CHAPTER I

INTRODUCTION

1.1 Importance of the Human Cranial Vault

The fact that among all the sensory organs of the human body, brain is of particular importance, emphasizes the gravity of problems related to the cranial vault. The sensory nerves transmit impulses from the periphery of the body-initially from the skin to the spinal cord and then to the brain for interpretation. The various constituents of the cranial vault play a dominant role in the functioning of the different normal movements of the system. One of the vital constituents is the 'motor area' where the nerve cells initiate all voluntary movements. The cells in the upper part control the feet and those in the deepest part control the head, neck, face and fingers. The next important region is the'pre-motor area' which exists immediately in front of the motor area. A group of nerve cells in the lower part of this area has a strong control over the different movements necessary for speech. The frontal area extends anteriorly from this pre-motor area as a result of which a number of association fibres between this region and the other regions in the cranial vault is responsible for the behaviour, character and emotional state of the individual. The sensory region transmits sensations of pain, temperature, pressure and touch where the sense of muscular movement and the portion of joints are received and interpreted. There are a few more regions inside the cranial vault which have their own control to respond in hearing, the sense of smell, taste and sight. Thus for obvious reasons all these constituents have got their own importance.

Apart from the physiological importance of the cranial vault, it is also a well-established fact that approximately three quarters of the fatalities resulting from accidents involve injury to the head. This ascertains the disproportionate vulnerability of this part of the human body. Thus the study of the human cranial vault deserves special attention in understanding the mechanics involved in head injury. The importance of studies on the mechanics of the cranial vault will be discussed in a greater detail in a subsequent section of this chapter. In order to have a fuller understanding of the mechanics of the cranial vault, one must have a knowledge of the relevant anatomical and physiological concepts. This is why, before we deal with the mechanics of the cranial vault, we try to present in the three following sections, a bird's-eye view of the nervous system, the various components of the head and the composition of the brain matter.

1.2 The Nervous System

The nervous system is one of the vital systems basically involved in the coordination of various functions of the human system. It contains a large number of nerve cells and a special type of connective tissue. The unit of the nervous system is designated by neurone which envelopes the nerve cell with the different processes of the nerve cell viz. axon and dendrites.

The nerve cells differ considerably in shape and size and mostly large cells are found amongst themselves. They form the grey matter of the nervous system and are found at the periphery of the brain, in the centre of the spinal cord. Each and every nerve cell has one or more processes.

The processes of the nerve cells-axons and dendrites form the white matter of the nervous system, which are found deep into the brain and at the periphery of the spinal cord. The axons carry impulses away from the nerve cells while the dendrites carry impulses towards the nerve cells. Both have similar structures but the former is much larger in size than the later.

The nerve tissue being the main constituent of the nervous system, has the characteristics of irritability and conductivity. Irritability is the power to respond to stimulation while conductivity measures the ability to transmit an impulse. In the system of the human body, the stimulation may be described as partly electrical and partly chemical. On the other hand the impulse may be transmitted from (i) one part of the brain to another, (ii) the brain to striated muscle resulting in muscle contraction, (iii) muscles and joints to the brain, contributing to the maintenance of balance, (iv) the brain to the organs of the body resulting the contraction of smooth muscle or the secretion of glands, (v) organs of the body to the brain in association with the regulation of body functions, (vi) the outside world to the brain through sensory nerve endings in the skin which are stimulated by temperature and touch and (vii) the outside world to the brain through the special sense organs e.g. eyes, ears, nose and tongue.

1.3 Various Components of the Human Head

The human head consists of the scalp, the skull, the dura, the pia-arachnoid complex, the brain, the blood vessels, the cerebrospinal fluid and the blood. The head-neck junction must also be taken into consideration inasmuch as its physical characteristics significantly affect the response of the head either to a direct impact or to accelerations induced in some other parts of the body. A median view of the cranial vault is shown in Fig. 1.1, while a lateral view of the skull is illustrated through Fig. 1.2 .

