Transmission of Increased Intracranial Pressure

I. Within the Craniospinal Axis*

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During the latter part of the 19th century a widespread interest was manifested in the problem of cerebral compression and the etiology of the neurological deficits produced by an expanding intracranial mass. As methods were developed for recording intracranial and intraspinal pressure and for the experimental production of acute intracranial hypertension, it was noted by some investigators that increased pressure was not transmitted consistently from the intracranial to the intraspinal space. Hill maintained that rapid injections of fluid into the supratentorial subarachnoidal space forced the cerebral hemisphere downward into the tentorial incisura and the cerebellum into the foramen magnum with complete obstruction of the subarachnoidal space at both levels. On the other hand, Eyster argued that this could not occur because of the nearly incompressible fluid in the spinal canal, which he believed had no means of escape. Cushing stated that severe effects of compression could occur locally with little or no transmission to remote areas of the brain.

More recently Kahn produced experimental increased intracranial pressure by perfusion of distilled water into the common carotid artery and found that a differential of pressure developed between the supratentorial space and the posterior fossa. Meyers also found such a differential with injection of Ringer’s lactate into the lateral ventricle, but the gradients of pressure illustrated in these papers were relatively small.

Clinical interest in the transmission of increased intracranial pressure developed as a result of the demonstration of the importance of transtentorial herniation as a cause of rapid neurological deterioration and death in patients with a space-occupying supratentorial mass. This has been recently re-emphasized in a review by Finney and Walker. They found evidence of transtentorial herniation in 55.4 per cent of an unselected series of autopsied brain tumors, including an incidence of 88 per cent in glioblastomas of the cerebral hemisphere. In 23 per cent of supratentorial tumors herniations of both tentorial incisura and foramen magnum were present.

There have been few clinical studies in which simultaneous pressures were recorded above and below the tentorium in patients with intracranial pathology. Smyth and Henderson found a lower lumbar pressure in 8 of 33 patients with intracranial space-occupying lesions, most of which were tumors, but the maximum difference in pressure was 100 mm. H$_2$O. These findings and a statement by Evans: “We now know as a result of many observations that there is a close correspondence between the ventricular and lumbar pressures under almost all circumstances” contrast with the high incidence of transtentorial herniation demonstrated post mortem in patients with brain tumor.

The present investigation was undertaken in an attempt to produce experimental herniations of the tentorial incisura and foramen magnum and assess the physical factors responsible for their development. The monkey was selected as the experimental animal because of its fibrous tentorium in contrast to the bony tentorium present in the dog and cat. Also, the anatomy of the tentorial incisura in the monkey as well as

Received for publication December 16, 1963.

the manner of attachment of the tentorium to the petrous ridges and anterior and posterior clinoids are quite similar to man.

Materials and Methods

The data from these experiments were obtained from 28 rhesus monkeys. Each animal was anesthetized with approximately 60 mg./kg. of pentobarbital sodium and tracheal intubation or tracheostomy was performed. Small holes were made in the skull with an electric drill and the dura mater was punctured with a hypodermic needle. Polyethylene catheters with a lumen 1 mm. in diameter were then inserted into the subarachnoidal space. In most experiments 3 or 4 catheters were inserted over the cerebral hemispheres for recording of pressure and injections of saline. A midline incision was made in the posterior fossa and the atlanto-occipital membrane was exposed. After puncturing the membrane with a needle a polyethylene catheter was inserted into the cisterna magna and directed upward into the cerebellopontine angle. By using small flexible catheters it was possible to avoid damage to underlying brain tissue with consequent hemorrhage, and leakage of cerebrospinal fluid around the catheters was reduced. However, some leakage always occurred so that the opening pressure, in the position of lateral decubitus used for recording, was usually 0–3 mm. Hg. Needles were placed in the lumbar subarachnoidal space for recording of pressure and injection of fluid, and catheters were inserted in the femoral artery for recording systemic blood pressure and in the femoral vein for administration of fluids and drugs.

