Measurement of extradural pressure and its relationship to other intracranial pressures

An experimental and clinical study

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SUMMARY Disadvantages associated with the use of ventricular catheters for the prolonged measurement of intracranial pressure have resulted in the search for an alternative technique. Measurement of pressure from the extradural space is one such possibility, but widespread acceptance of this procedure has been limited by the technical difficulties associated with this measurement and lack of information on the relationship between cerebrospinal fluid and extradural pressures. A study to investigate this relationship and to develop a simple and effective technique for measuring extradural pressure is described.

In certain patients with head injuries and intracranial space-occupying lesions, acute rises in intracranial pressure producing brain shift or impairment of the cerebral circulation—may occur before changes in vital signs are recognized. Furthermore, the reduction of intracranial pressure by means of one of the several methods currently available is too often unpredictable. For these reasons patient management may be greatly assisted, and more readily programmed, if intracranial pressure is directly monitored (Lundberg, Troupp, and Lorin, 1965; Johnston, Johnston, and Jennett, 1970).

Lundberg (1960) described a technique for the direct closed measurement of intraventricular pressure which has been widely accepted. However, this procedure has several clinical disadvantages, as recognized by Lundberg (1972) himself. Because of the disadvantages, much attention has been focused on developing a simple alternative technique which does not require penetration of the dura-arachnoid membranes. Many of these techniques employ implanted electronic pressure-sensitive transducers which often give technical difficulties. Furthermore, the clinical interpretation of the

data is impeded by lack of firm knowledge of the relationship between pressure recorded in the extradural space and the intracranial pressure.

The aims of this study were: (1) to explore the relationship between extradural pressure, supratentorial subarachnoid pressure and ventricular pressure; (2) to assess the use of latex balloons as pressure-sensing devices in the extradural and subarachnoid spaces; (3) to evaluate a metal capsule, to be described, for clinical use in measuring extradural pressure over prolonged periods with minimal discomfort to the patient.

METHODS

ANIMAL STUDIES The experiments were carried out on 12 dogs, but two baboons were also studied because the dura mater in these primates is more like that in man, being only loosely attached to the skull. The dogs were intubated after induction with thiopentone sodium, and anaesthesia maintained with nitrous oxide, oxygen, and halothane. Artificial ventilation to normocarbida and normoxia was achieved with the aid of muscle relaxants. Body temperature was maintained at 37° C. The baboons were premedicated with phencyclidine 0.5-1 mg/kg

and the anaesthetic technique was the same as for the dogs, except that the induction was inhalational with nitrous oxide, oxygen, and halothane.

Arterial blood-pressure, central venous pressure and intracranial pressures were measured by electronic transducers mounted at the same level as the cisterna magna, all animals being in the right lateral position. Pressures were recorded on a multi-channel physiological recorder. At least one hour elapsed after the end of the operative procedures (to be described) before the recording of pressures.

1. Latex balloons The compliance of small latex balloons was measured *in vitro* by adding increments of saline, to a total of 2 ml. There was no significant increase in pressure recorded from these balloons over this volume range.

The balloons contained sufficient fluid to fill their dead space, care being taken to avoid air bubbles. In five dogs the balloons were implanted in the extradural space through a burr hole, after carefully stripping away the dura mater and achieving haemostasis. The balloon then lay in the extradural space away from the skull opening. A catheter was inserted into a lateral ventricle through a separate burr hole. All openings in the skull were closed with dental cement. A standard volume (0.5 ml.) of fluid was injected into each balloon after insertion into the extradural space, and the pressures from both sites recorded.

FIG. 1. Stainless steel extradural capsule.

2. Extradural metal capsule A small stainless steel capsule was constructed (Fig. 1). It was 9 mm in diameter and 2 mm in height, with multiple side holes connecting with a central catheter. Side holes, rather than an end hole, were chosen to facilitate recording and to minimize occlusion by the dura mater. This device was inserted in seven dogs and two baboons through a burr hole, to lie in the extradural space under one parietal eminence.