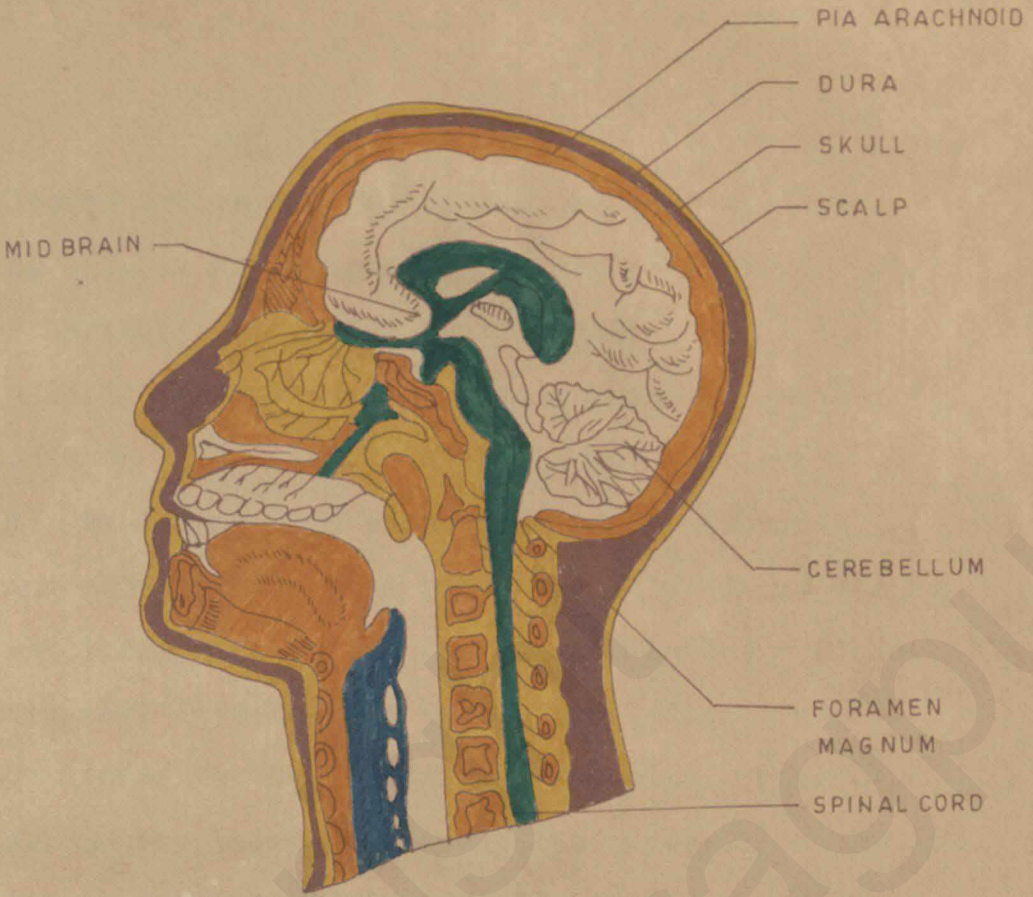

FIG. 1·1. A MEDIAN VIEW OF THE HUMAN CRANIAL VAULT

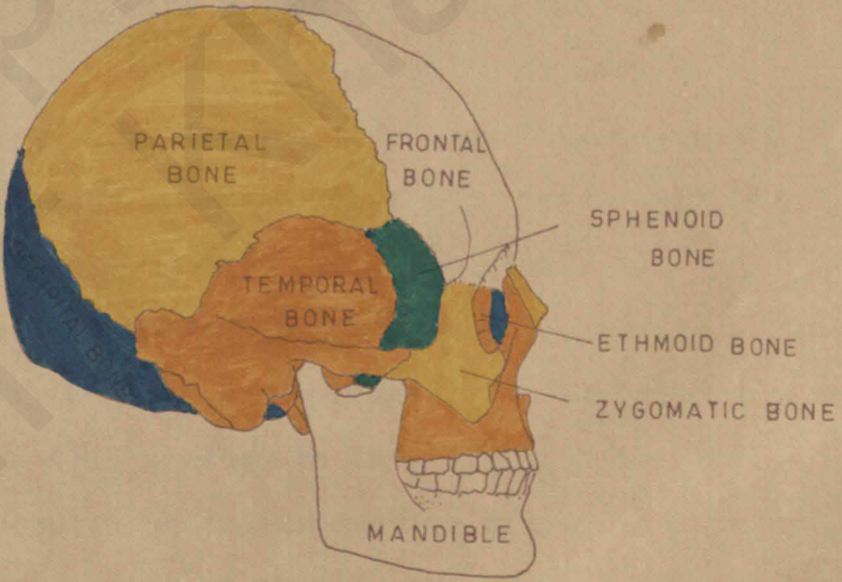

FIG. 1·2. A LATERAL VIEW OF THE HUMAN SKULL

The scalp is a combination of five different tissues overlaying the cranial bone as shown in Fig.1.3. It has a leathery consistency and is under a constant low tension in the living human. This leathery layer is arranged in a descending sequential order as (i) the skin with its hairy covering, (ii) the layer tela subcutanea (loose fibrous connective tissue that binds the skin to the deeper structures), (iii) the aponeurotic layer (a fibrous structure representing very much flattened tissue that connects the frontal and occipital muscles), (iv) a very loose subaponeurotic layer of connective tissues and (v) the pericranium (a tough vascular membrane with a somewhat looser zone).

The skull rests upon the upper end of the vertebral column and its structure is divided into two parts - the cranium and the face. The cranium is composed of eight separate bones viz. one frontal, two parietal, two temporal, one occipital, one sphenoid and one ethmoid bones while the face is comprised of fourteen bones forming the skeleton of the face. As the face appears to have a negligible influence with respect to the production of the head injury, which is the subject of the present thesis, its further consideration for the subsequent discussions is deemed

