CEREBRAL SWELLING: ITS PHYSIOLOGY, PATHOLOGY, CLINICAL SYMPTOMS AND SIGNS, DIFFERENTIAL DIAGNOSIS AND TREATMENT

by
W. J. Atkinson, M.D., F.R.C.S.
The London Hospital, Whitechapel, E.1.

INTRODUCTION

THE SUBJECT OF brain swelling is of considerable importance to the neurosurgeon because not only does it complicate head injuries and intracranial operations but it is associated in various degrees with intracranial inflammations and neoplasms. It is often difficult to separate the disturbances due to the primary pathological lesion from those caused by the associated cerebral swelling.

Much confusion and controversy has arisen over the definition and criteria of brain swelling and for my thesis it is defined as any increase in brain volume however small. The term " cerebral swelling " applies more strictly to any increase in the volume of the cerebrum. The arguments as to when its volume has actually increased in relation to its surroundings will be obvious in subsequent sections and the subject of cerebral or brain oedema will be discussed in the light of those arguments.

PHYSIOLOGY

The influence of respiratory movement. The dural sinuses and the cerebral veins contain blood which is directly continuous, without the intervention of valves, with that in the right auricle of the heart. The excursions of the thorax produce variations in the pressure within the right auricle which are transmitted directly to the dural sinuses. These are almost inelastic, and can neither collapse nor expand and any alteration in their contained pressure is directly transmitted into the cerebral veins. During inspiration the pressure in the right auricle falls and during expiration it rises. This variation of pressure is transmitted directly to the dural sinuses and the cerebral veins.

The brain may be observed directly in man in the course of an exploratory craniotomy, and, in some conditions, such as intracranial aneurysm or pituitary adenoma, the exposed brain may be said to be normal. The transmitted cardiac impulse may be readily seen in the arterial pulsation on the surface of the brain. Less distinctly, alterations in brain volume can be seen in the different phases of respiration. During the latter part of inspiration the brain appears to recede from the dural defect and in the latter part of expiration it appears to swell towards the dural defect.

This " respiratory " excursion of the brain in response to the different phases of respiration is of considerable importance in the interpretation of physiological and pathological events relating to brain volume. It is logical to presume that it occurs when the cranial cavity is intact; the

alterations in pressure exist whether the cranium is intact or not. There must still exist the tendency for the brain to swell in the latter phase of expiration and to recede from the dural walls in the latter phase of inspiration owing to the alterations in pressure in the thoracic cage. Presumably some medium must take the place of the brain during its phase of recession from the dural walls ; when the cranial cavity is opened, as in a craniotomy exploration, air serves as that medium. In the intact skull, that medium may be cerebrospinal fluid. If this is true then, within the intact cranium, there is a continuous alternation between the volumes of the brain and cerebrospinal fluid. In the latter phase of inspiration the brain volume tends to diminish and cerebrospinal fluid is " drawn " vertically from the basal cisterns towards the superior sagittal sinus by the lessened pressure in the supracortical subarachnoid spaces. In the latter phase of expiration when the brain volume tends to increase and the supracortical subarachnoid spaces diminish in size, the cerebrospinal fluid is presumably dispersed either into the arachnoid villi or into the basal cisterns.

The choroid plexuses secrete cerebrospinal fluid, according to most authorities, into the ventricular system and its rate of formation appears to be constant relatively to the arterial blood pressure. In its central position this cerebrospinal fluid " fountain " is ideally situated to provide the medium which alternates with the cerebral venous blood in the different phases of respiration.

With these assumptions in mind certain events, observed in the exposed brain, may be explained. (1) When any condition disturbs the thoracic respiratory rhythm the cerebral excursions during respiration appear to be accentuated. An excessively slow rhythm increases the amplitude of the excursions whereas a rapid rhythm is associated with a much less perceptible rhythm in the cerebrum. During a prolonged expiratory phase the rising pressure in the superior sagittal sinus, and therefore the cerebral veins, makes for a more marked swelling of the brain towards the dural defect ; and a prolonged inspiratory phase occupies a longer time in draining the superior sagittal sinus and cerebral veins. When thoracic excursions are limited the influence of respiration on the cerebrum excursions is less pronounced because the alterations in pressure within the superior sagittal sinus are less. (2) When the systemic arterial pressure is below the region of 90/60 mm. mercury a similar increase in the cerebral respiratory excursions may be seen. In these circumstances the ordinary thoracic excursions may be present and impose their ordinary influence on the drainage of cerebral venous blood, but the entry of blood into the brain is presumably delayed, owing to the lower arterial pressure ; the cerebral excursions are therefore increased because the respiratory influence is more effective in draining less venous blood. (3) An interesting event happens in the experimental animal when it is anaesthetised by means of local infiltration of the skin areas with procaine solution and the intravenous injection of curare, artificial inspiration being carried out with an alternating pressure apparatus through an endotracheal tube.

If the brain is exposed it will be seen that the respiratory phases are reversed from their normal character ; the phase of inspiration is now associated with a movement of the brain *towards* the dural defect instead of one away from it and the phase of expiration is associated with one away from the dural defect. Under these circumstances artificial respiration is carried out through an endotracheal tube with a machine which alternates the intrapulmonary pressure from atmospheric to one more than atmospheric—the period of most positive intrapulmonary pressure corresponds to inspiration and this is the opposite of what prevails normally when inspiration is the period of lowest negative intrathoracic pressure. Likewise the phase of expiration is that of the least intrapulmonary pressure, i.e., atmospheric, and again this is the opposite of normal conditions in which the phase of expiration is that of highest intrapulmonary pressure. In these artificial conditions then, the cerebral excursions caused by respiration are reversed because the phases of alternating pressure within the chest are reversed. (4) In the course of a neurosurgical craniotomy the effect of a sudden increase in intrapulmonary pressure may be seen if the patient is permitted to cough. There is an immediate swelling of the brain towards the dural defect ; sometimes the surgeon can tell before the anaesthetist that there is likely to be such an event, so readily is the intrathoracic pressure transmitted to the brain. It is always serious because the cerebral swelling that results embarrasses both the patient's cerebral circulation and the surgical endeavours.

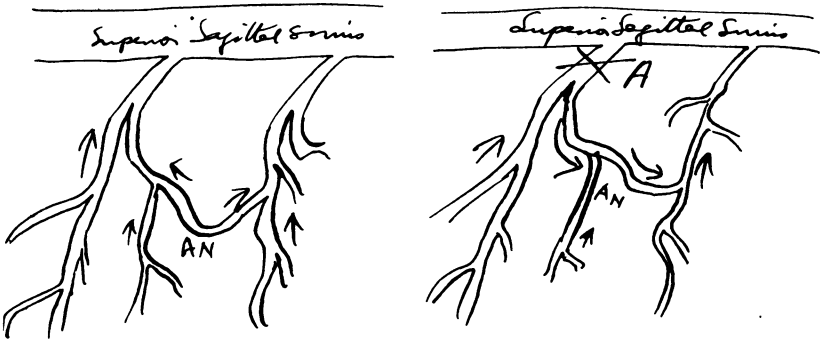
The influence of respiratory gases. In 1928 Wolff and Lennox carried out experiments on animals to measure the influence of various respired gases and injected drugs on the calibre of pial vessels, exposed by craniotomy and dural defect. They found that any increase of the normal proportion of carbon dioxide in the respired gases produced the most marked and immediate increase in the calibre of the vessels ; a diminution of the oxygen proportion had a similar but much less marked effect. The significance of these observations may be seen sometimes in the course of a neurosurgical operation when the brain is exposed and the oxygen supply has failed. There is an immediate increase in the cerebral volume which may reach alarming proportions. Similarly, if an experimental animal is permitted to rebreathe its own air in a restricted space, the brain, exposed in the usual way, is seen to swell *pari passu* with the increase in respiratory excursions. Presumably in both human and experimental examples there exists an excess of carbon dioxide and a lack of oxygen. (See Appendix I.)

The influence of the vasomotor system. Brain which is exposed through a dural defect, but is otherwise under normal conditions, pulsates with each heart beat. This minute alteration in cerebral volume is increased whenever the systemic arterial pressure rises. This may be seen in the experimental animal if it is given an intra-peritoneal injection of adrenaline ; the brain is seen to swell towards the dural defect as the systemic arterial pressure rises and then to recede as the pressure returns

to normal. Under these conditions an increased amount of blood flows into the cerebral capillaries while the ordinary means of cerebral venous drainage from respiratory excursions does not alter significantly. The cerebral veins cannot " take on " the increased influx of blood immediately and the brain therefore swells.

If an experimental animal is subjected to an excess of carbon dioxide, as when it rebreathes its own air in a restricted space, and is then given an intraperitoneal injection of adrenaline it will be obvious that the brain is subjected to at least two of the influences described above. The exposed brain will then be seen to swell considerably towards and even through the dural defect. Here the increase of cerebral swelling can be attributed to the combination of dilatation of the cerebral vessels under the influence of carbon dioxide excess and increased blood flow occasioned by the adrenaline injection and consequent rise in systemic pressure. (Appendix I.)