A latex balloon was inserted in the subarachnoid space through another burr hole on the opposite side, to lie over the anterolateral surface of the parietal cortex. Each balloon was carefully filled with 0.5 ml. saline. All burr holes were sealed with

dental cement. A fine catheter was inserted under direct vision through the tectorial membrane and its tip positioned to lie in the cisterna magna. A three-way tap attached to this catheter allowed either the recording of pressure or small infusions of normal saline into the posterior fossa (Fig. 2).

Saline (0.2 ml.) was injected into the extradural capsule and, between three and 15 minutes later, pressures were simultaneously obtained from all three measuring sites, while the intracranial pressure was altered by means of small intermittent infusions into the cisterna magna. In each animal there were at least four such studies over a wide range of pressures. All measurements were completed within six hours of insertion of the extradural capsule. At the end of each experiment methylene blue was injected into the capsule to establish whether a complete seal had been achieved around the capsule. Three dogs were excluded from the results because a leak was demonstrated.

CLINICAL STUDIES Patients considered to be at risk from increased intracranial pressure in the period after neurosurgery had a ventricular catheter inserted for pressure measurement. An extradural capsule, modified for clinical use by incorporating a threaded metal plug to allow fixation to the skull (Fig. 3) was implanted through a separate burr hole into the extradural space.

The extradural pressure capsule was sited over the convexity of the skull in the frontal or parietal area. An incision 3 cm long was made and the pericranium stripped from the skull. A skull perforator with matching cone and rose were used to make the skull opening. Alternatively, the opening could be made with an electric or compressed air-driven skull perforator. It is essential that the diameter of the hole is such that the extradural pressure capsule will fit securely, both from the point of view of patient safety and for obtaining reliable recordings. The extradural pressure capsule is made of EN58 stainless steel, and has a self-tapping thread. In order to assist fixation using minimum force on the capsule itself, a tapping screw was also used to prepare the skull to receive the capsule. Histacryl tissue glue was used in the early cases to seal the capsule in position, but this technique was given up since use of the glue is unnecessary when the capsule is properly and firmly inserted.

Before inserting the capsule into the skull it was necessary to secure haemostasis in respect of the dural surface and the extradural space. If small vessels on the surface of the dura mater bled they were gently controlled with coagulation diathermy current. If extradural oozing of blood persisted, this was stopped by tiny pieces of Surgicel tucked gently

FIG. 2. Schematic diagram of dog study. Cerebrospinal fluid pressure is altered by infusion of fluid into cisterna magna. P_{ED} , pressure recorded from extradural space. P_{CSF} , pressure recorded from supratentorial subarachnoid space. P_{FF} , pressure recorded from posterior fossa.

into the extradural space. This was not often necessary unless the capsule had been placed near the midline of the skull.

Before inserting the capsule the burr hole opening and the exposed dura mater were irrigated thoroughly with saline at body temperature to remove any debris, bone dust or blood. A spray of topical antibiotic (Polybactrin) was also used to minimize the risk of infection.

The scalp was sutured in a single layer with interrupted black silk sutures. When the capsule was removed the wound was checked under good illumination. No evidence of haemorrhage or infection

was found in our cases. The wound was always closed in a single layer, no deep suture being employed in the secondary closure.

The practical clinical problems encountered in this study were:

a. The capsule could not be inserted if the skull opening was too small. Similarly, if the opening were even marginally too large the capsule was unsafe and recordings were not valid. This difficulty can be overcome by the use of a tapering screw capsule and work on this is in progress.

b. The head bandages had to be arranged around the device in such a way as to allow access to the wound without disturbing the wound or the head dressing.

c. In very thick skulls—for example, in patients with acromegaly or Paget's disease—the capsule may be too small and for these patients a deeper capsule is necessary. Similarly, for children a shorter capsule was used, otherwise the skin could not be closed over it.

d. Where extradural bleeding or oozing welled up immediately after its insertion, the capsule had to be removed, cleansed, and rinsed through before reinsertion.

The technical aspects of the use of the capsule did not prove difficult or troublesome in our hands, and the insertion and removal processes are now routine. They are mentioned none the less as guidance to others who may use the technique.

FIG. 3. Extradural capsule modified for clinical use.