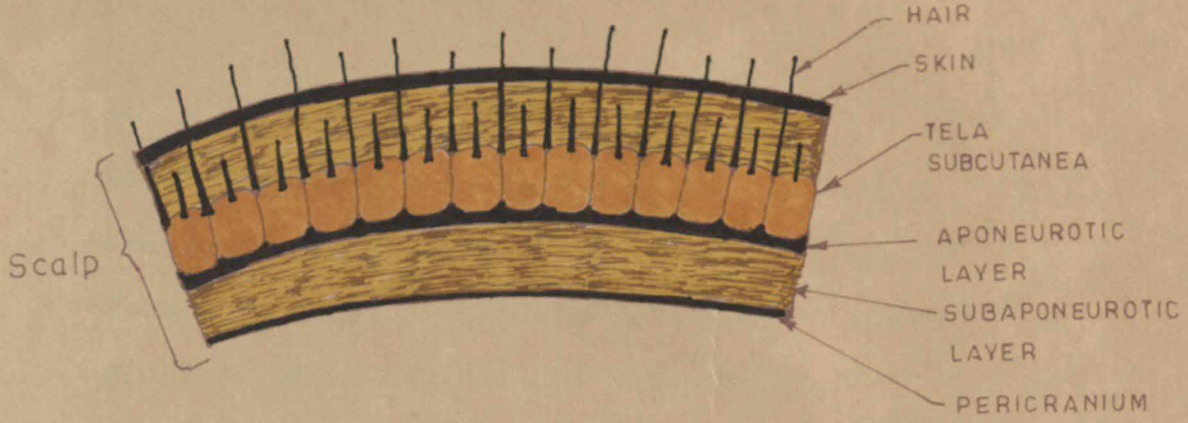

FIG. 1·3. VARIOUS LAYERS OF THE SCALP

FIG. 1·4. THE LOBES OF THE CEREBRUM

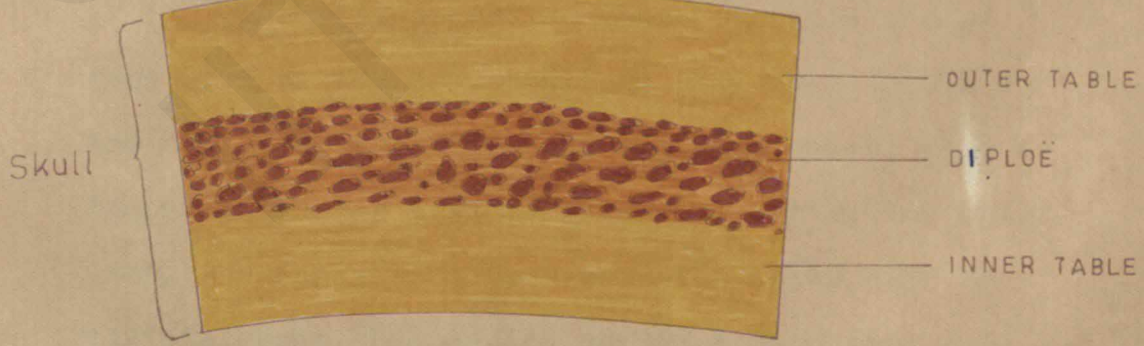

FIG. 1·5. THREE LAYERS OF THE SKULL BONE to be unnecessary. The constituents of the cranium are, to some extent, responsible in causing cranial trauma and hence for studies on the cranial trauma, a knowledge of the locations of different parts of the skull is quite useful. For this reason, a brief discussion on the various bones forming the skull is presented below. (cf. Fig. 1.2) .

The frontal bone : This bone belongs to the forehead, the inner surface of which is grooved by the brain and blood vessels. At birth the bone is separated into two parts by the frontal suture but union is usually complete by the eighth year of life.

Parietal bones : These two bones form the sides and the top of the skull. They articulate with each other and with the frontal, occipital and temporal bones. The inner surface is concave and also grooved by the brain and blood vessels.

Temporal bones : These boneslie one on each side of the head and form immovable joints with the parietal, occipital and sphenoid bones. Each temporal bone is divided into four parts. The first part, the fan-shaped portion articulates with the parietal bone. The second one is a thickened part which can be felt just behind the ear and it contains a large number of very small air sinuses which communicate with the middle ear. The third part forms the base of the skull which contains the organ of hearing. The fourth and the last one is directed forward and articulates with the zygomatic bone to form the zygomatic arch. The temporal bone has an articulating surface for the only movable bone of the skull, the mandible. The inner surface is deeply ridged by the brain and large blood vessels.

The occipital bone : The back of the head and the part of the skull base is formed by this bone. It makes the joints with the parietal, temporal and sphenoid bones stationary. Its inner surface is deeply concave and the concavity is completely occupied by the cerebellum and a few large blood vessels, while the roughened area on the outer surface gives attachment to muscles. It has two articular condyles where it forms a hinge joint with the first bone of the vertebral column and between these condyles there is a large foramen called the foramen magnum through which the spinal cord passes.

The sphenoid bone : It occupies the middle portion of the base of the skull. The shape of the bone is like a bat with its wings outstretched towards the sides of the cranium. It articulates with the temporal, parietal and frontal bones. On the smooth surface of the body of the bat there is a little saddle-shaped depression in which the pituitary gland rests. The body of the bone contains some fairly large sinuses which are in communication with the nasal cavities and foramina for the passage of blood vessels and nerves.

The ethmoid bone : It occupies the anterior part of the base of the skull and helps to form the orbital cavity, the nasal septum and the lateral walls of the nasal cavity. It is a very delicate bone having many air sinuses which appear to have the same characteristic as those of the sphenoid bone. It has a horizontal flattened part which forms the roof of the nasal cavities and has numerous small openings through which nerve fibres of the sense of smell pass upwards from the nasal cavities to the brain.

Next inward skin is known as dura. It consists of two layers of dense fibrous tissues - the outer layer forming the lining of the skull while the inner layer provides a protective covering for the brain and the spinal cord. The venous blood from the brain is drained into venous sinuses which are formed between the layers of dura matter. This matter continues downwards to line the vertebral canal and goes beyond the end of the spinal cord.

The next inward tissue, the arachnoid, a non vascular membrane is separated from the dura by a narrow non-communicating capillary known as the subdural space, which is filled with lymphlike fluid. There is another delicate membrane known as pia closely investing the brain and contains white fibrous tissues and the arachnoid is connected to it. The cerebrospinal fluid flows within the sub-arachnoid space where the arachnoid matter is separated from the pia matter by a definite space. It continues downwards to envelop the spinal cord and ends by merging with the dura matter at the level of the second sacral vertebra.

1.4 Composition of the Brain

The brain, almost completely enclosed by the skull (except for the foramen magnum), consists of the cerebrum, the mid brain, the pons varolii, the medula oblongata and the cerebellum. The cerebrum constitutes the largest part of the brain and is divided by a deep cleft named the longitudinal cerebral fissure into two distinct parts - the right and the left cerebral hemispheres. Both the hemispheres are connected by a mass of white matter or nerve fibres to the deep within the brain. The superficial part of the cerebrum is composed of nerve cells or grey matter forming the cerebral cortex. Each hemisphere of the cerebrum is divided into various lobes by means of superficial grooves viz. frontal, parietal, temporal, occipital, limbic and insula lobe as shown in Fig.1.4. The midbrain occupies the region of the brain between the cerebrum above and pons varolii below. The fibres from the cerebrum and the spinal cord pass through the mid brain upto the cerebrum and descend from the cerebrum to the cerebellum and the spinal cord. The nerve cells act as relay stations for the ascending and descending nerve fibres. Two groups of nerve cells provide cell stations for the transmission of nerve impulses from the optic nerves and the vestibular portion of the auditory nerves to the cerebellum. These nerve impulses play a dominating role in the maintenance of balance of the body. The pons varolii is accomodated in front of the cerebellum below the midbrain and above the medula oblongata. The nerve fibres of this region form a bridge between the two hemispheres of the cerebellum which pass between the higher levels of the brain and the spinal cord. There are also a few groups of nerve cells within the pons which act as relay stations and some of which are concerned with cranial nerves. The medula oblongata occupies the region between the pons varolii above and below the spinal cord which lies just within the cranium above the foramen magnum. Grey matter or nerve cells lie at the centre of the medulla while a few of these cells constitute relay stations for sensory nerves ascending to the cerebrum. The next and the last constituent of the brain is cerebellum which occupies the region behind the pons varolii and immediately below the posterior portion of the cerebrum. It consists of two hemispheres separated by a narrow median strip. The grey matter is found forming the surface of the cerebellum while the white matter lies deeply forming a branched appearance.