The influence of lesions of the brain stem. The artificial conditions imposed in the above experiments have their counterparts in events which may be observed either experimentally in animals or during the course of surgical operations in human cases. Sometimes the arteries supplying the hypothalamus or tegmentum are injured in the course of the removal of an intracranial tumour (Atkinson, 1949, and 1950). Alternately, a tenotome may deliberately make a lesion in these areas in animals. In either set of circumstances a rise in the systemic arterial pressure occurs and the alterations in the brain volume are exactly like those seen when an injection of adrenaline is given. If, at the same time, there is also an impaired respiratory mechanism a marked swelling of the brain will result. In the animal these conditions may be arranged by making it rebreathe its own air as in the previous experiments. In the human cases similar conditions occur because the arteries, the occlusion of which injures the brain stem, also supply relatively large areas of the cerebrum or cerebellum and their occlusion impairs the local tissue respiratory interchange in the territory concerned. For example, an occlusion of the basal part of one anterior cerebral artery often causes infarction of the anterior hypothalmic areas and head of the caudate nucleus on that side but also causes infarction of the cerebral hemisphere itself in the region of the paracentral lobule. Consequently when arterial injury affects the hypothalamus or brain stem and the systemic arterial pressure rises, the same arterial territory of cerebrum or cerebellum undergoes an accumulation of carbon dioxide and a lack of oxygen from the respiratory disturbances of ischaemia, and also it suffers the effects of a sudden rise in the systemic arterial pressure. This event has been seen in both the difficult surgery of tumours about the inner end of the lesser wing of the sphenoid and that of acoustic nerve tumours ; and acute and severe degree of brain swelling may result under these circumstances. It is interesting that it was this occurrence which Clovis Vincent noticed and described as " l'oedème aigu " in 1936.



(*a*) (*b*)

Fig. 1. (*a*) Normal circulation of venous blood into superior sagittal sinus. (*b*) Alteration of venous blood flow necessitated by occlusion of cerebral vein near superior sagittal sinus at Point A where the effect of the spur at the junction of venous tributaries is shown. Arrows show direction of venous flow of blood. Arrows show anastomotic venous channel.

The influence of cerebral venous compression. It has been claimed (Beck and Russell, 1946) that the division of cerebral veins near the superior sagittal sinus does not lead to "cerebral oedema." The exposed brain in these experiments was not noticed to swell, and, histologically, no evidence of oedema could be demonstrated. In a small animal a relatively large dural and cranial defect would accommodate a moderate degree of brain swelling without being macroscopically obvious. Also, small alterations of cerebral venous congestion are extremely difficult to show histologically by present known methods.

If, in the course of a neurosurgical operation, designed, for example, to explore the pituitary fossa (when the brain is presumably normal) a cerebral vein is occluded near the superior sagittal sinus, the gyri immediately adjacent to the vein may be seen to swell. This swelling is never considerable and the relatively large craniotomy adequately accommodates the extra brain volume without embarrassment to the surgeon. If several of the cerebral veins related to a frontal lobe are occluded then quite significant swelling of the brain results, the related gyri swell, become broader and paler, and lose their "respiratory excursions." The absence of valves in cerebral veins has led to the belief that cerebral venous blood may freely communicate in all cerebral veins and any back flow from occlusion of these veins may be readily accommodated by the remaining patent cerebral veins. This is not necessarily so; the structure of the venous branch junctions may be so designed that any back flow can only be redirected with difficulty. (Fig. 1.)

An illustration of this may be seen in the freshly removed human brain. If normal saline is injected into a cerebral vein near the vertex of the cerebrum in a direction away from the vertex—i.e., in the reverse direction from the normal—the related gyri are seen to swell up and become pale rather like the appearance seen at a neurosurgical operation

when a cerebral vein is occluded near the superior sagittal sinus. If the cerebral venous system readily communicates throughout its extent, this reverse injection should not cause gyral swelling and congestion—even in the cadaver.

An application of this observation may be made in cases where the cranial vault is intact. A significant finding in cases of even small intracerebral " tumours " is that the overlying gyri are broadened, pale and *flattened.* This would be anticipated if the tumour had produced a local cerebral venous occlusion. Cerebral veins lie in the outer parts of the sulci adjacent to the inner surface of the dura mater and therefore may be readily compressed by an expanding intracerebral lesion. Presumably the venous blood in the abnormal area is shunted into the remaining patent veins. If the intracerebral tumour occludes more and more cerebral veins, there may come a moment when the remaining patent veins will be inadequate to deal with the shunted venous blood. At this moment the cerebral venous system in that hemisphere may be said to be relatively incompetent to take the incoming blood, and venous congestion becomes extreme. Transudation of fluid into the interstitial spaces, i.e., oedema, follows.

This " relative " venous incompetence may be the explanation for some cases of small meningeomata which occur on the convexity near the superior sagittal sinus. There may be unilateral cerebral swelling with considerable oedema of the white matter at postmortem. The small tumour may locally occlude cerebral veins whose territory must then be drained by the remaining patent veins. At some moment these veins may be further overloaded such as during an epileptic seizure or during a difficult induction of anaesthesia prior to surgical operation, when the intrathoracic pressure is excessively increased and the pressure in the dural sinuses and cerebral veins rises. The cerebral venous system may then become incompetent and the excessive venous congestion may result in generalized oedema of the hemisphere. If the tumour has also abnormal blood vessels about and within it, then obviously any venous congestion has a more marked effect about the tumour area. (*Vide* Pathology.)

PATHOLOGY

In 1905 Reichardt considered the relationship between brain and cranial volume and found a mathematical criterion for the diagnosis of brain swelling. He excluded many conditions in which the volume of the brain increased, e.g. those in which there was excessive vascularity or free fluid. Since that time many have differentiated between " swelling " and " oedema " by various methods and criteria. Alexander and Looney in 1938 attempted to show the presence of oedema by a comparison of the wet and dry weight of the brain postmortem, but it is impossible to differentiate, with this method, cerebral oedema from atrophic and hydrocephalic brains. In 1939 Stewart-Wallace found that oedema

fluid from the brain had a high chloride content but this observation can only be made in cases where the presence of cerebral oedema is obvious anyway to the naked eye. Le Beau in 1938 with Bonvallet and again in 1943 considered that " l'oedème cerebral " was synonymous with brain swelling and that any evidence of brain displacement was *ipso facto* evidence of " l'oedème cerebral." In his experimental as well as human material any protrusion of brain through a cranial and dural defect and any grooving of the brain by the tentorium cerebelli or foramen magnum was evidence of " l'oedème cerebral."

It is upon the fallacies of the arguments in the last paragraph and on the identification of " brain swelling " as an individual pathological entity that much of the present confusion over the subject of increases in brain volume has arisen. I have defined brain swelling as any state in which the volume of the brain has increased no matter how small that increase might be. Brain or cerebral oedema should be confined to its pathological significance, i.e., a state in which there is an increase in interstitial fluid. Greenfield in 1939 and 1947 discussed this problem fully both historically and histologically and he referred to Jaburek (1935) and Scheinker (1938) as well as his own studies, all of which suggest that in many conditions the state of brain oedema is but a later stage of a condition of brain swelling. In the light of my observations in the section on the physiology of cerebral swelling and of further observations in this section, that conclusion would appear to be reasonable. Not all conditions which cause the brain to swell lead to oedema of the brain and this too might be inferred from my physiological section.

The aetiology of cerebral swelling. To say that, because the brain moves towards a cranial and dural defect, the brain is therefore swollen is inaccurate. The brain may be displaced towards the defect by a condition outside the brain. If, in fact, the movement of the brain towards the defect is due to an increase in the volume of the brain, then any or all of the constituents of the brain may be responsible, by their own volume's increase, for the condition—cerebrospinal fluid, arterial, venous or capillary blood, nerve cells and fibres, interstitial tissue and fluid.

Cerebrospinal fluid may be formed in increased quantity or its pathway may be obstructed. Cases are occasionally seen in which a choroidal plexus papilloma has not, by its situation, appeared to obstruct the ventricular pathway and yet the ventricular system is considerably dilated. It has been suggested that in these cases the large surface of the papilloma continues to secrete cerebrospinal fluid and that the ventricular dilatation is due to increased production of fluid. Also, in malignant vascular hypertension, the intrathecal cerebrospinal fluid pressure is raised considerably above normal and it is possible that the high arterial blood pressure causes an increased secretion of fluid from the choroid plexuses. The many causes of raised intracranial pressure associated with obstruction of the cerebrospinal fluid pathways readily produce a tendency

for the brain to move towards a dural defect during a craniotomy, but, although the brain may be said to be swollen, the causes themselves attract interest rather than the brain swelling.

Cerebral arteries are often described as end-arteries. There is an extensive anastomosis of both small and large arteries over the surface of the cerebral and cerebellar cortex. Dye injected, postmortem, into major arteries readily passes into these arteries over the whole of the brain. However, the white matter of the brain is not so universally stained and each major artery has its own territory, only the boundaries of which can apparently be fed by other major arteries.

