THE MECHANISM OF SKULL FRACTURE

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Until recently, the mechanism of the production of linear skull fracture was not accurately understood since the over-all deformation patterns of the skull due to a blow were not known. Previous investigators have stated that a local deformation results in a depressed fracture and that general deformations result in linear fractures. This concept cannot be verified by a study of the actual deformation patterns. All impacts upon the skull result in local and general deformations of varying intensity if the energy expenditure is adequate. The production of a depressed fracture depends mainly upon the velocity of the injuring object, and to a less extent, its size and shape. A single linear fracture will result if the velocity of the blow is below a critical value and the energy available is between certain limits.

Aran,\(^1\) in 1844, described his irradiation theory of fractures. He stated that a fracture of the vault from impact on the vertex reached the base through the shortest possible route, implying that fracture started at the point of impact. Féliget,\(^2\) in 1873, stated that fractures result when an impact flattens out the curved surface of the skull. The fracture may then be guided by the presence of buttresses. He also observed that separation of buttresses, one from the other, due to an impact, may result in a fracture between them. His classical description of the buttresses of the skull is frequently quoted. He described single mid-frontal and mid-occipital and paired fronto-sphenoid and parieto-petrous buttresses. Bruns,\(^3\) in 1854, working with static loads found that compression of the skull resulting in shortening of the diameter in one direction, produced an increase in the diameter in the direction at right angles with the former. He also noted that although there was a certain degree of elasticity, the skull never returned to its former shape following static loading. He showed that the skull might be compressed from side to side, resulting in a shortening of its side-to-side diameter by as much as 12 to 14 mm. without failure. He found that when the load was removed, the side-to-side diameter was 4 to 5 mm. less than before its application. It was Bruns’ theory that pressure applied along one diameter would result in tearing apart forces in the portions of the skull at right angles to the direction of the force. In other words, that part of the skull where the radius of curvature decreased or where outbending took place eventually cracked. Obviously, compression when carried too far also resulted in fractures and depression at the point of application of the force. Rawling,\(^4\) in 1905, described his concepts of the mechanism of fractures involving the base of the skull. He stated that fractures of the base result from the force
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of the blow actually splitting the skull in the same manner that a hatchet can split a piece of board along its grain. This again implied that the fracture started at the point of impact. The work of LeCount and Apfelbach, in 1920, is also interesting in that they more or less substantiated some of the former concepts enunciated by Aran, Félixet, Bruns, and Rawling. In a recent text on head injury by Rowbotham, essentially the above material is given for the mechanism of skull fracture. For instance, the author speaks of local deformations resulting in depressed fractures and generalized deformations producing linear fractures.

In the next few paragraphs it will be shown that all blows to the head result in local deformations as well as general deformations. In the production of a linear fracture, the local deformation from an impact is elastic, the bone rebounding after the blow. In the depressed fracture, the bone fails locally at or about the point of impact.

CERTAIN ANATOMICAL CONSIDERATIONS OF THE SKULL

The skull is made up of vault and base. The vertex through its greatest extent consists of two layers of bone with an intervening cancellous structure constituting the diploë. Certain anatomical variations may occur in the vertex. Although most frequently the outer table is thicker than the inner table, at times the inner table may be quite thick due to the presence of certain diploic ramifications through the outer table of the skull. These variations in the anatomy of the flat bones of the skull may be important in the resultant deformation patterns, particularly as concerns fracture of the inner table. The base of the skull consists of membranous bone and it appears to be extremely brittle under impact. Many foramina are found at the base and these are areas of stress concentration and fractures usually extend toward foramina. Battle, Rawling and others recognized foramina as regions of weakness at the base.

Most injuries to the skull are due to blows over the vertex and along the junction of the vertex with the base. A few injuries undoubtedly result from impacts so delivered as to cause the spinal column to extend into the cranial cavity. Injuries may result from blows toward the base, such as a blow on the lower jaw, thrusting the condyloid processes of the jaw against the base of the skull. Occasionally, the head may be compressed between objects (such as a car and the ground).