Macroscopically, the egg-shaped brain is something like a jel and composed of (i) about 78 % water, (ii) 10-12 % phospholipids, an ester containing phosphate, fatty acids and nitrogeneous compounds, (iii) 8 % protein, (iv) small amount of carbohydrates, (v) inorganic salts and (vi) soluble organic substances. The length and transverse diameter of the human brain are about 165 mms and 140 mms respectively. The average adult brain is 1200 c.c. by volume and 1500 gms by weight.

1.5 Mechanical Properties of the Different Components of the Human Head

The problems dealt with in the present thesis are basically problems of Continuum Mechanics having physiological applications. So as in the study of other applied problems of the Mechanics of Continua, for the study of the Cranial Biomechanics too, a thorough knowledge of the mechanical properties of the various tissues composing the cranial vault described in section 1.3, is extremely essential. For this reason, the main mechanical properties of the principal components (which are particularly important in studying the mechanics of the cranial vault) will be reviewed in this section, basing upon the observations of previous experimental studies.

The experimental observations reported by Advani and Owings (1974) and Gurdjian (1975) indicate that the outermost component of the head, viz. the scalp possesses viscoelastic properties. The average value of the bulk modulus has been reported to be approximately 2 GPa while the ultimate tensile strength and elongation are reported to be around 0.46 MPa and 54 % respectively. Moreover, the scalp is anisotropic ; its thickness varies from 6.5 mms to 13 mms.

The skull consists of an outer and an inner table of solid bone separated by a trabecular domain (diploë) with a total thickness ranging between 6.5 mms and 7.9 mms. (cf. Fig. 1.5). As mentioned in a foregoing section, the skull consists of eight separate bones, their junctions in an adult specimen is so calcified that it composes a single structural unit. Thus mechanically the skull material is nonhomogeneous and non-isotropic. The mechanical properties of skulls reported by various researchers (Haynes et al., 1969 ; Hubbard, 1970 ; McElhaney et al., 1970 ; Melvin et al., 1970a, b ; Robbins and Wood, 1969 ; Roberts and Melvin, 1969) seem to vary widely; it appears that the properties vary according to the sites of a given skull specimen. The different conditions (e.g. biopsy, autospy, frozen, embalmed etc.) also contribute to the determined physical constants of the tested specimen. For unembalmed compact skull bone the average isotropic values of the tensile and compression modulus have values around 14 MPa while the tensile and compressive strength are approximately 70 and 165 MPa respectively. The tensile failure strain seems to lie between 0.55-0.7 % . The average value of the compressive strength of the diploë is 34 MPa . When the skull is treated as a composite structure possessing transverse isotropy, the average radial compression modulus ranges from 0.4-3.6 GPa while the compression modulus ranges between 2.6 GPa and 5.6 GPa. Also the modulus in tangential tension varies between 5.4 GPa and 3.8 GPa. The Poisson's ratio ranges from 0.19-0.22. Corresponding to a structural Young's modulus of 10.2 GPa, Hubbard (1971) determined the bending stiffness of the skull to be nearly 2.75 Nm^2. The equivalent shear modulus was found to vary from 138-745 MPa and 138-690 MPa for the composite and for the core respectively. Melvin and Evans (1971) as also Wood (1971) reported the values of the ultimate strength as 71-145 MPa and 50-97 MPa when the samples were tested in radial compression and in tangential compression respectively, the value in tangential tension being 43 MPa.

Piekersky (1970), Pope and Outwater (1972) as also Wright and **Hayes** (1977) observed that the stress intensity factor (S.I.F.) of cranial vaults varies with the density of cranial bone ; for a specimen of density 2 Kg/m^3, the S.I.F. has got the value 4.0 $MN/m^{3/2}$, the corresponding strain-energy release rate being reported to be 1600 $N\text{-}m/m^2$.

Vibrational modes in living humans have been found by Gurdjian (1975) and Gurdjian et al. (1970)

at about 300 (antiresonance), 600 and 900 Hz (resonance), with some variability depending upon the location of the driving force and topography of the individual. Below 200 Hz, the skull moves as a rigid body and will so respond to impacts of more than 5 ms duration. The quasi-static elastic modulus and ultimate shear strength of dura were found to be 42 MPa and 2.3 MPa while its complex Young's modulus has been determined as 32.8 + 3.45 i MPa from free vibration tests at a particular frequency of 22 Hz by Galford and McElhaney (1970).

Experiments show that brain exhibits viscoelastic properties. Its bulk modulus is around 2 GPa (almost equal to that of water). Jamison et al. (1968), Galford and Mc aney (1970) and Goldsmith (1972) reported that for a direct shear at 10 Hz, if the complex modulus G^* be represented as $G_1^* + iG_2^*$, the ranges for G_1^* and G_2^* are respectively 550-1100 Pa and 225-655 Pa. But the corresponding ranges for torsion tests executed from 2-400 Hz were found to be 827 - 137, 900 and 345-82,700 Pa respectively. Metz et al. (1970) carried out experiments on animal brain and observed a decrease in modulus with time after death. Completely different values ranging between 0.46 - 50 poises were reported by various investigators for the viscosity of brain, at normal body temperature, the differences being attributed to the method of measurement. It was remarked that an average value of around 40 poises near 20°C may be taken for practical purposes.

The blood vessels of the cranial vault are nonlinearly viscoelastic. It was reported by Yamada (1970) that the ultimate tensile strength of a carotid artery is around 115 KPa and the ultimate elongation is approximately 36 % . These values correspond to human specimens of the age group of 20-29 years ; of course both of these values decrease with increasing age.

Since in one of the problems considered in the thesis the effect of the head neck junction has been considered, a few available informations are also given here. Yamada (1970) reported that the average ultimate tensile strength and ultimate elongation for cervical vertebrae are around 0.33 MPa and 0.8 % . Also stress-strain curves for vertebrae, discs and skeletal muscle exhibit concave upward trends.

The main mechanical properties of dura which represents the interior lining of the skull, are anisotropicity and inelasticity.