The occlusion of a cerebral artery is an important cause of cerebral swelling. The related white matter in the injured artery's territory suffers ischaemia—carbon dioxide and other metabolites accumulate and the tissues do not receive sufficient oxygen. The capillary walls and other parenchymal and interstitial tissue cease to function adequately; the small vessels dilate, capillary endothelium becomes more easily permeable and fluid readily passes from the blood stream into the interstitial spaces. Two events therefore occur which tend to increase the volume of the brain —the pooling of blood in the dilated capillaries and other small vessels and the transudation of fluid into the interstitial spaces. A further process occurs when the anastomotic vessels carry blood into the injured territory from its periphery. Arriving from healthy vessels the blood finds injured capillaries which readily bleed and so more fluid escapes into the interstitial spaces of the affected territory. Finally, if has been suggested that myelin breaks down into intensely hygroscopic glucoside derivatives under conditions of anoxia as might occur when a major cerebral artery is occluded, and, therefore, attracts more fluid into the interstitial spaces.

Cerebral capillaries may be injured directly in conditions of general anoxaemia as in asphyxia or carbon monoxide poisoning. Diffuse fat embolism may also produce focal areas of capillary obstruction. Rarely are these conditions considered to cause the brain to swell and yet from the foregoing arguments it would be logical to assume that they did. It is also interesting that in these conditions the patients often pass into a stage in which there is a state of decerebrate rigidity and other signs of brain stem disturbance—signs which are also present in severe degrees of cerebral swelling. (See Clinical section.)

Cerebral veins and venules when obstructed may, as described in the previous section on physiology, give rise to swelling of the cerebrum. Rare cases of proven cortical thrombophlebitis show, postmortem, marked broadening and flattening of the cerebral gyri. The argument that cerebral tumours may add to the volume of the brain by venous occlusion and later by generalised venous incompetence has also been discussed in the previous section. When thrombosis extends back into an occluded vein's territory the brain not only suffers from venous congestion but also from stasis of blood in capillaries which become more readily permeable under the conditions of anoxia. Fluid

readily escapes into the interstitial spaces in the area involved as in arterial infarct.

Nerve cells and fibres are frequently swollen in situations near cerebral abscesses and other inflammations, and near some rapidly growing tumours. They stain more palely than normally and some show various degrees of chromatolysis. It is doubtful whether or not this swelling contributes materially to a state of generalised unilateral cerebral swelling.

Interstitial tissue, the glial and vascular elements of the brain, proliferates in some conditions in which there is also a chronic swelling of the brain. Astrocytes often appear swollen and stain less distinctly in the neighbourhood of cerebral inflammation or tumours. Again it is doubtful if these cellular changes by themselves cause cerebral swelling sufficiently to produce serious symptoms.

Interstitial spaces in the brain surround the capillaries and offer, as in other organs of the body, a considerable area for fluid from the blood stream to accumulate and cause a rapid expansion of the brain. The delicate balance between the osmotic pressures of the blood and of the interstitial fluid on the one hand and the permeability of the capillary membrane itself on the other are easily disturbed. In lesser degrees such disturbances do not appear to interfere with neuronal function ; in more severe degrees obviously more severe vascular changes occur from the same cause as the oedema. It has never been shown that the presence of excessive intercellular fluid in a state of true cerebral oedema does by itself paralyse neurones. Its chief significance lies in the disturbance of blood and cerebrospinal fluid pathways which follows excessive brain swelling.

The significance of swelling of the brain. Given that any or all of the above-named constituents of the brain may increase in volume, it is reasonable to suppose that there is a considerable subarachnoid space which can accommodate certain increases in brain volume. Part of this area may already be occupied by the mass of the primary pathological lesion—e.g., cerebral contusion, abscess or neoplasm, swellings in their own right, as it were. Should further increases in brain volume occur then this " surplus " space will become fully occupied ; and displacement of certain parts of the brain towards areas of least resistance will follow in the event of still further increases in brain volume.

Foraminal or hiatal herniation of the brain. In patients who have died following the occurrence of generalised cerebral swelling from any cause, swelling and grooving of the inferior surfaces of the hippocampal gyri of the brain may often be seen postmortem. The grooving is caused by the free edges of the tentorium cerebelli which resists the downward pressure of the caudally displaced inferior surfaces of the temporal lobes. Sometimes it is restricted to the region of the uncus of the hippocampus. In other cases it extends posteriorly on the hippocampal gyri and sometimes on to the inferomedial aspects of one or both occipital lobes. It may not affect the underlying cortex of the hippocampal gyri or the cortex

may be contused in the region of the groove. These various degrees depend upon the rapidity of movement caudally of the cerebrum and therefore upon the acuteness of displacement or swelling of the cerebrum; it is with the latter cause of this "tentorial" herniation that this thesis is concerned. By itself, however, the tentorial grooving of the hippocampal gyri indicates only that these gyri have been displaced caudally against the free edge of the tentorium.

Similar evidence of brain displacement may be seen in the herniation of the tonsils of the cerebellum downward into the foramen magnum. The tonsils become elongated and swollen and protrude through the foramen; their outer and inferior surfaces may show a shallow groove produced by the margins of the foramen. Swelling or displacement of the brain in the posterior fossa is usually responsible for this type of herniation but it may also occur from disturbance arising above the tentorium cerebelli.

Herniations of lesser importance but similar significance to the above types occur through the basal foraminae in the dura mater, e.g., Meckel's cave. Similarly, in a state of severe cerebral swelling, the infero-posterior surfaces of one or both frontal lobes may be grooved by the posterior edge of the lesser wing of the sphenoid bone, as this part of the frontal lobe herniates downwards into the middle cranial fossa. Also, the pericallosal cerebral cortex and cingulate gyrus on one side may likewise be grooved by the inferior edge of the falx cerebri as a unilateral swelling displaces that hemisphere (again on the lines of least resistance) towards the opposite side.

It must be emphasised that all the brain displacements referred to above may be due to many causes, only one of which is swelling of the brain as the *result of disturbances of its normal physiology*. The parts played by the primary pathological lesions in the neurological disturbances are well known and it is only with the additional significance of the resultant brain swelling that this thesis deals.

In the process of cerebral swelling and consequent cerebral displacement towards the tentorial hiatus there must arise a period during which the hippocampal gyrus on one or both sides comes to lie over the cisterna ambiens which surrounds the mid-brain. In a previous section the importance of respiration and of alternation of pressure within the dural sinuses was emphasised in the discussion of the drainage of cerebral venous blood and the flow upward of the cerebrospinal fluid through the tentorial hiatus. If the flow upwards of cerebrospinal fluid through the tentorial hiatus is prevented or hindered by the overlying hippocampal gyri or gyrus, then the tendency for the brain to recede from the dural walls during the latter phase of normal inspiration is likewise prevented because the cerebrospinal fluid cannot flow upwards around the cerebrum to take the place of the lessened cerebral volume.

It is admissible that cerebrospinal fluid circulates by simple diffusion but the flow from the alternating "respiratory" pressures and movements

in the brain must also be admitted. A needle and manometer connected to the lumbar intradural subarachnoid space, the cisterna magna or the lateral ventricles, readily demonstrates how quickly any alteration of respiratory excursions is registered in the cerebrospinal fluid pressure.

Given that (1) displacement of the hippocampal gyri downwards on the cisterna ambiens may prevent cerebrospinal fluid from flowing upwards to the supracortical subarachnoid space and (2) the passage of cerebrospinal fluid into the supracortical subarachnoid space is necessary for the adequate function of the respiratory mechanism of draining cerebral venous blood, then it follows that the displacement of the hippocampal gyri on to the cisterna ambiens will hinder or prevent that respiratory mechanism, i.e., the drainage of cerebral venous blood into the superior sagittal and other dural sinuses in response to the variations in intrathoracic pressure will not take place properly. In this event the flow of blood from the brain will depend entirely upon the vis-a-tergo from the arterial side.

Presumably the arterial pressure is adequate to maintain the cerebral blood flow into the dural sinuses. However, the dural sinuses are connected without valves with the right auricle of the heart and their contents are therefore directly influenced by alterations of intrathoracic pressure. Any rise in intrathoracic pressure passes directly on to the conditions within the dural sinuses which, being inelastic, transmit the alteration in pressure back into the cerebral veins. Ordinarily the equilibrium between the cerebral venous blood and the cerebrospinal fluid could accommodate such a back pressure. When, however, the hippocampal gyri have been displaced on to the cisterna ambiens, then that equilibrium no longer exists. Cerebral venous congestion can therefore more readily occur from any condition which raises the intrathoracic and therefore intrasinal pressure; an attack of coughing or an epileptic fit would serve as such a condition. At such a moment the brain is in a precarious condition. All the various factors are present which make the cerebrum swell; the brain depends on the arterial pressure for the whole of the cerebral blood flow, is very susceptible to rises in intrathoracic pressure and finally swells still further from the progress of these factors which are also displacing it caudally. It is reasonable to suppose that after two or three occasions in which the hippocampal gyri occlude the cisterna ambiens, a further attack of cerebral venous congestion would cause the brain to swell still further and the hippocampal gyrus or gyri would become impacted caudally in the cisterna ambiens. This more final stage of tentorial herniation has been described by many authors, chiefly by Jefferson in this country, but few have drawn attention to the preceding stages of the condition and none has emphasised the part played by rises in the intrathoracic pressure in finally causing the condition and making it worse when established. Attention will be drawn to the implications of this process in the section on treatment and anaesthesia for patients with any degree of cerebral swelling.