OBSERVATIONS

Time Period of Disturbance Following Blunt Impact. With the use of modern techniques, it has been possible to determine the time period of disturbance following impact upon the human head and to study the deformation patterns that result from impact. The total time period of disturbance following impact is in the neighborhood of 1/250 of a second.*

* This work was described in the paper "The mechanism and management of injuries of the head," by E. S. Gurdjian and J. E. Webster, J. Amer. med. Ass., 1947, 134: 1072–1076, and is based upon strain gauge studies of deformations of the skull in human autopsy heads.
During the first 0.0006 of a second following the impact, the scalp compresses. At this point the deformation of the skull begins. The deformation of the skull resulting in fracture takes another 0.0006 of a second. In Fig. 1, a strain gauge record of a cadaver head with scalp and contents intact is shown. Following a deceleration impact, the instant of contact of the scalp is noted by the disappearance of one line of a two-gun oscilloscope tube. The other channel is used to show the deformation of the skull proper. In this particular specimen, the fracture line crossed the strain gauge, thus completely opening the circuit. The time at which the circuit opened may be considered the time of initiation of the fracture line. From the time of

![Image](image_url)

**Fig. 1 (left).** Human cadaver head with scalp and contents intact prepared for strain gauge measurement. The portion of the scalp and subcutaneous tissue has been removed from over the skull and the strain gauge has been placed in position with glue. Following the deceleration impact the fracture line completely disrupted the strain gauge. The oscillographic record of this case may be seen in Fig. 2.

**Fig. 2 (right).** A two-gun oscillographic record with one beam to show the time of contact of scalp with steel slab and the second beam of light to show the deformation of the skull ending in a fracture which opened the circuit. It is to be noted that there elapsed 0.0006 of a second from the time of contact of the scalp with the steel slab to the time of beginning deformation of the skull and there elapsed another 0.0006 second until the bone fractured and the circuit was opened since the fracture went right through the strain gauge. (Retouched)

contact of the scalp with the steel anvil, to the time of beginning of deformation of the skull, 0.0006 second elapsed. From the time of beginning of deformation of the skull, to the time when the circuit was opened (when the fracture occurred), another 0.0006 second elapsed. These figures may be of importance in connection with engineering techniques to decrease the rate of deceleration of the skull to counteract the injurious effects of blows of this magnitude and velocity occurring in auto and plane accidents.

**Deformation Patterns Following Blunt Impact.** Deformation patterns following impact were studied with the "stresscoat." This technique utilizes a strain sensitive lacquer applied both to the external and internal surfaces of the skull. The lacquer cracks due to tension stresses. The cracks in the lacquer appearing on the outside of the skull result from outbending. Those
appearing on the inside of the skull are due to inbending.* By this technique an accurate determination of the deformation pattern of the skull following impact may be obtained.

"Stresscoat" experiments have shown that following impact there is always an area of inbending immediately beneath and around the point of the blow. If the energy is adequate and if the velocity is sufficiently high, this area of inbending may fail, resulting in a depressed fracture. If the inbending is not severe enough to cause a fracture at the boundary of the inbended area, the skull rebounds. The inbending about the point of the blow is associated with discrete areas of outbending peripheral to the area of inbending. This outbending may be severe enough to cause tearing apart forces resulting in a linear fracture. The fracture line then extends both toward the point of impact and in the opposite direction. It extends toward the point of impact rather than to one or the other side for the following reason: Initially the area of impact is inbended or in compression on the external surface, but immediately afterward, it is in tension or outbended. As such, it represents an area of tensile stress. The fracture line at a distance will be directed to this area of stress concentration since the maximum tensile stress will occur at the point of impact after rebound.