The catheter from each site of recording was led to a Sanborn transducer, then to either a 4- or 8-channel Sanborn polygraph. Advantage was taken of the mechanism of "zero suppression" of the polygraph whereby a large range of pressure may be covered without change in attenuation. This accounts for the difference in base-line figures present in many of the illustrations. All animals were artificially ventilated in order to prevent any effects of respiratory alterations on the phenomena of pressure recorded.

The supratentorial pressure was increased by injection of saline into a 5 cc. balloon inserted in the extradural space over the cerebral hemisphere or by injection of saline through one of the catheters into the subarachnoidal space. A 2 cc. balloon was placed in the infratentorial extradural or subdural space in order to create a mass in the posterior fossa. Injections of saline were also made into the catheter in the posterior fossa and into one of the lumbar needles. Occasionally, in order to produce sustained intracranial hypertension for brief periods, saline was infused into the subarachnoidal space from a reservoir placed at measured distances above the animal's head.

An electroencephalogram was recorded from six needle electrodes inserted into the scalp over the frontal, temporal, and posterior parietal areas bilaterally. Increasing the intracranial pressure led to awakening and artifact of movement in lightly anesthetized animals, so that additional pentobarbital was administered intravenously in increments sufficient to prevent movement.

Results

Since communication of pressure from the supratentorial space to the posterior fossa is dependent upon patency of the basal cisterns surrounding the brain stem in the tentorial incisura, an early manifestation of obstruction of the incisura is the development of a differential of pressure between the supratentorial and infratentorial spaces.* In these experiments transtentorial obstruction was said to be present whenever the infratentorial pressure fell below the supratentorial pressure during supratentorial injection of fluid.

The development of a progressive obstruction of the incisura is illustrated in Fig. 1. Several small injections, to a volume of 2.0 cc., had been made into an extradural balloon prior to injection in ① where there is still full communication of pressure to the cisterna magna and lumbar subarachnoidal space. In ② the peak of the pressure in the cisterna magna fell below the supratentorial pressure, and in ③ a 15 mm. Hg differential had developed. In ④ the increase of pressure with injection was followed by a secondary rise in intracranial pressure, and with the subsequent injection obstruction of the tentorial incisura was virtually complete.

Injection of saline into the lumbar subarachnoidal space or cisterna magna invariably reduced the transtentorial obstruction (Fig. 1 ⑤), and this occurred irrespective of the height of the supratentorial pressure. In one preparation the supratentorial pressure was raised to 250 mm. Hg and main-

* The term obstruction is used in preference to herniation since herniation cannot be diagnosed on the basis of a differential of pressure alone.
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FIG. 1. Pressures are recorded from the lumbar and supratentorial subarachnoidal spaces and the cisterna magna. Pressures in this and all subsequent illustrations are recorded in mm. Hg. Injections were made into the supratentorial subarachnoidal space to a supratentorial pressure of approximately 50 mm. Hg. In (a)–(f) the lumbar and cisterna-magna pressures lag behind the supratentorial pressure, and in (g) and (h) the pressure continues to rise after the injection is stopped. In (i) there is nearly complete obstruction at the tentorial incisura. In (j) the obstruction is readily relieved by lumbar injection but gradually reverts in (k). The secondary increase in intracranial pressure following cessation of injection seen in (l) and (m) is similar to the phenomenon described in detail in patients with increased intracranial pressure by Lundberg. In all experiments the speed of the polygraph was 1 mm. per sec, so that each large division equals 5 sec.

Fig. 1 illustrates that with release of pressure below the tentorium the obstruction gradually redevelops, and this is also demonstrated in Fig. 2. In this experiment the lumbar injection resulted in a maintained supratentorial hypertension, but with absorption of the injected saline the lumbar pressure and that of the cisterna magna fell rapidly, resulting in nearly a 50 mm. Hg differential of pressure across the incisura. Because it was undesirable for the purpose of some experiments to have a persistent transtentorial obstruction, a strenuous effort was occasionally made to effect a more lasting reduction. Occasionally this was accomplished by emptying the extradural balloon and infusing the lumbar subarachnoidal space at a pressure in excess of the supratentorial pressure. However, the obstruction recurred with relatively small-volume additions to the balloon.