The pia-arachnoid complex is made up of a gossamer tissue whose strength characteristics are ignorable. The cerebrospinal fluid contained in the subdural space (described in section 1.3) is a colourless fluid having specific gravity of 1.004-1.008 and can be approximately represented as a Newtonian fluid.

1.6 Experiments on Skulls of Cadavers, Live and Dead Animals and Use of Experimental Models

All the experimental studies which were referred to in the preceding section were made for the determination of the mechanical properties of different components of the cranial vault. In the present section, an attempt is made to briefly review some of the important experimental investigations which were performed on the skulls of embalmed and unembalmed cadavers, live and dead animals and artificial head forms in order to ascertain causes of head injury and to collect enough pathological information to establish tolerance limits.

Evans et al. (1958) studied the relationship of energy, velocity and deceleration to skull fracture in their experimental investigation. The intact human heads from adult embalmed cadavers were taken in their free and guided fall tests on to an automobile instrument panel and they have come to the conclusion that not only the magnitude of the available energy but also its rate of absorption is important to consider the mechanism of skull fracture. Lissner et al. (1960) investigated whether or not the body weight augmented the impact of the head in the sense that whether the body was attached to the head produced a more severe impact to the head than if the head alone were dropped on the panel. By making a gelatin-filled head strike a thin still plate, an automobile panel and a large steel block they tried to establish a relationship between the acceleration and the intracranial pressure. Gurdjian et al. (1950) observed the areas of different stress levels in the skull subjected to blows in various locations on the skull surface and finally correlated their observations with clinical skull fractures. In 1961, Gurdjian and Lissner (1961) investigated the relationship between intracranial acceleration and impact velocity in their experiments in which the heads of human cadavers struck laminated tempered safety glass panels.

Mertz and Patrick (1967) observed the kinematics of rear-end collisions based on known acceleration pulses of actual car-to-car collisions on a crash simulator using anthropomorphic dummies, human cadavers and a volunteer. The responses of both dummies used were not comparable with those of cadavers or the volunteer or to each other. Based on their observations, they arrived at a conclusion that the head torque rather than the neck shear or axial forces is the major factor in producing neck injury. Ommaya et al. (1966a) tried to illustrate the possible injury mechanisms occurring in whiplash and head impact. From their experimental observations on monkeys they concluded that multiple mechanisms are involved in cerebral concussions ; among them rotational acceleration of the head, flexion-extension-tension of the neck and intracranial pressure gradients are perhaps the most significant. Patrick (1966, 1967) performed an experiment impacting cadavers with automobile windshields to investigate the potential head and neck injury.

Hodgson et al. (1967) measured the force input by using a force generator attached directly to the skull of an embalmed human cadaver and obtained the effective mass and stiffness in the frequency range (5 to 5000 Hz) with the help of a linear simple degree-of-freedom model. The driving point impedance characteristics of the human and monkey head over the frequency range 30 to 5000 Hz was determined by Stalnaker et al. (1970). In vitro experiments on a fresh human cadaver as also both the in vivo and in vitro experiments on monkeys were carried out. Using a linear two degrees of freedom model, the results were presented with appreciable accuracy.

Holbourn (1943), in his experimental study with a gelatin-filled model, illustrated the stress paterns generated between the brain and the skull owing to an input angular acceleration. He also observed that the shear strains produced by linear acceleration are found mainly in the neighbourhood of the foramen and in the neighbourhood of the ventricles due to slight differences in density between the cerebrospinal fluid and the brain tissue. He further concluded that the shear strains produced by linear acceleration could be neglected compared to those produced by rotational acceleration. Gurdjian and Lissner (1961) further observed that the generation of pressure gradients arising from acceleration or deformation of the skull may cause shear stresses in the brain stem area. They used a two dimensional photoelastic model to show that the region of the craniocerebral junction is an area of high shear stress concentration.

Unterharnscheidt and Sellier (1966) pointed out that head acceleration and skull deformations produce intracranial pressure changes in sufficiently reduced form which result in cavitation at the antipole and points of skull outbending. They claimed that this cavitation hypothesis is the principal cause of brain damage. Gross (1958) produced experimental cavitation by impacting water-filled flasks. By taking a water-filled human skull, the pressure gradients were measured in three mutually perpendicular directions by Roberts et al. (1966) and the regions of negative pressure were pointed out. Gurdjian and Lissner (1961) also concluded that the foramen magnum of the model is a region in which an external blow to the skull responds in the development of shear strains in the fluid. A plastic model of a sagittal section of the skull including formamen magnum filled with 1.5 % solution of milling yellow was used for their experiment.

1.7 Head Injury Mechanics, Different Types of Head Injuries

That the behaviour of a head during and immediately after the application of a blow can be studied by employing Newton's laws of motion through the use of the physical properties of the various components of the head, indicates that there exists a mechanics of head injury.

An injury to the head may occur due to damage of its various components, viz.

i) Scalp damage : A damage to the scalp may occur owing to an impact with a sliding object, which may result in denuding the superficial skin or due to a cut of the skin by a sharp object. The injury to the skull may also involve leakage of blood from the broken vessels into surrounding tissues below the skin.

ii) Skull damage : There may be various reasons for skull damage. It may be in the form of a depression of the skull due to a high speed projectile or a heavy falling object (e.g. bricks or stones) or interior vehicular structures under crash conditions, which may lead to perforation of the skull bone and fracture. The depression may also be caused due to a missile which may lead to fragmentation of the bone. A damage to the brain may also occur due to a static or quasi-static loading on it, produced by a relatively long time crushing of a heavy object. In the case of young children where the skull is a bit shofter, there may be a permanent deformation of the skull without fracture.

iii) Brain damage : The two types of damages to the head, described above are invariably due to a direct impact or a blow, whereas a direct impact or an impulsive load due to a sudden acceleration (or deceleration) of a considerable magnitude can cause brain injury. The injury may be in the form of concussion, contusion, laceration or intercerebral hematoma. In most cases, an injury to the brain can not be easily detected. This is why, the occurrance of brain injury has to be speculated by neurological or pathological malfunction. Based upon the observations of past experimental as well as theoretical investigations on intracranial trauma, three different, relatively independent, postulates have been put forward, which help understanding the growth and development of neurological damage.

