A continuous, accurate knowledge of intracranial pressure would be of great value as a guide for therapy and as an index of the clinical state in many neurosurgical cases, particularly in recording pressure changes in acute head injury cases. The response of intracranial pressure to hypothermia, fluid deprivation, mannitol or urea, corticosteroids, and improved ventilatory exchange could then be recorded. Intracranial pressure recordings could also be correlated with other physiological measurements, such as blood pressure, cardiac rate, and respiratory rate.

We are describing a technique which we have evaluated in experimental animals and subsequently used in two patients who had anaplastic cerebral tumors treated by cryosurgery. In these two patients, we anticipated that an increase in intracranial pressure would occur following focal freezing of the lesions. We desired to observe the extent and duration of this pressure alteration as well as to have an opportunity to consider the method for further use in patients with severe acute head injuries.

Operative Technique

A miniature pressure transducer which had been gas-sterilized was introduced through a burr hole into the subdural space through a small slit in the dura. The transducer was placed under the intact bone to provide the necessary resistance (Fig. 1). The transducer leads were brought out through the burr hole and held in position by a small tantalum flange and screw fixed to the edge of the burr hole. Leakage of cerebrospinal fluid through the small dural slit was minimal; however, the burr hole opening was closed with bone wax as an added precaution.

The transducer was immediately connected to a suitable recorder for baseline pressure determination. Cryosurgery was then carried out through a second burr hole. When the scalp incision was closed, the leads were brought out of one end of the wound and further stabilized in the head dressing. The patient and recorder were returned to the ward for continued recording for 1 week postoperatively. The transducer was then removed under local anesthesia through partial reopening of the original incision. No complications related to the recording technique were noted in these two patients.

Recording Technique

A Scientific Advances (Columbus, Ohio) Model MM-BW pressure-sensitive transducer was used in this study. It was connected to a Grass Instruments Company Model 5B polygraph through a cable and several resistors, to permit the use of a Model 5P1 Low Level DC preamplifier. This MM-BW transducer is a 6.35 mm diameter disc, 0.5 mm thick, containing four arms of a Wheatstone bridge. It is designed to operate at 26 to 35 inches of Hg with a temperature variation of 0.2% of full scale per degree Fahrenheit. Thus, at the pressures expected, there could be as much as a 20% error caused by temperature changes of 1°F.

To compensate, the temperature effect upon the transducer was calibrated in terms...
of the resistance change (balance voltage) required to maintain recorder-pen stability. Following intracranial implantation of the transducer, the “balance voltage” dial could then be adjusted correctly for concurrently measured body temperature in order to afford manual temperature compensation. This permitted temperature correction to within 1% of full scale, using the closest 0.1°C, which is better than the precision of reading the pen recording. With the highest sensitivity used, an error of 0.1°C was equivalent to 6 mm H₂O. An additional 4 mm H₂O error could occur by a one unit error in setting the “balance voltage” dial. Hence, the maximum error was ±10 mm H₂O with a usual precision of ±5 mm H₂O at all sensitivities. To operate the preamplifier at the middle of the “balance voltage” dials (actually precision resistors), and since the numbers are arbitrary for the present purpose, a 10,000 ohm resistor was added parallel to these precision resistors (Fig. 2).

Since the manufacturer’s suggested input voltage of 3.0 V heated the transducer more than necessary, a voltage divider was incorporated in the transducer cable which made available the stable 12 V DC excitation voltage from the preamplifier and decreased the excitation voltage of the strain gauge to below 2 V. With this arrangement (Fig. 2), it was possible to calibrate the transducer against a Statham strain gauge as well as against mercury and water manometers. No additional resistor was added to the “bridge calibration” switch; when it was depressed, a 34.0 mm deflection of the recorder pen calibrated the record to 2000 mm H₂O for full-scale pen deflection (40 mm) at a sensitivity of 0.5 mV/cm. All other calibration settings of the polygraph were done according to the Grass manual. By increasing the sensitivity by a factor of 5, a 200 mm H₂O intracranial pressure could be recorded in the middle of a channel. It should be noted that the calibration deflection and the balance voltage setting will vary slightly when using other 5P1 preamplifiers; therefore, each preamplifier must be individually calibrated.