In conditions of brain swelling which give rise to tonsillar herniation a similar process probably takes place to that described above for tentorial herniation. In the early stages the cerebellar displacement and swelling " drives " the tonsils caudally towards the foramen magnum and, in successive occasions of raised intracranial pressure, the tonsils become elongated and finally lie caudally, occluding the lateral parts of the cisterna magna, and through the foramen magnum. In this position the tonsils impair the egress of cerebrospinal fluid from the fourth ventricle and a mounting internal hydrocephalus occurs (or, as is more likely, that already arising from the effects of the primary pathological lesion is greatly and acutely accentuated).

With impaction and herniation of the brain into the tentorium cerebelli and the foramen magnum the blood vessels which get " caught " in the process give rise to effects of considerable importance. In tentorial herniation the branches of the posterior cerebral artery on one or both sides may be occluded by the sharp edge of the tentorium as they cross it on the under surface of the occipital lobe. Postmortem, it is not uncommon to see infarction of the infero-medial aspects of the occipital lobes in the territory of these branches. Obviously this further effect on the cerebrum also contributes still further to the cerebral swelling and makes the tentorial herniation worse.

The sequence of events which occurs following the onset of tentorial herniation is disputed, but certain assumptions may reasonably be made. First, as the cerebrum becomes displaced and swollen so also must the brain stem itself be displaced caudally. Presumably the herniation of the temporal lobes constricts the mid-brain to a certain extent, and, by constricting the aqueduct of Sylvius causes a rise of intraventricular cerebrospinal fluid pressure ; this adds its own complement to the cerebral swelling. More important is the movement caudally of the mid-brain because the upper (rostral) end of the basilar artery and the proximal parts of superior cerebellar arteries are not so readily displaced. Presumably the posterior cerebral arteries, by their fixation to the occipital lobes over the free edge of the tentorium, tether the rostral end of the basilar artery while the brain stem is displaced caudally. The smaller branches of the rostral bifurcation of the basilar artery and of the proximal parts of the superior cerebellar arteries pass directly into the mid-brain and are occluded. This is the conclusion which was reached when the lesions found in the brain stem following tentorial herniation were studied and correlated with the clinical state before death (Atkinson, 1950).

In tonsillar herniation the clinical effects of respiratory arrest are often attributed to the compression of the medulla oblongata by the herniated cerebellar tonsils, but it is also possible that the posterior inferior cerebellar arteries are, with the vertebral arteries, displaced caudally, or compressed by the herniation and that the resultant arterial injury to the medulla causes the respiratory centre's embarrassment.

CLINICAL EVIDENCE OF CEREBRAL SWELLING

To correlate clinical symptoms and signs with the lesions found, post-mortem, in cases dying with cerebral swelling is obviously difficult. It is important, however, to appreciate states of cerebral swelling at various stages clinically before irreparable damage has been inflicted on the brain stem. The differentiation between the clinical effects of the primary pathological lesion and those of the cerebral swelling associated with it must be made. Often a cerebral tumour occupies a part of the brain which may be removed, without danger to life and with no more neurological damage than had already been wrought by the tumour; and yet such a site is sometimes associated with considerable swelling of the affected hemisphere—at operation the swelling is obvious when the dura is reflected, and, postmortem, the effect of the swelling may be seen in the foraminal herniations. Two cases may therefore be seen with identically similar tumours. One suffers only the local neurological effects of the tumour and the other, to considerable degree, the effects of raised intracranial pressure and tentorial herniation. I submit that the difference may be accounted for by the different incidence of cerebral swelling in the two cases.

Consciousness may be impaired by any condition which disturbs those mechanisms by which consciousness is maintained. To correlate drowsiness and the other signs of raised intracranial pressure with the lesions of cerebral swelling found postmortem is difficult. Where no cerebral swelling is associated with the primary pathological lesion and the latter is not of a size which imitates a state of cerebral swelling (in displacing the brain caudally) then consciousness is not usually impaired. In the opposite extreme, when the brain is also excessively swollen and displaced caudally then consciousness is severely impaired and other signs of raised intracranial pressure are present. It is my contention that consciousness is impaired in cases of cerebral tumour according to the extent of displacement of the brain caudally unless the tumour actually invades the thalamus. It has not been shown that the cerebral cortex is essential to consciousness because an individual or animal without cerebral cortex can carry out certain actions such as eating and maintaining posture. In this sense it is important to note that much of the cerebral cortex is found unaffected in cases dying with considerable cerebral swelling (Greenfield, 1939).

Consciousness may be defined as the awareness of environment. Environment may be internal or external; the doctor at the bedside can only assess properly the response of his patient to external environment. The internal environment, or "vie de nutrition" as Bichat called it, requires a fully conscious patient for its assessment and even then it is difficult to decide what autonomic " sensations " ever reach consciousness.

For a patient to be aware of his external environment those pathways of sensation must be intact which provide him with information about his body and its relation to surroundings. If he loses part of those pathways then logically he is no longer conscious of the sensation which is

normally conducted through that part It is interesting to contemplate the manner in which any sensation is initiated. Every sensation or the awareness of any modality of our surroundings depends upon the element of change from one state to another. If a limb is held completely immobile and one's eyes are closed it is possible to reach a stage of unawareness of the limb entirely by virtue of its immobility and the lack of any sensation of its presence being produced.

In the mid-brain the lateral and medial lemnisci convey all the sensations of the body, except that of vision and smell, through the narrow area at the lateral and inferior borders of the tegmentum. If this area were damaged, as in arterial infarction, then the patient would no longer be conscious of his external environment except for that part of it which is conveyed to him by vision and smell.

In states where the cerebrum is displaced caudally, as in tentorial herniation, vascular lesions are often found, postmortem, in the mid-brain in those regions through which the lemnisci pass (Moore and Stern, 1938 ; Atkinson, 1950). It is therefore possible that impairment of consciousness is due to lesions of the brain stem where cerebral swelling of severe degree exists. Consequently, impairment of consciousness is of very serious importance because the lesions of the brain stem may become irreversible and the impairment permanent. The dangers of prolonged impairment of consciousness will be discussed later.

Vision is often impaired in states of severe cerebral swelling because, as already described, the branches of the posterior cerebral artery on one or both sides may become occluded by pressure against the free edge of the tentorium. Another mechanism, that of vision, in the appreciation of external environment is therefore endangered and impairment of consciousness is correspondingly increased. Under these conditions it would appear that the patient could not be aware of his external environment at all ; with vision impaired, completely deaf, unable to appreciate any form of tactile, thermal or painful stimuli and insensitive to his own body image he could not be conscious in the sense that I have defined that term, i.e., the awareness of environment. It is in this state that patients have been kept alive, although comatose, sometimes for many months and only reflex movements have been noted, no sign of recognition of external environment having been noted.

Other causes for the impairment of consciousness in states of cerebral swelling have been postulated. The generalized cerebral and cortical compression seen postmortem as a flattening of the gyri has been held responsible. The histological changes in the cortex are, however, rarely severe or sufficiently generalised to account for loss of consciousness (in the sense in which I have defined that term). The disturbance produced directly by the primary pathological lesion itself is also considered the cause of impairment of consciousness. Here again the area of cerebrum involved directly by the primary pathological lesion itself is often removable without impairment of consciousness ; only lesions of the thalamus

appear to be followed by persistent impairment of consciousness and in this case the argument set forth about the impairment of ascending sensory pathways also applies.

Pari passu with the development of cerebral swelling consciousness becomes impaired. At first the patient is somewhat confused and disorientated in time and place ; his response to the spoken voice, the passive movement of his limbs or any slight stimulus is immediate and reasonable. Although always ready to sleep he is readily roused. At a later stage he is less easily roused and the stimulus necessary to rouse him must be coarser and more severe, such as a pin prick or even supraorbital pressure. When roused under these conditions he answers only in monosyllables indistinctly, he is obviously inattentive and he readily lapses into a sleep-like state. Finally a stage is reached in which no evidence of any appreciation of external environment is seen except for a slow movement of the eyes when the eyelids are opened. Failing consciousness is then an important symptom of cerebral swelling to a degree which impairs the function of the brain stem.