In order to assess the relative importance of a space-occupying mass and increased intracranial pressure per se in the etiology of

FIG. 2. Transtentorial obstruction is evidenced by the 30 mm. Hg differential in pressure between the supratentorial subarachnoidal space and the cisterna magna. A lumbar injection produces immediate relief of the obstruction when the pressure in the cisterna magna exceeds the supratentorial pressure, but following injection the obstruction redevelops and is accompanied by a secondary increase in supratentorial pressure.
transtentorial obstruction, saline injections into an extradural balloon were compared with supratentorial subarachnoidal injections with the balloon deflated. In the one instance a gradually expanding mass is produced and in the other the fluid is rapidly absorbed. Fig. 3 graphs the results of an experiment in which multiple injections of saline were made into the supratentorial subarachnoidal space, each injection to a pressure of 40 mm. Hg. The pressure was then allowed to return to normal, and each supratentorial injection was followed by a lumbar injection in an attempt to counteract any trend toward transtentorial obstruction. With all 7 subarachnoidal injections there was excellent communication between the supratentorial space and the cisterna magna. The 8th injection was made into the extradural balloon, also to 40 mm. Hg, and transtentorial communication of pressure was still present. However, with the subsequent injection into the balloon a 22-mm. Hg differential of pressure developed, and following the 3rd injection into the balloon obstruction was complete. With this last injection the supratentorial pressure was raised to only 18 mm. Hg to avoid irreversible damage of the midbrain. A lumbar injection followed each injection of the balloon as before. The extradural balloon was then evacuated, and two subsequent supratentorial subarachnoidal injections failed to reproduce the transtentorial block.

When herniation of brain tissue occurs secondary to a space-occupying mass in the posterior fossa there is caudal displacement of the cerebellar tonsils into the spinal canal with obstruction of the foramen magnum, and upward herniation of the cerebellum through the tentorial incisura may also be present. In initial experiments a balloon was placed in the extradural space in the posterior fossa in order to create a space-occupying mass, but with gradual inflation of the balloon stripping of the dura mater from the skull over the transverse sinus occurred, and the balloon expanded into the supratentorial space. Therefore, the infratentorial balloon was inserted in the subdural space over the lateral and inferior aspects of the cerebellum. Failure of communication of pressure from the infratentorial to the supratentorial space then occurred with inflation of the balloon (Fig. 6), but less frequently than caudal transtentorial obstruction with a supratentorial balloon.

At postmortem examination of these monkeys the occipital bone was removed and the occipital lobes were elevated before disturbing the posterior fossa. In one animal subjected to prolonged and maximum expansion of the balloon in the posterior fossa the dura mater had been torn from its attachment to the falx and stripped back over a large herniation of the cerebellum (Fig. 4). Communication of pressure between the two chambers was complete since they had been converted into virtually one space. Thus, in this experiment there was full transmission of pressure across the tentorium in both directions in the presence of massive herniation of the cerebellum.

Failure of communication of pressure between the posterior fossa and the spinal subarachnoidal space was easily produced, obstruction of the foramen magnum often occurring at the time the balloon was placed in the posterior fossa. Also, opening the catheter in the cisterna magna to the atmosphere was sufficient to produce a block of the foramen magnum if this did not occur at the time the balloon was inserted.
Fig. 4. Immediately following death of the animal bone was removed over the cerebral hemispheres and the occipital lobes were elevated with a pair of forceps. The posterior fossa was not disturbed. The balloon in the posterior fossa had been inserted in the subdural space along the left lateral and inferior surfaces of the cerebellum. Inflation of the balloon had resulted in tearing of the tentorium along its free edge and at its attachment to the falx cerebri. At the time of this photograph the balloon in the posterior fossa contained 2.0 cc. saline.