1.8 Hypotheses on Brain Damage

The first hypothesis for explaining the mechanism of brain injury, usually described as the cavitation hypothesis, illustrates the contrecoup lesions which are usually observed at the pole opposite to the point of impact. According to this postulate, following an impact on the head, an area of negative pressure is developed at the contrecoup site and this causes capillary rupturing in this region. The pressure in the contrecoup region is described as 'negative' by Unterharnscheidt and Sellier (1966) in the sense that the pressure is less than that before the impact has occurred. They examined the effect of a blow on a fluid-filled spherical vessel as a physical replica of the head and observed that if the vessel be struck by a blow of a duration longer than the transit time of a pressure wave through the vessel, the pressure that is developed within the vessel varies linearly from the point of application of the blow to the contrecoup site where the negative pressure is developed. Similar observations were also reported by Roberts et al. (1966). In an attempt towards determining the extent to which the flexibility of the shell and the compressibility of the fluid can be ignored, Kopecky and Ripperger (1969) used a sealed cylindrical shell (the shape of the shell being considered unimportant) made of plexiglass and filled with a hydraulic oil of specific gravity 0.85 and concluded that in the case of a real fluid, the absolute pressure (atmospheric pressure minus magnitude of the 'negative pressure') can never drop below the cavitation pressure of the fluid and that the negative pressure at a given acceleration varies nonlinearly with the bulk modulus of the fluid. Sellier and Unterharnscheidt (1965) also reported that the capillaries mentioned above are normally subjected to a pressure differential of only a few mm Hg. In most cases the maximum value of the developed negative pressure is around - 1 atmosphere, but as the acceleration is increased, the pressure exerted by the surrounding tissues is rapidly reduced and thereby the pressure differential across the capillary wall is increased enormously. As a result the small vessels rupture. They, however, remarked that the word 'contrecoup' does not fit well in reference to cavitation hypothesis, since the injury to brain occurring in the antipole region is not due to the impact of tissue on bone.

The second postulate suggests that brain injury can occur due to flexion or extension of the upper cervical cord followed by fracture and dislocation of the cervical spine. Such fractures can occur when the head is fixed but is subjected to severe hyperextension while the body moves further forward. This situation is described as 'whiplash' and is possible in the case of a rear-end vehicular collision. It has been reported in the literature that such a situation may also lead to cerebral concussion (Ommaya et al., 1967).

The third postulate described as the rotation hypothesis, states that angular acceleration of the head plays a very important role in causing damage to brain. In fact some investigators are of the opinion that rotational acceleration is the most serious cause of brain damage. Holbourn (1943, 1944) seems to be first to propound this idea on the basis of his experimental observations. He remarked that the effect of translational or linear acceleration is meagre, compared to that of rotational acceleration, in producing maximum shear. The angular acceleration causes a shear which is normal to the radius of rotation. As pointed out by Strich (1969), the shear may damage tissues in the cortical and subcortical regions when the forces are considerably great. In resulting concussion also, the effect of angular acceleration on pressure gradients across the skull is significantly important. The experimental observations of Ommaya et al. (1964, 1967a, 1967) also confirmed this postulate. Deny-Brown (1945), Deny-Brown and Russel (1941) as also Sellier and Unterharnscheidt (1965a, 1965b) determined the velocity and acceleration that can cause cerebral concussion in experimental animals.

1.9 Importance of Model Studies in the Realm of Cranial Biomechanics

Since harmful experiments cannot be carried out on living human beings and since observations on the tests carried out with experimental animals cannot be readily used for human bodies, the consideration of models in the study of human head impact has got its own importance. For this purpose one can consider either physical models or mathematical ones. It is agreed that although physical models can be constructed more realistically than the mathematical models available till date, their applicability has got limitations due to difficulties one faces while taking necessary measurements and due to the time required to collect the necessary data. But by considering mathematical models one can explore a variety of cases in a comparatively small span of time. The use of such models is also inevitable in cases where experimental investigations are rather difficult or even sometimes impossible.

1.10 Geometrical Shape of the Head

In most of the previous model studies, the geometry of the brain case was considered to be perfectly spherical. This assumption simplyfies the studies to a considerable extent, whether it is a case of a mathematical model or a case of experimentation by the use of a physical replica of the head. But Unterharnscheidt et al. (1966) and Goldsmith (1972) indicated that the eccentricity of most of the skulls is considerably pronounced. Goldsmith (1972) suggested that a prolate spheroidal shell (with the ratio of its major to minor axis equal to 4/3) could be a better representative of the human head than a spherical shell. In fact the skull eccentricity was proved to be a potential factor in the studies of various aspects of the cranial biomechanics by several investigators (cf. Merchant and Crispino (1974), Talhouni and DiMaggio (1975), Misra (1978a, 1978b), Misra et al. (1977, 1978)).

A brief account of previous theoretical studies relevant to the problems considered in the present thesis is given in the following section.

1.11 A Brief Account of Previous Analytical Studies on the Mechanics of the Cranial Vault

Since World War II a good number of analytical studies on the mechanics of the cranial vault with particular emphasis on the head injury mechanics has been made alongwith relevant experimental investigations. The importance of analytical studies in this area has been indicated in section 1.9 . A brief account of theoretical studies relevant to the problem considered in the thesis, will be presented here.

The first systematic study in this area through the use of a simple mathematical model seems to be made by Anzelius as early as 1943. He considered the effect of a certain impulse load on a mass of inviscid liquid contained in a closed rigid spherical vessel. The vessel considered was assumed to have a constant translational velocity for $t<0$ and suddenly brought to rest at $t=0$.