Headache, vomiting and papilloedema are generally acknowledged to be clinical evidence of raised intracranial pressure but the cause of each has not yet been identified with any pathological process within the cranium. They certainly occur before the onset of signs of tentorial herniation and by themselves may continue for many weeks. They certainly indicate raised intracranial pressure and it is possible that they occur during the period before established tentorial or other foraminal herniation, when the " surplus " subarachnoid spaces are being taken up by the expanding primary pathological process and/or its associated cerebral swelling. However, when excessive cerebral swelling supervenes on a condition in which these signs are already present they often become much worse *pari passu* with the impairment of consciousness ; this is especially so of headache and vomiting. If these signs have been absent previously, then they occur for a short time at the onset of the foraminal herniation, before consciousness becomes severely impaired.

Facial and neck pain is also a symptom of the early stages of foraminal herniation shortly before consciousness is severely impaired. The neck pain may be attributed to herniation of brain into the tentorial hiatus or foramen magnum—when it is usually associated with neck rigidity ; and the facial pain is considered to be due to the herniation of brain into Meckel's cave.

Respirations are not affected in the early stages of cerebral swelling when consciousness is still complete. When consciousness is impaired they may become stertorous and mucus secretions may collect in the upper respiratory air passages. In conditions of severely impaired consciousness the cough reflex fails and the pharynx and larynx become anaesthetic. Under these conditions, if adequate drainage of the secretions of the upper respiratory passages is not ensured, the respiration rate increases and the respiratory character becomes shallower. Cyanosis develops and the bronchial tree is filled with moist sounds. The pulse rate and later the

temperature increase. These signs are seen commonly in the terminal stages of cerebral swelling which have led to tentorial herniation. It is possible to correlate the embarrassment of respiration in these cases with the cause of death and with the lesions of the brain stem found post-mortem. Conditions of both excessive bronchial secretion and pulmonary oedema have been ascribed to lesions of the brain (Cameron, et al.). Such experiments that have apparently supported this view have all caused an acute rise in intracranial pressure and, since many autonomic nervous pathways lie in the brain stem, lesions of the latter have been held responsible—it is suggested that some autonomic nervous upset could directly cause the bronchial and pulmonary disturbances. It is also known that lesions of the vagus nerves may not only abolish the cough reflex and lead to anaesthesia and paralysis of the pharynx and larynx but are also followed by the accumulation of excessive bronchial secretions.

Whilst a central cause of the difficulties of respiration is possible it is likewise possible that the associated disorder of consciousness by itself may give rise to exactly similar difficulties. When consciousness is seriously impaired there is a deterioration in all the functions which the conscious patient performs. The occasional act of swallowing lubricates the mouth and nasopharynx in the conscious patient, whilst in the comatose patient these areas become foul from inactivity. The cough reflex is similarly depressed by the lack of appreciation of laryngeal stimuli and the upper respiratory air passages are infected and invaded by secretions which are aspirated down into the bronchi, unimpeded by reflex actions. In this state of " impaired protection " of the upper respiratory passages mucus and other infected material can find their way into the finer bronchi. Areas of lobular pulmonary collapse occur and the respiratory difficulties increase. Cyanosis and the rapid respiratory rate impose a severe strain on the cardio-respiratory system. A condition arises very comparable with that described as " aspiration pneumonia." Finally, the heart begins to fail and this adds the complement of pulmonary oedema to the respiratory difficulties. The post-mortem pulmonary lesions are a mixture of excessive sticky bronchial secretions, areas of infected lobular collapse, and pulmonary oedema.

In conditions of severe impaired consciousness cooperation for the examination of eye movements is lacking, but the pupils give some indication of the integrity of the oculomotor nerves. In established tentorial herniation there is often dilatation of one or both pupils which are then inactive to light. Earlier stages show lesser degrees of this change, and on one side there is often a slight dilatation of the pupil and its reaction to light is sluggish. These pupillary changes first make their appearance always on the side of most temporal lobe herniation and almost invariably on that of the primary pathological lesion. They are considered to be due to the pressure downwards of the uncus of the hippocampal gyrus on the third cranial nerve as it crosses from the interpeduncular fossa to the anterior part of the free edge of the tentorium, and they were described originally by

Jonathan Hutchinson in 1867. An alternative explanation has been suggested for the occurrence of these pupillary changes; the third nerve passes forwards between the superior cerebellar and posterior cerebral arteries, and, if the brain stem is displaced caudally whilst the posterior cerebral arteries tether the rostral end of the basilar artery rostrally, then the nerve is stretched by the distortion of vessels and brain stem.

The corneal reflexes are usually retained until consciousness has become very seriously impaired. Their integrity serves to indicate the caudal extent of brain stem injury in conditions of tentorial herniation and the rostral extent in those of tonsillar herniation.

The motor system may show varying degrees of weakness in conditions of cerebral swelling which are chiefly due to the direct neurological effects of the primary pathological lesion. A spastic hemiparesis or even hemiplegia may, however, be seen in some cases on the same side as the primary pathological lesion. This is considered to be due to the pressure of the crus cerebri on the opposite side of the primary pathological lesion against the free edge of the tentorium. The swelling of the cerebral hemisphere on the side of the primary pathological lesion and herniation of temporal lobe displaces the brain stem across to the opposite side. This injury to the contralateral crus cerebri was first described by Kernahan in 1929.

It has been argued that the herniation of the temporal lobe on the side of the primary pathological lesion may give rise to a hemiparesis on the contralateral side from pressure of the hippocampal gyrus against the ipsilateral crus cerebri. I doubt that this ever occurs; have never seen it proven, and can see no reason why the somewhat soft herniated hippocampal should produce direct injury to the crus cerebri. Any case, where a hemiparesis contralateral to the side of the primary pathological lesion has been observed, has invariably had evidence of direct involvement of the motor pathways by that lesion.

As cerebral swelling increases and the brain stem suffers more injury, so the motor pathways in the mid-brain become involved; a generalised increase in limb tone, and deep tendon reflexes, and bilateral extensor plantar responses occur. Later still, easily elicited and abnormal reflexes may be seen. At a gentle touch or the slight passive movement of a limb, the lower limbs stiffen in extension with the feet turning into inversion, and the upper limbs either flex at the elbow, wrists and metacarpophalangeal joints whilst extending at the interphalangeal joints and adducting at the shoulders or extend at the elbows and internally rotate at the shoulders. The movements are somewhat slow and may occur spontaneously. They are characteristic of the state of decerebrate rigidity, are always associated with generalised spasticity and extensor plantar responses, and are a very late stage in the condition of tentorial herniation. Probably the lesion in the mid-brain responsible for these signs is in the region of the red nuclei because lesions through these centres in animals give rise to an identical condition. In such animals "righting reflexes" may be elicited and sometimes in man where decerebrate

rigidity occurs there may be similar movements of the limbs in response to passive movement of the head.

The pulse rate often slows and the pulse wave becomes full and bounding in the early stages of acute cerebral displacement whether from cerebral swelling or the primary pathological lesion. This is attributed to a lesion of the tegmentum of the mid-brain (Atkinson, 1950), which causes the systemic arterial blood pressure to rise; this sign lasts only for a short period (up to half-an-hour). Later, the blood pressure returns to normal for a number of hours until the respiratory changes already discussed occur; from that time on, the pulse rate rises and finally the systemic arterial blood pressure falls. The temperature is not elevated in the early stages of progressing cerebral swelling and only rises when the impairment of consciousness is severe and the respiratory changes are advanced; terminally it may reach very high levels.

Displacement of the contents of the posterior fossa into the foramen magnum produces much less disturbance of consciousness than does tentorial herniation unless respiration ceases. Attacks of headaches, vomiting and pain, rigidity and retraction of the neck usually preface the onset of established tonsillar herniation. Sometimes the characteristic slowing and cessation of respirations come suddenly without warning, especially when the primary pathological lesion is in the posterior fossa. The respirations may cease suddenly or there may be a short period in which they become periodic and then of pronounced Cheyne-Stokes character. They may cease altogether or they may return to be very slow (about four per minute) for a number of hours; during that time, unless the condition is relieved, consciousness is lost, and after an initial slowing, the pulse rate rises; later the blood pressure fails and finally the heart rate ceases.

In the established stage of tonsillar herniation, before consciousness is lost, nystagmus becomes pronounced and spontaneous and this sign appears when respirations recover (or, if cessation of respirations has not occurred, it persists throughout) and lasts until either the condition is relieved or the heart fails. Similarly, small pupils occur with established tonsillar herniation, presumably as the result of the medullary injury, and they remain so until all reflex activity fails with respiratory failure. Generalised increase in tone and limb reflexes usually occur but the plantar responses are invariably extensor. Paraesthesiae radiating down both sides of the neck and along the radial borders of the upper limbs are occasionally a symptom before respirations fail. Hiccough may be also a premonitory symptom and in some cases restlessness may be extreme shortly before the respirations fail.