FIG. 4. Graph showing the effect of altering the volume of fluid in extradural balloons on the accuracy of the pressure recorded from the system. EDP, extradural pressure. IVP, intraventricular—measured by catheter. Upper curve shows the effect of adding fluid to the balloon; lower curve the effect of withdrawing fluid.

Over a 12 month period 25 such patients were monitored by both techniques. The extradural and ventricular catheter were connected to a miniature electronic transducer which was mounted externally on the head bandage and could therefore be readily calibrated. Pressure measurements were taken from both sites, three to 15 minutes after injecting the capsule with 0.2 ml. saline. The capsule was removed under local analgesia, usually 48 to 72 hours after operation, when measurements were no longer considered necessary for clinical management.

RESULTS

ANIMAL STUDIES 1. *Latex balloons* The extradural pressure (EDP) readings obtained from latex balloons were unreliable, either over-estimating or under-estimating the extradural pressure in an unpredictable manner, when filled with the standard volume of 0.5 ml. In order to study this further, in one dog 0.1 ml. aliquots of saline, to a total volume of 0.5 ml., were injected and removed, and pressures from both the balloon and ventricle were recorded after each volume change. The extradural pressure measured was dependent upon the volume of fluid in the balloon, and upon whether the balloon was being filled or emptied (Fig. 4). There was good correlation between extradural

FIG. 5. Comparison of posterior fossa pressure (measured by catheter) and supratentorial subarachnoid pressure (measured by latex balloons) in dogs. PFP, posterior fossa pressure. SAP, subarachnoid pressure.

and intraventricular pressure (IVP) for a short but inconstant time (minutes), following the temporary distension of the balloon with 0.5 ml., at an initial volume of 0.5 ml.

2. Extradural metal capsule During several

FIG. 6. Comparison of extradural pressure (measured by capsule) and supratentorial subarachnoid pressure (measured by latex balloons) in dogs. Broken line—line of identity.

FIG. 7. Extradural pressure (means and standard errors) observed from capsule with 5 mmHg changes in supratentorial subarachnoid pressure in four dogs.

separate infusions into the cisterna magna of four dogs, 103 observations were made of pressures recorded simultaneously from the posterior fossa and the supratentorial subarachnoid cerebrospinal fluid. Figure 5 demonstrates the close correlation found between these two pressures. Figure 6 shows similar close correlation between extradural and supratentorial subarachnoid pressures, based on 156 measurements from the four dogs. All points lie close to the line of identity, except in one dog during one

FIG. 8. Effect on accuracy of measurement of EDP of a poorly-sealed capsule. Arrow denotes injection of 0.2 ml. saline into the capsule. SAP, supratentorial subarachnoid pressure. Horizontal bars indicate halothane administration.

infusion. Subsequent infusions in this dog produced results consistent with those found in the remaining animals. The mean values shown in Fig. 7 demonstrate that, over the entire range of pressures that would commonly be encountered, no appreciable pressure gradient occurred across the dura mater under the conditions of measurement described. The attainment of a completely leak-free system was seen to be essential because any decompression of the extradural space led to underestimation of pressure (Fig. 8). In the baboon, similar results were obtained for the relationship between extradural pressure and supratentorial subarachnoid pressure.

CLINICAL STUDIES In five of the 25 patients a comparison between the extradural and ven-

FIG. 9. Relationship of extradural pressure to intraventricular pressure within six hours of craniotomy. Solid line—regression line. Broken line—line of identity.

tricular pressures could not be made post-operatively. Difficulty in locating a small ventricle prevented the insertion of a catheter in one and obstruction or displacement of the catheter accounted for the exclusion of two others. Of the remaining two patients, one had a separate burr hole 5 mm away from the capsule and it was considered that decompression from the extradural space was occurring through this. In the last patient, the capsule was palpably loose in the burr hole. This problem

has not recurred since the insertion procedure has been modified to include the use of a bone-tapping tool.

In the remaining 20 patients the extradural and intraventricular pressures were compared and the results have been divided into three groups, based on time of measurement after insertion of the extradural capsule.