Gütinger (1950) put forward a similar analysis for a fluid filled rigid spherical shell initially at rest and at t=0, a momentary impact force was assumed to accelerate instanteneously the vessel to a constant velocity which the vessel retained for all $t>0$. Though their basic assumptions were slightly different, both of them concluded the same idea regarding the cause of brain damage. They concluded that an initial compression wave arises from the pole of impact and due to the rigidity of the shell, instantaneously a tension wave is emitted from the counterpole and finally both the waves approach towards the geometric centre of the system. The superposition of the two waves at the centre produces large changes in the fluid pressure. This fact was considered to be the cause of brain damage. A one-dimensional version of the Anzelius-Gütinger model was considered by Hayashi (1969). He also examined the case of a rigid vessel containing an inviscid fluid (representing the brain) when the vessel is connected to a linear spring which represented the composite structure of the scalp, skull etc. The effects of mild and hard impacts on the structure were studied analytically. But due to the assumption of rigidity of the container, the studies mentioned above fail to account for the influence of skull deformation on the craniocerebral trauma and to determine the possible locations of the skull fracture.

This defect led Goldsmith (1966) to suggest that for studying the mechanics of head injury, the braincase be considered as elastic. By removing the restriction of rigidity of the shell, Engin (1969) made an improvement of the problem and studied the axisymmetric transient response of a thin elastic spherical shell filled with inviscid compressible fluid subjected to a local radial impulsive load, as a model for head injury. He considered the shell material and fluid inside to be linear, homogeneous and isotropic. A continuum model, intended for vertical impact studies, based on small deformations and rotations was proposed by Liu and Murray (1966) consisting of an elastic rod surmounted rigidly to a mass, the rod being the representative of the torso and the attached mass that of the head. The model was improved subsequently by Martinez and Garcia (1968) as also McKenzie and Williams (1971) by considering linear and nonlinear lumped parameter models. Axisymmetric vibration of a fluid-filled elastic spherical shell (with reference to a head) was considered by Engin and Liu (1970), using thin shell theory. Further Engin and Liu (1970) like most of the earlier investigators, considered the skull to be thin and homogeneous. Lee and Advani (1970) studied the effect of torsional impact acceleration of the head by considering a mathematical model. They studied the transient response of a linear elastic sphere to a step input acceleration about a diametrical axis through the use of superposition principle. Corresponding results for the linear viscoelastic response were also derived. Benedict, Harris and Rosenberg (1970) in their investigation considered the skull to be a thin, homogeneous and isotropic spherical shell as also the brain to be an ideal acoustic fluid and the impact to be arbitrary time dependent. Engin's solution was further extended by Liu, Chan and Nelson (1971) by retaining bending terms and considering a finite duration pulse as input. Engin and Roberts (1971) studied the response of a fluid-filled elastic shell subjected to a global axisymmetric impulse on its boundary. The determination of the excess pressure distribution in the fluid was considered to explain the behaviour of the brain under conditions in which the application of local forces on the skull is avoided. This study may be considered as a generalisation of the models used by Anzelius and Gütinger mentioned above, in the sense that the restriction of the rigidity of the shell was removed in this study.

A poroelastic spherical shell model for the human head was studied by Nowinski and Davis (1970). In this study, the osseous tissue was considered to be a linear perfectly elastic solid while the fluid substances filling the cavities was treated as Newtonian viscous. In the analysis, they made use of the Heinrich - Desoyer formulation of the consolidation theory of Terzaghi - Biot adapted to the spherical bodies and the Laplace transformation.

A mathematical model based on the principles of continuum mechanics was developed by Engin and Wang (1970) for the determination of the viscoelastic behaviour of in-vivo primate brain. The complex dynamic shear modulus of the primate brain in-vivo was obtained from the combined relationships of theoretical analysis and experimental data. From the mathematical point of view, the problem being taken up was that of steady state response characteristics of a solid sphere of linear viscoelastic material whose mating surface with the rigid boundary is free from shear stresses. The external load was chosen to be local radial harmonic excitation. This theoretical model corresponded to an experimental set up consisting of an electromechanical device with a small driving point impedance probe which was placed in direct contact with the pia-arachnoid through a hole in the skull of a Rhesus monkey.

By using three dimensional equations of linear viscoelasticity both for the skull and the brain, the steady state solutions for the case of axisymmetric torsionless deformations were obtained using a Fourier synthesis by Hickling and Wenner (1972). The distribution of stresses in the skull and the brain as well as the pressure distribution in the brain was also estimated by using their analysis. They all considered spherical geometry for the head.

By assuming the skull as a rigid spherical shell and the brain as a linear viscoelastic material, the problem of finding the steady state response characteristics of a head subjected to a local radial harmonic excitation, was studied by Wang and Wineman (1972a). They established an equation for the material parameters in terms of the force and displacement of the excitation and developed a technique for solving these parameters when experimental data are known. With similar assumptions for the skull and the brain, Wang and Wineman (1972b) considered the stress relaxation induced by a small step displacement of a probe. The problem was formulated as a quasi-static boundary value problem ; a nonlinear Volterra integral equation is established from which the shear stress relaxation function can be solved in terms of the probe displacement and force. A numerical method of solution was also developed.

A finite element analysis for the skull treated as an elastic material was put forward by Hardy and Marcal (1973). They concluded that the skull is stronger to front loads than the side loads. On the basis of tensile fracture at maximum elastic stress loads of 1600 Kgs and 635 Kgs (approx) were predicted for the fracturing of the skull due to front and side loading respectively.