Following implantation, the amplifier settings were verified twice a day. Further, the preamplifier settings were verified in two ways: 1) a reduction of the sensitivity by one-half should reset the pen one-half of the way towards the baseline, which represents atmospheric pressure; 2) pushing the “bridge calibration” switch at a sensitivity of 1.0 mV/cm should deflect the pen by 17.0 mm. Temperature compensation was, of course, continuously carried out by appropriately setting the “balance voltage” dial. All readings were compared to a second pen, whose galvanometer switch was turned off to eliminate any errors from paper weave. The “half amplitude high frequency” switch may be turned to 15 to reduce any possible 60 cycle hum, to 3 to further reduce pulse waves, or to 0.5 or 0.1 to reduce respiratory
excursions of the pen when recording at slow speed; 0.3 mm per second has been found a useful paper speed.

Results

Figure 3 shows concurrent recordings of the transducer and strain gauge while both were connected to a bottle of air which could be pressurized by a manual squeeze bulb. A U-tube mercury or water manometer was also included in the system. There was a leak in the bottle stopper around the transducer cable, which necessitated repetitive pumping of the bulb and permitted comparative evaluation of the two transducers when calibrated so as to give identical-sized excursions.

Figure 4 shows concurrent recordings of the rise in intracranial pressure in a dog as Ringer’s solution was pumped from a pres-
sure bottle into the cranium to a pressure above systolic blood pressure. A typical Cushing’s reflex occurred, and upon release of the pressure, both pens returned toward the baseline. The differences between the two records reflected the difference in location of the two transducers. The strain gauge was connected to the pressure tubing and adjusted to give zero pressure indication at rest. The pressure transducer was set for zero pressure prior to implantation within the skull and, when in place, was subjected to a wedge pressure at all times.

Figure 5 shows a typical clinical record of intracranial pressure in a patient. The total wedge pressure was 1475 mm H$_2$O, which corresponded to baseline intracranial pressure. The pulse pressure, when not filtered out, was about 70 mm H$_2$O at the site of recording of the half-sitting patient and showed a dicrotic wave (Fig. 5, top, b to c). Respiratory cycles caused variations in intracranial pressure of about 40 mm H$_2$O, and coughing or sneezing raised it by 200 mm H$_2$O on some occasions.

The infusion of urea showed an immediate response of the intracranial pressure reading. In one patient, the pressure dropped from 2500 mm H$_2$O to 2180 mm H$_2$O during 1½ hours, while in the other patient it decreased from 3800 mm H$_2$O to 2800 mm H$_2$O in 1 hour (Table 1). In both patients, a second infusion a few hours later resulted in negligible effects. Occasionally, a relatively steady intracranial pressure record changed to a wavy pattern (Fig. 6). The waves reached a peak of 300 mm H$_2$O over the trough intracranial pressure within a period of approximately 30 to 90 seconds.

### Discussion

The clinical importance of intracranial pressure evaluation has long been recognized. Only with continuous recording has it been feasible to study its constancy or the factors that alter it.\(^1\)\(^2\)\(^3\)\(^4\) The definitive monographs by Lundberg\(^5\)\(^6\) reported a catheter implanted in a ventricle and connected to an external strain gauge. Such a system required accurate knowledge of the location