1. *Readings within six hours of inserting extradural capsule* For various reasons unrelated to the extradural device, readings were not taken from four patients within six hours of operation, reducing this group to 16. Figure 9 shows the relationship between EDP (Y-axis) and IVP

FIG. 10. Relationship of extradural pressure to intraventricular pressure within 6 to 24 hours after craniotomy. Solid line—regression line. Broken line—line of identity.

FIG. 11. Relationship of extradural pressure to intraventricular pressure within 24 to 48 hours of craniotomy. Solid line—regression line. Broken line—line of identity.

(X-axis) obtained from 178 observations taken between three and 15 minutes after flushing the capsule. The readings form a band which crosses the line of identity, with the extradural pressure tending to exceed the intraventricular pressure at low values of the latter. With ventricular pressures greater than 100 mm H₂O, the converse relationship may be noted. Of the seven patients in whom the intraventricular pressure was low, all had had removal of sub-

FIG. 12. Effect of injecting 0.2 ml. saline into extradural capsule in a post-craniotomy patient. V, ventricular trace. F, time of injection. E, extradural trace. Top trace: time marker. Gaps at one minute intervals.

TABLE

Period after operation (hr)	Readings (no.)	Correlation coefficient	Slope of regression line	Intercept of regression line (mm H ₂ O)
6	178	0.48	0.59	+48
24	222	0.64	0.67	+48
48	220	0.79	1.06	+84

stantial quantities of cerebrospinal fluid at operation.

2. *Readings about 24 hours after insertion of extradural capsule* Figure 10 shows the values obtained from 222 observations on 20 patients after flushing the extradural capsule. At this stage the band of readings has moved closer to the line of identity.

3. *Readings about 48 hours after insertion of extradural capsule* All but 16 of the 220 readings of extradural pressure taken from 18 patients at this time lie above the line of identity, with the line of best fit being 80–100 mm H₂O higher than, and approximately parallel with, the line of identity (Fig. 11). In almost all patients flushing of the capsule resulted in a localized rise in extradural pressure. In none was more than 50 mm H₂O of this pressure increase transmitted to the ventricle (Fig. 12).

In general, the magnitude and duration of the extradural pressure rise after flushing depended on the time that had elapsed after insertion of the capsule.

The correlation coefficients and values for intercept and slope of the calculated regression lines are shown in the Table.

DISCUSSION

The direct closed measurement of intraventricular pressure described by Lundberg (1960) was a significant step forward in the management of head injuries, and allowed a quantitative assessment of the efficacy of the measures designed to reduce cerebral oedema (Lundberg, *et al.*, 1965; Coe, Nelson, Rudenberg, and Garza, 1967; Johnston, *et al.*, 1970). However, this technique has serious disadvantages—namely, the difficulty of locating a displaced or compressed

ventricle, alteration in intracranial hydrodynamics with possible disastrous effects when cerebrospinal fluid is withdrawn or inadvertently lost (Schettini, McKay, Majors, Mahig, and Nevis, 1971; Nornes, personal communication) the possibility of introducing infection directly into the ventricular system, and difficulty in maintaining an unobstructed catheter/manometer tube system over a prolonged period (Lundberg, 1960; Lundberg *et al.*, 1965; Jacobson and Rothballe, 1967). In our own series of 25 patients, the ventricle could not be located in one, and obstruction or displacement of the catheter occurred in two. In no case was there clinical evidence of infection.

In addition to intraventricular pressure measurement, a number of pressure-sensing devices have been implanted intracranially. In the subdural space, fluid-filled latex balloons (Hoppenstein, 1965), pneumatic switches (Numoto, Slater, and Donaghy, 1966) and electronic transducers (Hulme and Cooper, 1966; Coe *et al.*, 1967; Richardson, Hide, and Eversden, 1970) have been used. This approach, however, involves breaching the integrity of the dura mater, and therefore miniature transducers of varying design (Nornes and Serck-Hanssen, 1970; Schettini, McKay, Majors, Mahig, and Nevis, 1971) have been designed for implanting in the extradural space. These have not been widely accepted for clinical monitoring because of technical difficulties concerning zero drift, calibration, and hysteresis.