* Experimental work to show that it is proper to use the freshly dry human skull for study of deformation patterns may be found in "Deformation of the skull in head injury," by E. S. Gurdjian and H. R. Lissner, *Surg. Gynec. Obstet.*, 1945, 81: 679–687.
Fig. 5 (left). This patient fell sustaining a bruise in the posterior parietal region on the left side. The area of the bruise was considered to be the point of impact and circular radiopaque wire was placed surrounding this area. Note that the fracture extends toward this point from the temporal region. Note, also, that the fracture is much more evident in the temporal region than near the point of impact where it tapers to a fine line. The fracture began or was initiated away from the point of impact, and due to outbending of the skull. It then extended toward the point of impact because, although initially the area of impact was pushed in or in compression, immediately afterward, it rebounded and therefore it was in tension, and as such, a fracture would tend to extend toward this area with the bone in tension.

Fig. 6 (right). Cadaver head with scalp and contents intact following a posterior parietal blow on the left side with resultant linear fracture extending up toward the point of impact. Note that in this instance the zygomatic arch is also fractured.

Fig. 7 (left). "Stresscoat" preparation following a posterior parietal blow which was much heavier than the blow in Fig. 3. Note that cracks in the lacquer appear not only in the temporal region, but also in the parietal region superiorly and in the mastoido-parietal region posteriorly and inferiorly. The cracks in the temporal region represent the area of greatest weakness and if a single linear fracture were to result from a blow, the fracture would be initiated in this region; but if the blow were more severe, a second line of fracture would be initiated in the superior parietal region extending toward the point of impact and if the blow were still more severe, a stellate fracture would be obtained.

Fig. 8 (right). Diagrammatic representation of areas of stress level following a posterior parietal impact. The temporal area is the weakest area with tearing apart forces denoting the area of primary stress level (1). The superior parietal region is the next weakest region, denoting the area of secondary stress level (2), and the parieto-mastoid region inferiorly is the region of tertiary stress level (3). With adequate energy a single linear fracture would be initiated in the area of primary stress level. If still more energy were used, a second line of fracture would be initiated in the area of secondary stress level; and if still more energy were utilized, then a stellate fracture would result.
With the use of the “stresscoat” it has been possible to delineate the areas of outbending following impact in a given region of the skull. It is interesting to note that as the energy of impact is increased, outbending is noted in more than one region. The location of cracks in the lacquer caused by outbending obtained with the smallest amount of energy expenditure represents the area of greatest weakness. This has been previously termed “the area of primary stress level.” After energy expenditure of larger magnitude, evidences of outbending occur in a second area in addition to the area of primary stress level. This region is called the area of secondary stress level. With the expenditure of still greater amounts of energy, cracks are noted in the lacquer due to outbending in additional regions and these are called areas of tertiary stress level.

The significance of these results which have been corroborated experimentally by tests of intact cadaver heads is that the area of primary stress level denotes the region of greatest weakness, and where a linear fracture would be initiated with adequate energy expenditure. If more energy were

Fig. 9. These 4 skulls are from cadaver head experiments with scalp and contents intact. In the upper left, a single linear fracture is obtained from a posterior parietal blow. In the upper right, a two-line fracture is obtained from a posterior parietal blow on the left side. In the lower left, a three-line fracture is obtained from a posterior parietal blow on the right side. In the lower right, a stellate fracture is obtained from a posterior parietal blow on the left side. The resultant fractures are found to follow the “stresscoat” predictions quite accurately.
used to obtain more than a single linear fracture, the second line of fracture would occur in the area of secondary stress level, and if still more energy were used, a stellate type fracture would result.4

On the basis of “stresscoat” experiments upon 100 skulls, we have delineated the area of primary stress level following impact in 12 regions into which the skull surface has been divided. Observations show that an adequate blow in a given region generally results in a linear fracture in a specific area. If

The velocity of the injuring object, provided the energy is adequate, is the important factor in the causation of depression. The higher the velocity, the greater is the possibility of depression and perforation. If the velocity is higher than a certain critical value, a neat hole is produced by the injuring object. Under these circumstances, distant deformations are minimal or absent. If the velocity is extremely high, the radial acceleration imparted to the skull by the missile causes extensive shattering. With the velocity of the blow lower than a certain critical value, varying degrees of dis-