Following recovery from acute tonsillar herniation the patient's respirations recover at their normal rate and depth, but other medullary signs may persist. They are well shown in a case of a patient, E.W., (recently under the care of Mr. D. W. C. Northfield) who was correctly considered to have a cerebellar tumour. On the morning of operation, whilst she was

having her head shaved, her respirations suddenly ceased and she lost consciousness. After five minutes her respirations returned to four per minute. An endotracheal tube was passed and artificial respiration continued. In the operating theatre she was placed in the face-down position, the lateral ventricles tapped and the high cerebrospinal fluid pressure relieved; the cerebellar medulloblastoma was removed macroscopically completely from the right cerebello-pontine angle and upper surface of the right cerebellar hemisphere. In the course of this removal, her respirations recovered at a rate of 14 per minute and assumed their normal character. Post-operatively, on the following day, she recovered consciousness partially, maintained normal respirations but had for ten days a persistent vascular hypotension—80/60 mm. mercury. Also there was evidence of bilateral vagal paralysis; the palate, nasopharynx and larynx were insensitive and paralysed and she regurgitated any fluid that she attempted to swallow for six weeks. In this period excessive bronchial and upper respiratory secretion collected and a tracheotomy was necessary to ensure their adequate removal at the third post-operative week. Consciousness fluctuated and was worse at the time of excessive bronchial secretions. Finally after two months she recovered all the " vagal " functions and is now well.

The further investigation of a patient with cerebral swelling, albeit one of urgency, is directed to the localisation and identification of the primary pathological lesion. A few points about this are important in these cases. A lumbar puncture is not only rarely of value (Henderson and Mahoney, 1950) but is dangerous where there is evidence of cerebral swelling and displacement, because foraminal herniation of one kind or other may be either precipitated or made worse by this measure. The interpretation of cerebral arteriograms is made difficult by the presence of unilateral generalised cerebral swelling, because parts of the brain remote from the primary pathological lesion may displace the major cerebral vessels enough to resemble that of the primary lesion; e.g., there may be a shift of the anterior cerebral to the opposite side and an elevation of the middle cerebral vessels exactly like the appearances of a temporal lobe tumour and yet the tumour may be wholly confined to the occipital lobe. Such a finding suggests that both the frontal and temporal lobes have swollen in response to the presence of the occipital lobe tumour.

DIFFERENTIAL DIAGNOSIS

Diagnosis is difficult in those cases where cerebral swelling and displacement obscure the symptoms and signs of the primary pathological lesion. With special investigations such as cerebral arteriography and ventriculography that difficulty may be overcome. There are, however, some conditions in which the clinical state resembles that of progressive cerebral swelling. Hypertensive encephalopathy may cause both focal and general cerebral signs and I present here a case, exactly resembling the clinical state of hiatal herniation; E.C., a man of 26 years, who had complained of

headache and vomiting during the previous month, was admitted to the National Hospital for Nervous Diseases, Queen Square. During the previous week the headache had become much worse and had become associated with paraesthesiae radiating down the radial borders of the upper limbs, and pain and stiffness in his neck. On examination he was very restless and disorientated, suffered from severe pain, rigidity and tenderness in his neck with head retraction, and was found to have intense bilateral papilloedema with exudation and haemorrhages and a blood pressure of 200/120 mm. mercury and albuminuria. He died of respiratory failure on the day after admission and, post-mortem, was found to have one small contracted granular right kidney and no left kidney; herniation of the cerebellar tonsils into the foramen magnum was also present. It is presumed that in this case the signs in the neck and upper limbs were due to the tonsillar herniation; the primary pathological lesion must be attributed to the vascular hypertension, for there was no other lesion of the brain to be seen.

Acute subarachnoid haemorrhage from intracranial aneurysm or cerebral angioma in severe cases resembles acute cerebral swelling clinically; the history of sudden onset with neck pain before the loss of consciousness and the presence of neck rigidity and positive Kernig sign may all appear in both conditions. The acuteness of the condition without respiratory failure is more like that of acute subarachnoid haemorrhage and justifies a lumbar puncture. The finding of subarachnoid blood confirms the diagnosis.

Acute intoxication and post-anaesthetic "cerebral anoxia" may closely resemble the clinical state of tentorial or tonsillar herniation. States of decerebrate rigidity or of respiratory embarrassment, nystagmus and ataxia are occasionally seen following a difficult anaesthesia for any surgical operation. Aspirin, the barbital derivatives, morphia and alcohol each have distinctive clinical manifestations and their implication in the patient's condition can be confirmed by blood or gastric analysis in some cases. For similar reasons multiple fat embolism in the brain, e.g., following fractures of bones or lacerations of limbs, sometimes causes states of decerebrate rigidity and impairment of consciousness, usually ending fatally. The absence of the clinical evidence, of a primary intracranial lesion and the history of injury all help in the difficult differentiation which may require special investigation for confirmation.

Following a head injury, there may occasionally be seen a clinical state in which there are all the signs of decerebrate rigidity. The reflex postural changes described above, as well as the spasticity, increase in deep tendon reflexes and extensor plantar response may all be present and yet the pupil reflexes are intact and the patient evinces moaning sounds when molested in any part of his body. Usually the patient recovers spontaneously in the second week and it is concluded that the injury has directly impaired the function of the brain stem instead of indirectly as the result of cerebral swelling. The integrity of the pupillary reflexes

as well as the retention of some level of consciousness in the presence of decerebrate rigidity help in the differential diagnosis from brain stem injury due to cerebral swelling. Burr holes placed in various parts of the skull do not reveal more than a wide supracortical subarachnoid space and the ventricular system is found to be normal in situation and size.

PROGNOSIS

A patient may readily recover from the effects of the early stages of cerebral swelling if the primary pathological lesion is removed and an adequate decompression of the intracranial contents is performed. When decerebrate rigidity or cessation of respirations has supervened from the severity of the caudal displacement of the brain stem then recovery, in spite of surgical relief, is rare. Several cases have been seen where this has occurred but they are in the extreme minority and post-operative medical and nursing care in such cases is the most difficult of neurosurgical problems. Between these extremes of cases the relief of intracranial tension and removal of the primary lesion have a proportionate success.

The level of consciousness is the most important guide to progress. Not only does the recovery of consciousness indicate the integrity of the brain stem pathways but also the various complications of impaired consciousness can then be avoided ; the respiratory and feeding difficulties particularly are easily managed when consciousness recovers. Once consciousness of external environment is lost for more than three weeks then its recovery is excessively rare.

Dilatation and loss of light reflex of the pupil on the side of the primary pathological lesion, slowing of the pulse rate and extensor plantar responses are important indications of serious brain stem displacement in tentorial herniation. Small pupils, pain and stiffness of the neck and marked periodicity of respirations are similarly important signs of advancing tonsillar herniation. In both kinds of herniation at these stages recovery will usually follow adequate treatment provided it is not delayed any longer. Inadequate or conservative treatment invariably leads to irreversible changes in the brain stem and death.

TREATMENT

The treatment of brain swelling includes (1) the general care of the patient, (2) the removal of, or relief from, the primary intracranial lesion and (3) the alleviation of the effects of the brain swelling.

(1) In the state of impaired consciousness which these patients suffer, frequent careful turning of the patient, the proper and diligent removal of nasopharyngeal collections of mucus and other fluids, and attentive nutritional care all require the most patient nursing. A patient suffering from the effects of cerebral swelling should lie on his side and horizontally, with only a low pillow beneath his head. If accumulations in the nasopharynx are evident then the foot of the bed should be raised on low blocks and no pillow should be allowed. The nasopharynx should

be aspirated with a soft rubber catheter attached to a suction apparatus every ten minutes, or, if the secretions are excessive, then more often. Naso-oesophageal feeding is essential if there is any doubt as to the integrity of swallowing and cough reflexes. An adequate fluid, caloric and vitamin intake must be ensured ; at least 2,500 c.c. of fluid and 2,000 calories a day are necessary and should be given in small quantities frequently—if a naso-oesophageal tube is passed, then, before each feed, the contents of the stomach should be completely aspirated. Regurgitation of stomach contents is frequent in the late stages of cerebral swelling and should be looked for by the nursing staff frequently because of the dangers of aspiration into the lungs. An oxygen tent is an important aid whenever there is any respiratory difficulty in these cases. Occasionally a tracheotomy has been performed and has greatly facilitated the aspiration of secretion from the trachea. More direct measures of relieving cerebral swelling medically are often made by giving hypertonic solutions in the form of magnesium sulphate enemata or as intravenous sucrose solutions. Occasionally, following the use of these measures, a temporary benefit may be seen in the improvement of the level of consciousness and relief of respiratory embarrassment. The effect is only temporary and should not be repeated often because dehydration of all tissues results, and this adds to the respiratory and other disturbances.

(2) The treatment of the primary pathological lesion follows standard neurosurgical procedures and is not the subject of this thesis.