Expansion of a supratentorial mass rarely produced an obstruction of the foramen magnum. It is apparent that a distinction between obstruction of the tentorial incisura and foramen magnum can be made only by recording the pressure in the posterior fossa in addition to that in the supratentorial and lumbar spaces. The fact that the mere insertion of a catheter into the cisterna magna predisposes to a block of the foramen magnum, because of the unavoidable escape of a small quantity of spinal fluid, appears to be an adequate explanation of this finding. Furthermore, since the pressure in the posterior fossa falls so abruptly with obstruction of the tentorial incisura under the present experimental conditions, it is most unlikely that in acute experiments, in which pressure is not recorded from the cisterna magna, a sufficient differential of pressure can be developed between the posterior fossa and intraspinal space to produce a herniation of the foramen magnum. The incidence of concomitant herniations of the tentorial incisura and foramen magnum in patients with supratentorial tumors is undoubtedly the result of the chronicity of the process with a gradual caudal displacement of the brain stem and cerebellum.

One of the most interesting findings in these experiments was the demonstration that injections of saline into the subarachnoidal space above the foramen magnum reduced the obstruction whereas lumbar injections did not. In Fig. 5 (1 and 2) there is full communication from the lumbar space to the infratentorial and supratentorial spaces as demonstrated by supratentorial subarachnoidal and lumbar injections. The catheter in the cisterna magna was then disconnected from the polygraph and opened to the atmosphere, and a subsequent lumbar injection resulted in no communication to the supratentorial space (3). The catheter was reattached to the polygraph and injection into the lumbar space demonstrated a

Fig. 5. Saline injections into the supratentorial subarachnoidal space (1) and lumbar space (2) showed complete communication. The catheter in the cisterna magna was then opened to air (3) and lumbar injection resulted in no communication to the supratentorial space. The catheter was then reattached to the transducer and lumbar injection of saline shows no significant communication to the posterior fossa (4). However, injection of saline into the supratentorial space eliminates the obstruction of the foramen magnum (5).
virtually complete block between the spinal canal and posterior fossa (4). Saline injected into the supratentorial subarachnoidal space then appeared to completely relieve the obstruction (5).

Two explanations for this observation were considered: (i) mechanical conditions at the foramen magnum are such that fluid injected under pressure from above can be forced between the obstructing cerebellum and the dura mater so as to raise the cerebellar tonsils out of the foramen magnum; and (ii) the herniation is actually increased by the supratentorial injection and the rise in lumbar pressure is caused by the additional volume of brain tissue herniated into the spinal canal. The latter explanation was ruled out by the experiment illustrated in Fig. 6. The lumbar injection (1) demonstrates minimal communication to the intracranial space. Following injection of 0.6 cc. of saline into a balloon in the posterior fossa a supratentorial injection reveals poor communication to the lumbar space (2), and a repeated injection with a total of 1.4 cc. saline in the balloon demonstrates a partial obstruction at the incisura and a complete one at the foramen magnum (3). The balloon was then emptied, and a supratentorial subarachnoidal injection shows complete relief of the obstruction (4). If there had been an increase in the volume of the herniation, accounting for the delayed rise in lumbar pressure, inflation of the balloon would have accentuated this effect. In fact, the lumbar pressure increased with the supratentorial injection only after the balloon had been evacuated and the original conditions restored.