Fig. 10. The 12 areas into which the skull surface has been divided. Blows administered in each one of these 12 areas in 62 human skulls to delineate the area of primary stress level have been studied.
tant deformations may be obtained with resultant linear fracture or fractures from outbending of the skull, accompanying the depression. Also, with higher velocity and energy, the area of inbending resulting in a depression may be more and more patterned after the shape of the injuring object. A bullet of average velocity may make a neat hole in the skull, whereas a baseball, which travels much more slowly, results in a rather large area of depression, with the bone fragmented by three to five lines arranged in a stellate fashion. The radius of curvature of the skull is another factor affecting the extent of the area of depression, in these lower velocity injuries.

Mechanism of Depressed Fractures. There are six varieties of depression based upon the velocity, the kinetic energy and, to a lesser extent, the shape of the injuring object.

1. An object moving with extremely high velocity (a high-powered rifle bullet) will not only perforate the skull, but will cause shattering of the bone from radial acceleration imparted to the skull and contents, resulting in tremendous increase in intracranial pressure (bursting fractures).

2. An object moving with fairly high velocity (a pistol bullet) will perforate the skull resulting in fragments of bone being indriven into the substance of the brain. If the kinetic energy is not high and most of it is dissipated at impact with the bone, the outer table alone may be depressed or perforated.

3. A blunt object moving at a lower velocity than those previously mentioned, such as a baseball, brick or hammer, may cause an area of depression in which most of the expended energy is absorbed in producing the depression. Under these circumstances there is inbending of an oval or circular area of bone with fragmentation by three to six radial fractures and separation of the inner and outer tables. The border of the oval or circular area usually presents a curvilinear fracture and this is caused by tearing apart forces on the external surface of the skull at the junction of the inbended and not-inbended bone. The fragmentation of the area of depression roughly follows the pattern shown by the “stresscoat” on the internal surface of the skull around the area of impact and is due to tearing apart forces from inbending. The outer and inner tables of the skull may be torn apart. Under
the circumstance that the energy of the missile is almost completely dissipated at impact, the outer table may be depressed or if the inner table is thicker, the inner table may be depressed.

4. A slowly moving object, causing a localized blow upon the skull, may result in a depression with simultaneous deformation in regions other than the area of impact. Under these circumstances, not only is there an area of depression, but there are also one or two linear fractures extending toward the area of impact which have resulted from tearing apart forces from distant outbending of the skull.

5. A slowly moving object, fairly sharp or pointed in contour, may cause an area of depression more or less patterned after the shape of the object. Under these circumstances, distant deformations of the skull resulting in linear fracture or fractures may or may not be present.

6. Depression by a slow-moving, high kinetic energy blunt surface may result in extensive comminution with radial fracture lines extending from the center of impact and circular fracture lines at varying distances surrounding the area of impact. This type is frequently seen with deceleration impact.

CONCLUSIONS

The mechanism of skull fracture has been described. This work has been based upon “stresscoat” studies describing the deformation pattern of the skull following impact. Whether a depressed fracture or a linear fracture is obtained depends entirely upon the velocity, the kinetic energy and, to a less extent, the shape of the injuring object. The area of impact is inbended, and in discrete regions of the skull there are evidences of outbending if the energy expenditure is adequate. If the area of inbending following impact rebounds without fracturing locally, a linear fracture may be initiated at a distance from the area of inbending due to tearing apart forces from outbending of the skull. The fracture then extends both toward the point of impact and in the opposite direction. If the area of inbending fails due to the magnitude and velocity of the blow, a depressed fracture is obtained. Linear fracture or fractures from outbending at a distance from the area of impact may be obtained if the velocity of the injuring object causing the depression is not too high. Tearing apart forces due to an impact are produced by bending of the bone and not by direct stress.

REFERENCES