(3) The treatment of cerebral swelling itself by surgical operation involves (a) the decompression of the intracranial contents by removing part of the cranial wall and opening the underlying dura mater and (b) the relief of brain stem distortion by removing the cause of injury to it at the tentorial hiatus or foramen magnum. The ordinary craniotomy undertaken for the relief of the primary pathological lesion is the best means of decompressing the intracranial contents. The orthodox subtemporal decompression is only of questionable value, on the non-dominant side, when the primary lesion is either non-localisable or of a generalised character, such as external hydrocephalus, and gives rise to papilloedema and the danger of visual failure. As a means of decompressing a cerebral tumour it is of no value ; the herniation of brain through the defect causes as much disturbance as the tumour and cerebral swelling, and no benefit results. Also the operation is itself more difficult than the ordinary exploratory craniotomy because there is often very little means of relieving the intracranial tension whilst the dura is being opened and, in closing the wound, as well as subsequently, there is inevitably more danger to the brain from its herniation through the defect.

Apart from the usual nursing care, the pre-operative preparation of the patient for craniotomy must include thorough pulmonary, cardiac and renal examinations, haemoglobin and blood group investigations and the search for infective foci on the head and elsewhere. If the intracranial condition permits the time, a course of antibiotics should be prescribed

for 24 hours if infection is obvious ; this does not apply so rigidly to the respiratory difficulties which are characteristic of cerebral swelling, as these respond best to the decompressive operation. Bronchoscopic drainage, however, should be carried out immediately before and after operation if bronchial secretions are excessive.

The argument set forth in the sections on physiology and pathology on the factors which produce cerebral swelling are particularly relevant in the matter of anaesthesia for craniotomy. Any increase in intrathoracic pressure, such as by coughing, any rise in the carbon dioxide content of the blood and any increase of systemic arterial blood pressure, such as occurs in a frightened anxious patient before operation, may cause considerable increases in the amount of already existing cerebral swelling or may initiate such a swelling if it has not already occurred. I have seen a case taken to the theatre and, after an induction of anaesthesia of some difficulty, a lateral craniotomy flap was turned revealing a very swollen brain ; pre-operatively there was no evidence of severe cerebral swelling—the patient was fully conscious and alert and suffered from hemiparesis and occasionally focal seizures. Operatively, the flap was not turned over the small meningioma, the wound was closed with considerable difficulty and the patient died ten days later with all the signs of unrelieved cerebral swelling. Post-mortem the meningioma was the size of a golf ball and yet there was an excessive degree of cerebral swelling with well-marked tentorial herniation. On section, the cerebral hemisphere on the side of the tumour was very oedematous (see last paragraph of Physiology). I consider that the excessive swelling in this case only arose at the time of the induction of anaesthesia and was due to the ill effects of raised intrathoracic pressure and carbon dioxide excess in the inhaled air. It is the stage of induction which is the most dangerous. The continuation of anaesthesia once the scalp incision has been made is usually very simple since there are no sensitive parts to injure, apart from the region of the dura at the Sylvian point. At no stage, however, should the oxygen supply be imperilled and neither should there be any distress in the patient's respiratory efforts, e.g., from an imperfect airway or an over-inflated anaesthetic bag.

The patient is placed in the most suitable position for the exposure of the primary pathological lesion, having already had the head shaved, and the scalp is marked out in the usual way. It is also advisable in all cases to mark out the site for a burr hole over the opposite ventricle ; the ventricular cerebrospinal fluid pressure may be lowered later if the intracranial contents appear too tense for the safe opening of the dura mater. The reflection of the scalp flap is made in the usual manner and then the cranial flap is outlined and reflected. It is always wiser to turn a larger cranial flap than is necessary for the exposure and removal of the primary lesion only.

The lower squamous part of the temporal bone should be removed as soon as the skull flap is turned back, being nibbled away down into

the floor of the middle cranial fossa, forwards to include the pterion and backwards to the root of the zygomatic process at least. This is best done at this stage before the dura is opened, otherwise there is considerable danger of injuring the brain once it is allowed to protrude. The lateral ventricle on the side of the lesion should be tapped through the dura and, if that does not lower the intradural tension sufficiently or (as is more likely) that ventricle is unobtainable, then the opposite ventricle should be tapped through the separate burr hole and its pressure lowered.

The intradural tension reduced as much as possible, the dura is opened as rapidly as possible, preferably by an incision on a grooved director, so that a lateral dural flap is hinged by a narrow attachment parallel with and near to the midline. At this stage an important decision is necessary; if at all possible the primary pathological lesion should be removed not only for the relief of the patient's troubles in the future but to allow an " internal " decompression as well. If a glioma is merely left *in situ* at this stage then the swelling into the dural defect which follows will embarrass the immediate convalescence very dangerously. Only when the glioma is in the motor and speech area and is obviously of the spongioblastoma multiforme (glioblastoma) type should the mass be left *in situ*.

The primary pathology dealt with, the closure of the wound is carried out in the usual manner; at this stage a review of the necessary extent of the bony decompression is made. The dura is radially split down into the temporal fossa and up into the lateral flap, allowing the edges of the original dura incision to be re-apposed (where they lie under the bone incision).

In primary lesions of the posterior fossa where a serious degree of brain swelling has supervened the question of surgical intervention may have been precipitated by the cessation of respirations. The nursing and resident medical staff should be trained to deal with this problem in the initial stages. As soon as it is obvious that respiratory embarrassment has occurred all steps should be taken to make burr holes in the skull, to tap the lateral ventricles and to leave a soft rubber catheter draining one lateral ventricle. Often the cessation of respiration comes suddenly and even unexpectedly. The nearest individual should turn the patient's head to one side and start artificial respiration immediately, slowly and gently at no more than 18 excursions a minute (too often artificial respiration is " pursued " too vigorously). The resident doctor should then be called; he should take over the artificial respiration while calling for an anaesthetist who should pass an endotracheal tube and continue artificial respiration with his bag. The patient is taken to the operating theatre, placed on the table with the face down in the cerebellar head rest, and the head is then shaved, the head and neck are cleaned and the skin marked out in the usual manner with a solution of procaine and adrenaline (2 mm. of 1 in 1,000 solution to the oz. of procaine solution). When the

lesion is known to be in the posterior fossa the horse-shoe incision of Horsley (1906) is marked out as well as bilateral posterior burr holes over the lateral ventricles. The burr holes are made forthwith and the lateral ventricles tapped, their contained pressure being reduced slowly. A soft rubber catheter is passed into one ventricle and sewn to the edge of the wound. This tapping of each lateral ventricle is also a somewhat diagnostic procedure because, if the ventricles are found in their usual sites and contain excessive fluid under increased pressure, it may be assumed that the obstruction to the fluid pathways is either in the midline or in the posterior fossa. Accordingly, a cerebellar exploration may then proceed or it may be decided that it would be better to review the problem later. The decompression of, and removal of, a mass from the posterior fossa is the most important procedure and should be carried out as soon as possible even under artificial respiration ; often respirations will return to their normal rhythm as soon as the intraventricular pressure has been lowered. An adequate bony and dural suboccipital decompression should expose the whole of the cerebellum up to the transverse sinus, laterally to the lateral sinuses and inferiorly so that bone is removed from the entire posterior half of the foramen magnum. The posterior arch of the atlas would likewise be removed in its middle 1 cm. The dura mater should be opened over the site of the cisterna magna and then incised radially in triangular flaps to the periphery. The removal of the primary lesion should then follow the usual practice. The closure of the wound is similarly straightforward.

The post-operative care of cases of brain swelling follows the same principles as the pre-operative management. In the theatre an intravenous transfusion of saline-glucose is started and blood given as necessary. The saline-glucose infusion should be continued in the ward until the patient recovers consciousness and can swallow normally without regurgitation ; the naso-oesophageal tube may be replaced after 24 hours if swallowing is unsatisfactory and the intravenous drip removed. Nursing care is once more of the highest importance. Daily passive movements of all limbs should be given by trained physiotherapists and frequent exhortation of the patient to cough and move his limbs should be given by his doctors and nurses.

Apart from the impaired level of consciousness and upper respiratory secretions which may persist in the less satisfactory cases after operation, there may be other complications which must be looked for. Probably the commonest is the so-called cortical thrombophlebitis. It is really a syndrome in which the level of consciousness is not so much impaired as the local cortical functions. Focal epileptic seizures arise about the second to seventh day and paresis or sensory signs increase for a few days (about ten usually). It is characteristic of this condition that, although focal signs are apparently severe, consciousness is not severely impaired, and is usually retained. The prognosis is good. I have always regarded it so because an adequate decompression accommodates any brain

swelling which may result from the vascular changes which are presumably responsible for the condition. The signs are always immediately related to the cerebral area involved at operation. The seizures require anti-convulsant drugs such as luminal (usually 1 gr. b.d.) and subside completely in almost all cases. The subsequent onset of epilepsy depends more upon the nature of the primary pathological lesion and its treatment both surgically and medically than upon the cerebral swelling.

The ordinary complications of any cranial operations such as collections of blood and infection should be watched for. More general complications such as pulmonary consolidation or embolism likewise require the usual prophylactic early mobilisation and observation and are treated when present along the usual lines.