It was for these reasons that we decided to evaluate a simple system for measuring extradural pressure. The first approach was to test latex balloons in the extradural space of experimental animals, where they were found to be unreliable; pressures recorded were dependent on the contained volume and on the *in situ* hysteresis of individual balloons. Similarly unreliable results were obtained in a few post-craniotomy patients in whom small balloons were implanted in the extradural space. A possible explanation of the unreliability of the balloon readings is that adherence of the dura mater to the skull limits the free expansion of the balloon.

The difficulties associated with latex balloons in the extradural space were not found when the balloons were inserted into the subarachnoid space, where a close correlation was seen

between the posterior fossa pressure and the supratentorial subarachnoid pressure. This agrees with the finding of Langfitt, Weinstein, Kassell, and Gagliardi (1964) and justifies the use of balloons in the supratentorial subarachnoid space as a means of measuring accurately cerebrospinal fluid pressure in this region.

Balloons having proved unsatisfactory in the extradural space, a metal capsule was designed for the implantation in this site and consistent repeatable results were obtained. In order to ensure patency, the capsule was flushed intermittently with 0.2 ml. saline, this being its internal volume. This metal capsule demonstrated that the pressure in the extradural space of experimental animals was identical with the subarachnoid pressure over a range of intracranial pressure up to 100 mmHg (Fig. 6). This implies that the dura mater fully transmits the subarachnoid pressure to the artificial extradural space. The results of Langfitt *et al.* (1964) would appear to be in line with this conclusion. These workers also investigated the stretching of dura mater and concluded that *in vitro* it is a virtually non-elastic material. Thus, our finding in animal experiments, that no pressure gradient existed, must imply that the dura mater is not fully distended *in vivo*. This non-distensibility of the dura mater accounts for the need to seal the cranial cavity completely.

Schettini and co-workers (1971)—using an extradural transducer—found that ‘brain surface pressure’ exceeded posterior fossa pressure in dogs, which apparently contradicts our findings and those of Langfitt *et al.* (1964). They postulated that there exists at the brain surface a tissue pressure which exceeds subarachnoid pressure, due to the presence of a gradient across the pia mater. They further believe that their extradural transducer, which incorporated a non-sensitive coplanar ring, pushed on to the brain through the intact dura mater, detected this ‘brain surface pressure’. As we are not comparing the same pressure, their results do not necessarily conflict with ours.

Turning now to the clinical results, and beginning with measurements made in the first six hours after operation for neurosurgical procedures, it was found that in approximately 60% of the patients the extradural capsule recorded pressures lower than the intraventricular pres-

sure during the 12 minute observation period. A similar picture had been seen in dogs known to be decompressing around a poorly-sealed capsule (Fig. 8). In the case of patients, however, injection of methylene blue through the capsule into the extradural space did not result in staining of the scalp tissues. This suggests that decompression may have been occurring elsewhere, possibly through the mobile bone flap. In the remaining patients in whom extradural pressure exceeded the intraventricular pressure, the ventricular pressure was usually found to be low and associated with removal of substantial amounts of cerebrospinal fluid in the course of the surgical procedure. On the next day the slope of the regression line had moved closer to the line of identity, and this may have been due to sealing of the bone flap and expansion of the cerebrospinal fluid volume. By 48 hours after surgery the regression line was virtually parallel with the line of identity, and measurements of extradural pressure correlated well with intraventricular pressure readings but systematically over-read by 80–100 mm H₂O for reasons that are still not clear. Possible explanations include tissue reaction to the capsule, accumulation of flushing fluid, and slow venous oozing. With regard to this last possibility, no clinically important amount of blood clot was discovered when the capsule was removed.

As mentioned previously, it was considered necessary to flush the capsule intermittently. This procedure produced small and transient elevations of extradural pressure immediately after insertion. With the progression of time after surgery, the rise in extradural pressure produced by the same volume of flushing fluid was higher and longer sustained. However, only an insignificant part of this was transmitted to the intraventricular pressure. This difference between extradural and intraventricular pressures after flushing can be ascribed to the non-distensibility of the dura mater already discussed and may indicate that the space in which the capsule is sited and the channels for absorbing the injected fluid are becoming obliterated by fibrin and organizing blood clot.