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**Table 1**

<table>
<thead>
<tr>
<th>Time of Measurement</th>
<th>Pressure in mm H$_2$O</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Patient WB</td>
</tr>
<tr>
<td>Pressure at time of insertion</td>
<td>1400</td>
</tr>
<tr>
<td>Zero time (start cryosurgery)</td>
<td>1410</td>
</tr>
<tr>
<td>10 min (end cryosurgery)</td>
<td>1550</td>
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<tr>
<td>1 hr</td>
<td>1460</td>
</tr>
<tr>
<td>6 hrs</td>
<td>1300</td>
</tr>
<tr>
<td>9 hrs (urea started)</td>
<td>1620</td>
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<tr>
<td>12 hrs</td>
<td>1900</td>
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<tr>
<td>24 hrs</td>
<td>2500</td>
</tr>
<tr>
<td>90 hrs</td>
<td>2180</td>
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<tr>
<td>100 hrs (urea started)</td>
<td>2600</td>
</tr>
<tr>
<td>101½ hrs</td>
<td></td>
</tr>
<tr>
<td>130 hrs</td>
<td></td>
</tr>
</tbody>
</table>

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\(^1\)\(^2\)\(^3\)\(^4\)\(^5\)\(^6\)
of the ventricles and was subject to the hazard of catheter collapse or occlusion; it also produced a considerable volume displacement during its introduction. Subdural emplacement was tried by Numoto, et al.,\textsuperscript{5} who used a homemade switch within a silastic envelope to indicate the relationship between the applied air pressure inside the envelope, which kept the switch open, and the intracranial pressure outside, which closed it. The system was manually operated, and readings were discontinuously available. While our present studies were underway, Hulme and Cooper\textsuperscript{2} reported the use of a small pressure transducer. Its fidelity was not evaluated although it was reported to be stable for prolonged periods.

While the placement of the intracranial pressure transducer between the brain and the skull places a "wedge" pressure upon the active element of the transducer, the pressures so determined are absolute pressures and therefore permit continuous evaluation of intracranial conditions. Thus, the infusion of urea caused the intracranial pressure to decrease quite promptly and it could be noted that the magnitude of the effect varied not only between patients but also with repetition of the dose in the same patient. Both patients showed brief changes upon coughing. Slow increases and decreases in pressure occurred in the several days following the freezing of the tumor in both patients, and cyclic pressure waves which occurred over a 10 to 30 minute period were also seen on occasion (Fig. 6).

Lundberg\textsuperscript{2} reported the existence of three classes of pressure waves which he labeled A, B, and C waves. The largest, A waves, lasted around 15 minutes and reached a peak of about 1000 mm H\textsubscript{2}O over baseline pressure. Hulme and Cooper\textsuperscript{2} also showed the existence of these large waves. B waves were described by Guillaume and Janny\textsuperscript{1} and by Lundberg\textsuperscript{2} as occurring at the rate of $\frac{1}{2}$ to 2 a minute. They varied in size from about 150 to 350 mm H\textsubscript{2}O, and were associated with a normal or pathological depression of wakefulness only by Lundberg\textsuperscript{3}. Similar waves were not reported by Hulme and Cooper\textsuperscript{2}. Both our patients showed bouts of "B" waves (Fig. 6) alternating with extended periods of no waves. Our data did not include the patient's state of wakefulness in order to permit behavioral correlation. C waves were only rarely seen by Lundberg\textsuperscript{2} and then only in association with A waves.

It is not the purpose of this report to discuss the meanings of the pressures recordable within the cranium (Table 1). We feel that general confirmation of the observations by others using intraventricular catheters is required before data from subdurally-implanted pressure gauges may be accepted. It appears that both methods are equally sensitive to minor intracranial pressure fluctuations. The subdural transducer is preferable since there is less brain tissue destruction and only an electrical cable leaves the head of the patient, thereby reducing the possibility of error in measurement due to kinking or change in level between transducer and brain site. It also reduces the possibility of infection from a fluid-filled passage (Guillaume and Janny\textsuperscript{1}, Lundberg\textsuperscript{2,4}) or air-filled passage (Hulme and Cooper\textsuperscript{2}, Numoto, et al.\textsuperscript{5}) entering the cranium of the patient.

**Conclusions**

We have described a technique for recording human subdural pressure which we believe provides an index of the general
intracranial pressure and therefore can be used for clinical purposes.

References