CONCLUSION

This thesis deals with the problems which arise from the swelling of brain which is already the seat of a primary pathological lesion. The significance of swelling in the physiology and pathology of the brain has been emphasised. To separate the symptoms and signs of brain swelling from those of the primary pathological lesion is important, both for the interpretation and treatment of a patient's intracranial condition. Above all, the prognosis, the nursing care and the dangers of anaesthesia in an individual case have been discussed precisely, and for the cerebral swelling, rather than for the primary pathological lesion.

I wish to acknowledge my gratitude to Dr. J. G. Greenfield for his untiring patience and encouragement and to Mr. D. W. C. Northfield for permission to report his case.

Appended are the notes of experiments carried out in the Department of Pathology at the National Hospital for the Paralysed and Epileptic, Queen Square, London; the work was supported by a grant from that Hospital's medical research advisory committee.

APPENDIX I

Experiments Relating to the Influence of Respiratory Gases and Adrenaline upon Cerebral Volume

Method and Materials.

Each cat was anaesthetised with nembutal solution, injected intraperitoneally (the quantity depending upon body weight, usually 2 c.c. of the "veterinary solution"). It was laid on its left side. A midline posterior incision was made along the vertex of the skull to the second cervical spine through skin, superficial fascia, galea and pericranium. Muscles and ligamentous attachments were rougined from the calvarium on both sides and from the sub-occipital area. Trephine holes (1·5 cm. diameter for each parietal area and 0·5 cm. for the occipital bone) were made in the parietal and occipital areas; the suboccipital area was enlarged until the dura was fully exposed below the venous sinuses over the cerebellum.

An incision was made in the neck and the carotid artery was exposed, tied distally, and cannulated proximally and the systemic arterial pressure was

recorded on a revolving smoked drum. When the arterial pressure had settled to a constant level and haemostasis had been secured, the dura over each cerebral hemisphere and cerebellum was opened. A photograph of the exposed brain was taken.

In the experiments on rebreathing a wire cone covered with gauze was placed lightly over the animal's nose and soaked with water to render it almost impervious to air. Where carbon dioxide was used a cylinder of this gas was turned on 5 in. from the animal's nose which was then not covered. An injection of adrenaline solution (1 in 1,000) of ½ c.c. was made into the peritoneal cavity.

Whenever such a procedure was carried out a photograph was taken every five minutes later and the time marked under the arterial pressure recording on the revolving drum.

Cat 40.—Anaesthetised with nembutal solution intraperitoneally; carotid arterial pressure was constant for 12½ minutes at 140/135 mm. of mercury. The cerebrum was exposed as described above. One half c.c. of 1/1,000 adrenaline solution was injected intraperitoneally and the arterial pressure rose 41 mm. steeply and maintained this level for three minutes and then slowly fell to the previous figure. During this phase the cerebrum swelled into the cranial defect and the vessels and cortex below the pia mater were seen to pulsate more forcibly. This effect subsided with the return of the arterial pressure to the previous level. This was repeated 20 minutes later, and again 15 minutes after that, with similar effects. Twenty minutes after a fourth similar injection of adrenaline, coal gas was "played" over the uncovered nose of the animal; one minute later an injection of adrenaline was given as before. This time swelling of the cerebrum was more and associated with cyanosis of the cerebral cortex with congestion of the cerebral veins. The animal died 15 minutes after the peak of the elevation of arterial pressure.

Cat 41.—Same technique of anaesthesia, arterial pressure record, and exposure of cerebrum as above. A constant recording of 65 mm. mercury systolic pressure was found. An injection of 1 c.c. of 1/1,000 adrenaline into the distal part of the internal carotid artery caused the arterial pressure to rise to 220 mm. mercury very steeply and this elevation subsided to 110 mm. mercury in 35 minutes from the height of the elevation. One-and-a-half minutes later, when the 110 mm. level appeared to be constant, coal gas was mixed with the inhalation of air, producing a small elevation in arterial pressure to 120 mm. mercury. Throughout the phase of rising and elevated arterial pressure, the cerebrum swelled into the cranial defect but not severely. Later, the coal gas-air mixture was replaced by air for a while and then the animal was made to rebreathe its own air; after a period of rebreathing of half-an-hour when cyanosis was added to the moderate degree of cerebral swelling, 1 c.c. of 1/1,000 adrenaline was injected into the distal part of the internal carotid artery again and this time a considerable swelling developed and persisted for a further half-an-hour when the animal died.

Cat 42.—Procedure as above, except that both sides of the cranium were opened to allow for the swelling of the cerebrum. The animal was permitted to rebreathe into an almost impervious nose cone whilst adrenaline 1/1,000 solution was administered intraperitoneally, ½ c.c. every quarter of an hour. A generalised cerebral swelling occurred, and this persisted over two hours in spite of removing the nose cone to permit air only to be inhaled.

Cat 43.—As in Cat 42, although the cranial window was small and unilateral; no definite herniation occurred. The animal had a low initial arterial pressure and was breathing in a stertorous manner before the experiment was undertaken.

Cat 44.—Was anaesthetised as above. Exposure as before but no arterial pressure recording. This animal was given an excess of carbon dioxide for a

period of two hours, after which it died. The mixture of gases was enough only to increase respiratory rate to 30-35 respirations a minute. No definite cerebral swelling occurred.

Cat 45.—Procedure as above. A mixture of carbon dioxide and air was inhaled and at half an hour intervals ½ c.c. of adrenaline 1/1,000 solution was given intraperitoneally. A distinct cerebral swelling occurred to a moderate degree which persisted but never attained severe proportions. Rebreathing was substituted for the carbon dioxide-air mixture and the cerebral swelling increased progressively from that point. Twenty minutes later the veins about the caudal swelling gave way and a secondary haemorrhagic swelling added to that already present. The animal died one and a half hours after the beginning of rebreathing.

Cat 46.—Poor response similar to Cat 43 although a definite cerebral swelling occurred. Again the animal was in poor condition as a result of faulty anaesthesia.

Cat 47.—A mixture of coal gas, carbon dioxide and air was given whilst 1 c.c. adrenaline 1/1,000 solution was injected intraperitoneally. A definite cerebral swelling immediately occurred but the animal died soon after this began.

Cat 49.—In spite of rebreathing and an injection of 1 c.c. of 1/1,000 adrenaline no cerebral swelling occurred but death ensued in 20 minutes.

Cat 50.—During a phase of rebreathing a brain stem lesion was made through the suboccipital area; no rise of arterial pressure occurred and no cerebral swelling took place.

REFERENCES

ALEXANDER, L. and LOONEY, J.M. (1938) *Arch. Neurol. Psychiat., Chicago* **40**, 877.
ATKINSON, W. J. (1949) *J. Neurol., Neurosurg., Neuropsych.* **12**, 137.
——————— (1950) *Ann. Roy. Coll. Surg. Eng.* **7**, 38.
BECK, D. J. K. and RUSSELL, D. S. (1946) *Journ. of Neurosurg.* **3**, 337.
BICHAT, M. F. X. (1800) *Recherches physiologiques sur la vie et la mort. Paris, Brosson, Gabon et Cie.* pp. 1—189.
CAMERON, G. R. and DE S. N. (1949) *J. Path. and Bact.* **61**, 375.
GREENFIELD, J. G. (1939) *Brain*, **62**, 129.
——————— (1947) *Proc. Roy. Soc. Med.* **40**, 695.
HENDERSON, W. R. and DE GUTIERREZ-MAHONEY, C. G. (1950) *Brit. Med. J.* **1**, 1461.
HORSLEY, V. (1906) *Brit. Med. J.* **2**, 411.
HUTCHINSON, J. (1867) *Lond. Hosp. Clinical Lectures and Repts.* **4**, 29.
JABUREK, L. (1936) *Arch. Psychiat. Nervenkr.* **104**, 518.
JEFFERSON, G. (1938) *Arch. Neurol. Psychiat., Chicago* **40**, 857.
KERNOHAN, J. W. and WOLTMAN, H. W. (1929) *Arch. Neurol. Psychiat., Chicago* **21**, 274.
LE BEAU, J. and BONVALLET, M. (1938) *C. R. Soc. Biol. Paris* **127**, 126.
MOORE, M. T. and STERN, K. (1938) *Brain* **61**, 70.
REICHARDT, M. (1905) *Allg. Z. Psychiat.* **62**, 787.
SCHEINKER, I. (1938) *Dtsch. Z. Nervenkheil.* **147**, 137.
STEWART-WALLACE, A. M. (1947) *Proc. Roy. Soc. Med.* **40**, 697.
VINCENT, C. (1935) *Internat. Neurol. Congress, London.*
——————— LE BEAU J. and GUIOT, G. (1947) *Proc. Roy. Soc. Med.* **40**, 689.
WOLFF, H. G. and LENNOX, W. G. (1930) *Arch. Neurol. Psychiat., Chicago.* **23**, 1097.

VISIT OF H.M. THE QUEEN TO LAY THE FOUNDATION STONE OF THE NEW COLLEGE BUILDINGS

H.M. The Queen has graciously consented to visit the College on Tuesday, 5th May, 1953, in order to lay the foundation stone of the new College buildings.