Previous evidence concerning the relationship between extradural pressure and intraventricular pressure in man is limited to a comment by Lundberg (1972), that: ‘extradural pressure

measurement may give adequate information about variations in ICP and, within certain limits, permit approximate quantitative assessment of the actual pressure level', and a figure of the comparison of the two pressures in one patient published by Nornes and Magnaes (1971). The results from this latter case showed extradural pressure to be higher than intraventricular pressure by a margin similar to that reported here.

From the results of this study it would seem that the use of a perforated metal capsule in the extradural space for the recording of intracranial pressure after neurosurgery has the advantage that the dura mater need not be breached, and thus avoids producing changes in intracerebral hydrodynamics and minimizes the risk of infection in the cerebrospinal fluid. In addition, a check on base-line drift of calibration can be achieved accurately and simply because the transducer is mounted externally on the head bandage. The animal studies indicate that, at least in the six hours after insertion of the device, the dura mater provides no barrier to the accurate transmission of pressure from the cerebrospinal fluid to the extradural space, provided the volume of fluid injected into the capsule is not excessive.

Observations from the clinical trial suggest that this system may be a valuable aid in clinical management 24 and 48 hours after operation. However, immediately after craniotomy, presumably because of continuing decompression of the extradural space, the method is a less reliable guide to intracranial pressure. In cases of closed head injury, where there is neither a mobile bone flap nor loss of cerebrospinal fluid, measurement of extradural pressure may give an accurate indication of intracranial pressure from the moment of capsule insertion, as was found in our animal experiments. A study of this extradural pressure measuring system in patients with head injury is in progress.

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REFERENCES

- Coe, J. E., Nelson, W. J., Rudenberg, F. H., and Garza, R. (1967). Technique for continuous intracranial pressure recording. *Journal of Neurosurgery*, **27**, 370-375.
- Hoppenstein, R. (1965). A device for measuring intracranial pressure. *Lancet*, **1**, 90-91.
- Hulme, A., and Cooper, R. (1966). A technique for the investigation of intracranial pressure in man. *Journal of Neurology, Neurosurgery, and Psychiatry*, **29**, 154-156.
- Jacobson, S. A., and Rothballe, A. B. (1967). Prolonged measurement of experimental intracranial pressure using a subminiature absolute pressure transducer. *Journal of Neurosurgery*, **26**, 603-608.
- Johnston, I. H., Johnston, J. A., and Jennett, B. (1970). Intracranial-pressure changes following head injury. *Lancet*, **2**, 433-436.
- Langfitt, T. W., Weinstein, J. D., Kassell, N. F., and Gagliardi, L. J. (1964). Transmission of increased intracranial pressure. 2. *Journal of Neurosurgery*, **21**, 998-1005.
- Lundberg, N. (1960). Continuous recording and control of ventricular fluid pressure in neurosurgical practice. *Acta Psychiatrica Scandinavica*, **36**, Suppl. 149.
- Lundberg, N. (1972). Monitoring of intracranial pressure. *Proceedings of the Royal Society of Medicine*, **65**, 19-20.
- Lundberg, N., Troupp, H., and Lorin, H. (1965). Continuous recording of the ventricular-fluid pressure in patients with severe acute traumatic brain injury. *Journal of Neurosurgery*, **22**, 581-590.
- Nornes, H., and Magnaes, B. (1971). Supratentorial epidural pressure recorded during posterior fossa surgery. *Journal of Neurosurgery*, **35**, 541-549.
- Nornes, H., and Serck-Hanssen, F. (1970). Miniature transducer for intracranial pressure monitoring in man. *Acta Neurologica Scandinavica*, **46**, 203-214.
- Numoto, M., Slater, J. P., and Donaghy, R. M. P. (1966). An implantable switch for monitoring intracranial pressure. *Lancet*, **1**, 528.
- Richardson, A., Hide, T. A. H., and Eversden, I. D. (1970). Long-term continuous intracranial-pressure monitoring by means of a modified subdural pressure transducer. *Lancet*, **2**, 687-690.
- Schettini, A., McKay, L., Majors, R., Mahig, J., and Nevis, A. H. (1971). Experimental approach for monitoring surface brain pressure. *Journal of Neurosurgery*, **34**, 38-47.