In these experiments failure to reduce a herniation of the foramen magnum by increasing the pressure caudal to the obstruction contrasts with the uniform ease with which a transtentorial herniation was relieved by injections into either the lumbar or posterior-fossa subarachnoidal space. On the other hand, an obstruction of the foramen magnum, produced by allowing a few drops of cerebrospinal fluid to escape from the cisterna magna, was alleviated by a subarachnoidal injection cephalad to the block, whereas the transtentorial obstructions were almost always made worse by supratentorial injection. Rarely, a transtentorial block was relieved by supratentorial injections as illustrated in Fig. 7. A transtentorial block had followed inflation of a supratentorial balloon and the obstruction of the foramen magnum was produced by opening the catheter in the cisterna magna. The supratentorial balloon was then evacuated. A lumbar injection shows complete obstruction at the foramen magnum (1), but a supratentorial subarachnoidal injection partially
relieves the transtentorial followed by complete reduction of both herniations (2). Subsequent supratentorial and lumbar injections demonstrate free communication (3 and 4).

Discussion

Obstruction of the tentorial incisura, manifested by a differential of pressure between the supratentorial and infratentorial spaces, was produced in every animal in which a supratentorial space-occupying mass was created. In fact, with the injection of small increments of saline into the balloon at relatively constant intervals of time, the volume required to produce obstruction at the incisura could be predicted with considerable accuracy.

During the early stages of transtentorial obstruction from a supratentorial mass a ball-valve effect was evident. Following each injection into the balloon the intracranial pressure fell as the result of a decrease in the intracranial contents, in large part a reduction of blood volume within the brain. Following the first injection, which produced evidence of obstruction of the incisura, the pressures gradually returned to normal. With the next injection there was initial communication across the incisura indicating that the obstruction had been relieved, but with each subsequent injection the infratentorial pressure lagged farther behind the supratentorial pressure, and finally communication of pressure through the incisura was completely abolished. At this point the subarachnoidal space between the temporal and occipital lobes and the incisura is undoubtedly obliterated, and further injections into the balloon would then result in herniation of cerebral tissue into the incisura.

Evidence that an expanding supratentorial mass is a most important factor in the etiology of transtentorial herniation has been presented in a comparison of injections into the balloon and subarachnoidal space. With injections of saline into the supratentorial subarachnoidal space there was full and equal communication of the increased pressure throughout the subarachnoidal space; that is, the pressure in the subarachnoidal space beneath the temporal lobe, for example, is approximately equal to the pressure at the site of injection over the superior surface of the hemisphere. Thus, the tendency for the brain to be shifted caudally was minimal and occurred only with very rapid injections. In the late stages of some experiments considerable cerebral swelling occurred as evidenced by herniation of brain through the catheter holes, and at this time the effects of injections into the supratentorial subarachnoidal space and balloon were the same.

Obstruction of the subarachnoidal space at the level of the foramen magnum occurred
with minimal manipulations in the posterior fossa, insertion of a small balloon into the subarachnoidal space over the cerebellar hemisphere often resulting in immediate obstruction of the foramen magnum. In comparing the responses of the subarachnoidal pressure below obstructions of tentorium and foramen magnum (Figs. 2 and 4), a significant difference was evident. An early transtentorial obstruction was manifested by the development of a differential of pressure at the peak of the supratentorial pressure, whereas the lumbar subarachnoidal pressure lagged behind the pressure of the posterior fossa with a herniation of the foramen magnum, then ultimately approached or equaled the intracranial pressure.

However, occasionally it was possible to demonstrate reduction of a transtentorial obstruction by continuing to increase the supratentorial pressure after development of the block. This suggests the presence of a similar mechanism whereby obstructions of the tentorial incisura and foramen magnum are relieved by subarachnoidal injections of fluid cephalad to the obstruction. That the mechanics of pressure involved are complex is emphasized by the observation that a transtentorial obstruction is immediately relieved by elevating the lumbar pressure above the supratentorial pressure whereas it has not been possible to eliminate an obstruction of the foramen magnum with lumbar injections to pressures as high as 100 mm. Hg.

Reduction of an obstruction of the foramen magnum by a supratentorial subarachnoidal injection occurred only in the absence of a space-occupying mass in the posterior fossa. When the obstruction was caused by inflation of a balloon in the posterior fossa, supratentorial and subarachnoidal injections of the posterior fossa had no effect on the obstruction.