In all the aforementioned model studies related to head injuries the geometry of the braincase was considered to be perfectly spherical. This assumption simplyfies the studies to a considerable extent. Due to lack of sphericity of the skull, Goldsmith (1972) suggested that a human skull can be better represented by a prolate spheroidal shell, with the ratio of major to minor axes of about 4/3. In fact the skull eccentricity was proved to have a significant contribution in the studies of various aspects of the cranial biomechanics by several investigators (cf. Merchant and Crispino, 1974 ; Talhouni and DiMaggio, 1975 ; Misra, 1978a, 1978b ; Misra et al., 1977, 1978). By considering a prolate spheroidal shell filled with an inviscid liquid, Talhouni and DiMaggio (1975) obtained the distribution of stresses in the shell and pressure in the fluid by finite difference method, the load applied on the shell surfaces, was in the form of a uniform step pressure. Also Merchant and Crispino (1974) studied brain damage caused by the generation of tensile pulses in the brain for axisymmetric impact by modelling the head as a fluid-filled spherical shell and a prolate ellipsoidal shell of revolution. Solutions were obtained by employing numerical techniques. The mechanical wave propagation generated in the brain when the head is subjected to an angular acceleration of a given amplitude and duration was studied by Bycroft (1973). He obtained a closed form solutions of the mathematically formulated problem and finally expressed the generated shear strain in terms of infinite series. His prediction mentioned above was on the basis of a numerical computation of the infinite series. Liu and Chandran (1974), however, raised questions regarding the accuracy of the numerical results reported by Bycroft. They pointed out that the type of infinite series as in Bycroft's solution is very slowly convergent and hence is not convenient for numerical computation in general and more particularly for small values of time. The exact, closed form solution of a wave propagation problem for the case of a purely elastic material contained in a rigid spherical shell subjected to a rotational acceleration considered as a general function of time, was reported by Liu and Chandran (1973). It was indicated that the infinite series in terms of which the analytical solution was obtained, were rapidly convergent. The response of a linear viscoelastic (Kelvin type) material contained in a rigid spherical shell subjected to rotational accelerations, in reference to rotational brain injury models, was studied by Liu et al. (1975). Numerical methods were applied for treating the problem. Ljung (1975) studied analytically the effect of a rotational impact on head. He considered rigid shells with viscoelastic material as models of his study. Three different geometries were examined viz a long cylindrical shell, a semi-infinite cylindrical shell bounded by a plane wall at one end and a spherical shell. By using a sandwich spherical shell model, a dynamic problem of cranial mechanics was analysed by Akkas (1975) through the use of numerical methods. He considered the shell to be thin and elastic while the fluid contained in it representing the brain was taken to be inviscid and compressible. In all the studies mentioned above, the skull brain system has been considered as a free-floating system. But in reality, the motion of the head is certainly controlled by the neck and its muscles and ligaments. The role of the neck in studies relating to injuries of the cranial system seems to be first discussed by Landkof, Goldsmith and Sackman (1976) who studied the problem through the consideration of a mathematical model as well as a physical model of the human head. They dwelt on direct axisymmetric impacts (of course non-destructive) on the head.

Recently, while considering the vibration of the human skull brain system, Misra (1978a) modelled the skull as a prolate spheroidal shell of visco-elastic material and the fluid contained in it (representing the brain) also as viscoelastic. This modelling of the human head seems to be the most improved one among all others available till date, in as much as the viscoelasticity of both the brain (as experimentally established by Jamison, 1968, Fallenstein, Hulce and Melvin, 1969) and the skull as well as the eccentricity of the shell was taken into account under the purview of a single analysis. The effects of various pulse shapes on injuries to the brain and the skull were also studied by Misra, Hartung and Mahrenholtz (1977, 1978) and Misra (1978b). Unlike most of the earlier studies, due attention was paid to the thickness of the skull in these investigations.

1.12 Scope of the Present Thesis

As reported in the previous section, a good number of analytical studies on cranial Biomechanics has been made by previous researchers. Even then it is felt that some important aspects of this domain of Biomechanics have not been paid due attention. The present thesis deals with a few problems of this field, which are believed to be of much interest to bioengineers as well as to medical persons. All the problems are treated by analytical methods together with the use of numerical techniques wherever necessary.

Of concern in the second chapter is the problem of free-vibration of the cranial vault. The dissipative material behaviour of both the skull and the brain (in conformity to observations of previous experimental studies reported in section 1.5) has been accounted for. Two models are considered for studying the problem. In one model, the layered structure of the skull is paid due attention, the outer surface of the skull being assumed to be traction-free. The second model assumes homogeneity of the skull but takes into account the mechanical influence of the scalp. Results of numerical computation of the derived analytical expressions indicate that the dissipative behaviour of the skull and the brain and also the mechanical effect of the scalp influence significantly the frequency spectrum of the freely vibrating cranial system.

The third chapter is devoted to a study on the threshold of concussion caused due to brain injuries which may occur owing to an input angular acceleration. The eccentricity of the cranium is incorporated through the consideration of a prolate spheroidal shell as the representative of the skull. Here too, viscoelasticity of the brain is considered, as in the preceding chapter. Prolate spheroidal coordinates have been used in the analysis. The solution of the problem after formulating it mathematically, is first sought in the Laplace transform space. Use of finite difference technique, and alternating - direction - implicit method together with Thomas algorithm are used for obtaining the transformed angular acceleration. The Laplace inversion is carried out with the help of numerical proocedures (Gauss quadrature formula is used for the purpose). The results of a parametric study are presented through graphs. The plots illustrate the threshold of cerebral concussion. A comparison of the computational results with those of previous investigations indicate that the eccentricity of the braincase plays a dominating role in the determination of the threshold of concussion.

The dynamic response of the head-neck system to an impulsive load is dealt with in the fourth chapter of the thesis. For this study too the eccentricity of the skull is taken into consideration and the fluid contained in it which serves as the representative of the brain matter is treated as viscoelastic. The neck is considered as a viscoelastic beam attached to the shell representing the skull. The impact force is assumed to be distributed uniformly over a particular region of the skull. The case of an input pulse varying sinusoidally with time is studied in particular. The problem is solved by resorting to numerical techniques.

In the fifth chapter we discuss the stability of fluid-filled shells under external hydrostatic pressures, with reference to head injury mechanics. The problem approximately represents the situation of skulls of skin divers who have been reported to reach pressures equivalent to 1000 ft. of sea water. By applying the energy method, the critical loads of such systems are examined.

A poroelastic model for the cranial biomechanics is considered in the sixth chapter. While the porosity of the skull has not been accounted for in the study of the problems described in the foregoing chapters, the analysis given here is based on the assumption that in between the outer and inner tables of the skull there is a porous layer (called the diploë) . The problem considered here corresponds to a case of an axisymmetric impact load applied to the head. The damping effect of the brain matter is paid due attention.

The seventh and the concluding chapter is concerned with the use of an analytical model to study the effect of solar radiation on a human-sized head. The braincase is taken to be consisted of two layers, -

one representing the scalp and the other, the skull. The material of each layer is considered elastic and transversely isotropic. The applicability of the model is illustrated through the computation of the stress-field in the scalp as well as in the skull.