussive blows.

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**Fig. 14.** The above sequence shows the occurrence of coup cavitation caused by snap-back of the locally deformed skull followed by resonance cavitation. Contrecoup cavitation can also occur simultaneously with the above coup cavitation because of the downward acceleration of the head.
ANIMAL EXPERIMENTATION

From the literature on animal experimentation, various researchers have reported difficulty in producing brain concussion in animals by impact to the head. Furthermore, the pathological findings in the experimental animals fail to show many of the characteristic types of damage found in the brain of man.

The above scale-effect findings are in accord with the theory being advanced. In the smaller animal, the length of fluid column along the impacting axis is much shorter than in man. The acceleration of the head required to produce contrecoup cavitation is, therefore, much greater.

ELECTRODYNAMIC CONSIDERATIONS*

The theories advanced to this point, attempting to explain the mechanism of brain concussion, have been based on the potential traumatic effect of the collapsing of cavities within the central portion of the brain.

Two basic objections to the above theory could be raised at this point. They are as follows:

1. Although the mechanism of the violent collapse of cavities within the centrum of the brain provides a plausible explanation of the origin of contusions of a focal nature, this mechanism fails to provide a sufficiently clear picture of just how functional centers are temporarily paralyzed because of the collapse of the cavities.

2. Collapse of the cavities within the centrum of the brain connotes structural cerebral injury, whereas pure brain concussion, as defined, is without structural alteration.

To attempt to fill the above apparent void in the theory presented, an additional supplemental mechanism is to be added to the mechanisms of cavitation already described.

There is a phenomenon, well-known in the field of cavitation research, known as "sonoluminescence." The name is derived from the fact that when certain fluids are driven to cavitation by ultrasonic generators, they will glow in the dark. The presence of this luminescence has been ascribed to high potential electrical fields being generated by the cavitation. An extensive bibliography on the subject of sonoluminescence may be found in the writings of Bergmann.1

If we truly have high potential electrical discharge associated with cavitation within the brain, we then approach a mechanism capable of producing brain concussion without overt structural injury.

CONCLUSION

A theory has been advanced on the dynamics of brain concussion and brain injury. This theory is based on the following mechanisms:

* Initial disclosure of this concept was made at the Office of Naval Research in Washington, D. C. on February 15, 1954.
1. Cavities are dynamically formed within the brain, producing contusions of a focal nature upon their collapse.

2. It is the violent collapse of the cavities that produces the tissue damage rather than the effect of the negative pressure.

3. Coup cavitation occurs at the site of the impact because of the snap-back of the locally deformed skull.

4. Contrecoup cavitation, associated with acceleration of the head, occurs at a point opposite the blow because of negative pressures being developed that are greater than the tensile strength of the fluid.

5. Resonance cavitation, disperse in nature, is developed within the brain as a result of radial oscillation of the skull induced by the collapse of coup or contrecoup cavities or the passage of a sharp pressure wave.

6. The transient paralytic symptoms associated with concussion of the brain can be caused by two possible mechanisms:

   a. The traumatic effect of minute cavities collapsing within or adjacent to the conscious centers.

   b. The paralytic effect of an electrical discharge associated with cavitation occurring anywhere within the cranium.

If it can be established that concussion of the brain is produced by, or occurs simultaneously with, cavitation, it then may be possible to obtain considerable information on the threshold of concussion from research on impact on human cadavers.

REFERENCES