Rapid lumbar injections of saline have been suggested as a means of reducing herniation of the tentorial incisura and foramen magnum, particularly if signs and symptoms of herniation develop at the time of lumbar puncture. LaLonde and Gardner have shown that the ventricles are readily filled with saline injected through the lumbar subarachnoidal space and have advocated this method of expanding the cerebral hemispheres after removal of a large extracerebral mass. They did not mention whether the injected fluid also appeared in the subarachnoidal space over the hemispheres. In the present experiments, we had expected an obstruction of the foramen magnum to be reduced more readily than a transtentorial block because of the presumed difficulty in delivering a significant head of pressure through the narrow basal cisterns to the tentorial incisura. In fact, the reverse situation was found to exist. As previously noted, the configuration of the base of the skull and the anatomy of the tentorium in the monkey are quite similar to man, so at present there is no reason to believe that the mechanics of pressure differ among primates.

A distinction has been made between obstruction of the tentorial incisura and foramen magnum as manifested by the development of a differential of pressure between adjacent intracranial and spinal compartments, and herniation of brain tissue which can be diagnosed with assurance only at postmortem examination. In monkeys with sustained intracranial hypertension secondary to a supratentorial space-occupying mass significant transtentorial herniation of the medial temporal lobe has been described.

Grooving of the temporal lobe by the tentorium was seen in the present animals, but this is also found in monkeys in the absence of a supratentorial mass and has been described in normal human brains by Le Beau.

On the basis of these studies it is probable that a sudden transtentorial herniation developing at the time of lumbar puncture could be reduced by the rapid injection of saline through the lumbar needle, but it has been demonstrated that the incisura is almost immediately reoccluded if the condition causing the obstruction remains. However, after the supratentorial mass is removed repeated injections into the lumbar canal can eliminate the obstruction effectively.

The sustained relief of a transtentorial ob-
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duction under these circumstances is undoubtedly the result of re-establishment of the cerebral subarachnoidal space. It will be shown that as long as the subarachnoidal space is patent increased intracranial pressure alone will not cause a transtentorial herniation because pressure is transmitted equally through the subarachnoidal pathways. If these pathways are obstructed a differential of pressure can be created between the supratentorial space and incisura, and herniation through the incisura will follow.

Cephalad herniation of cerebellum through the incisura occurred regularly with expansion of a balloon in the posterior fossa as determined at postmortem examination. Initially this produced failure of transmission of pressure from the infratentorial to the supratentorial space but as the herniation increased stretching and tearing of the tentorium occurred. The increased pressure was then transmitted directly from the cerebellum to the cerebral hemispheres because of the large surface-to-surface contact between these structures.

Summary

Experimental obstruction of the tentorial incisura is readily produced in the monkey by expansion of a supratentorial extradural balloon. The obstruction is relieved when the pressure in the posterior fossa is raised above the supratentorial pressure by injection of saline into either the cisterna magna or the lumbar subarachnoidal space. However, when the lumbar injection is discontinued the obstruction recurs immediately unless the supratentorial mass is removed.

An obstruction of the foramen magnum has been produced by insertion of a balloon into the posterior fossa. Prior to inflation of the balloon the obstruction of the foramen magnum can be relieved by injection of saline into the subarachnoidal spaces cephalad to the obstruction but it cannot be reduced by injections of lumbar fluid. After the balloon in the posterior fossa has been inflated, the obstruction cannot be relieved by injections of fluid either above or below the block.

It has been demonstrated that the presence of a space-occupying mass is more important than increased intracranial pressure per se, in the etiology of herniations of the tentorial incisura and foramen magnum, and this is believed to be caused by progressive obliteration of the subarachnoidal space with a mass lesion. Thus, the most important factor in preventing or treating herniations of the brain is the maintenance or re-establishment of the subarachnoidal space at the site where the herniation occurs.

References