Measurement of Fontanelle Pressure (part I)

—A New Instrument for Non-invasive Measurement of Intracranial Pressure via the Anterior Fontanelle—

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Summary: Intracranial pressure (ICP) is one of the most important parameters for evaluating intracranial conditions. The skulls of newborns and infants, unlike the tightly sutured skull of adults, provide non-invasive access for measurement of ICPs via the anterior fontanelle. A new transducer has been developed which is convenient for non-invasive, continuous measurement of intracranial pressure through the anterior fontanelle. The new transducer is thinner and lighter than the APT-16 type transducer (Hewlett-Packard). The principles of measurement of ICP with this new transducer, the results of basic experiments, and results obtained from clinical applications are described in this report.

Key words: Intracranial pressure — anterior fontanelle — adhesive strain gauge transducer — hydrocephalus — infant

Introduction

Intracranial diseases of the newborn and infant, especially hydrocephalus, involve some disturbance of cerebrospinal fluid circulation which leads to abnormal dilatation of the ventricle and an increase of intracranial pressure (ICP) as the main clinical signs. Today RI cisternography, metrizamide CT cisternography, and other techniques have been established to observe the circulation and absorption of the cerebrospinal fluid. CT scanners reveal the intracranial morphology safely and easily and are widely used. The remaining problem in the diagnosis and followup of hydrocephalus is to develop a method to safely and easily measure ICP. Since the ICP is a dynamic parameter that changes with other biological changes in the body, such as arousal, sleep, tension, crying, body fluid change, a simple technique

like lumbar puncture may be insufficient. Invasive techniques like ventricular puncture or epidural pressure monitoring are not suitable for routine studies.

Wealthall and Smallwood (1974) reported a method of measuring ICP via the anterior fontanelle with an APT-16 transducer using the applanation method (manufactured by Hewlett-Packard Company). We have frequently used this method on infants. Although the APT-16 transducer has sufficient accuracy, it is difficult to fix because of its weight and shape. After reexamining the advantages and disadvantages of APT-16 transducer, a new apparatus of the applanation type was developed to measure intracranial pressure with a paper strain gauge based on the principle of an adhesive resistance strain gauge (Fontanelle pressure sensor: F.P. sensor, manufactured by Sanei-Sokki Inc.). This apparatus has been demonstrated in the

present study to be useful not only for a single measurement, but also for continuous measurement of ICP over many hours.

Principle and Apparatus of Measurement

1. Principle of measurement

The applanation method described by Welthall and Smallwood (1974) is used for this apparatus. This principle has already been applied to an ophthalmic tonometer. When an area (A) is pressed flat with a force (W), the tension (T) of the scalp over the anterior fontanelle is exerted in a tangential direction (X axis), and therefore does not become a counter-force of (W) in the direction of Y axis. It is a vector unrelated to the intracranial pressure. Further if the volume displaced by the applanation surface (A) is sufficiently small, the increase of intracranial pressure (P) is negligible. Then the Imbert-Fick equation, $W/A = P$ (pressure per unit area), is applicable providing the objects are relatively elastic and spherical, such as the eyeball and the infantile cranium (Fig. 1).

2. Apparatus

The apparatus for measuring the ICP consists of a transducer and a pressure indicator. The transducer has a foot plate with an out ring and a central plunger. It is important that the foot plate and plunger are on the same plane (Shojima, 1980). The inner structure of the transducer is shown in Fig. 2. A thin spring plate of phosphorus bronze is connected to the plunger and to paper strain gauges (Fig. 2). The mode of pressure transmission is as follows. Pressure on the central plunger is transmitted to the spring plate. The strain in the direction of Y axis is detected by the 4 paper strain gauges and amplified. The thickness of spring plate can be changed arbitrarily between 0.10 and 0.25 mm. In a preliminary study to decide the most suitable thickness of spring

Fig. 1. The ICP measured via the anterior fontanelle by the applanation method on the basis of the Imbert-Fick equation. Pressure (P) equals the force (W) per unit area (A). If a segment of a flexible sphere is flattened by a plane surface, pressure in the sphere acting on the flattened area is in balance with an applied force.

plate, mechanical appropriateness of each spring thickness (0.10, 0.15, 0.20, 0.25) has been confirmed (Fig. 3). The spring plate of 0.25 mm thickness was too hard for actual intracranial pressure measurements. Therefore it seemed inappropriate for practical use. Conversely, the thinner spring plates 0.10 and 0.15 mm, were confirmed to have a sufficiently linear relationship within the clinical range of intracranial pressure, however the linearity was lost above 600 mmH₂O. Since the sensitivity was high, an excessive increase of amplitude (overshooting) was observed during sudden body movements. Since the plunger has its own weight, deviation of the 0 point reached a maximum [the max-

Fig. 2. A drawing of the F.P. sensor. A thin metal board (spring plate) is connected to a plunger and four gauges. A change in ICP is transmitted to the strain gauges through the plunger and the strain is electronically converted to a voltage signal.

Fig. 3. Relationship between weight on the plunger and signal output (mm pen deflection) with spring plates of several thicknesses. There was a linear relationship with spring plates, 0.15, 0.20, 0.250 mm thick.

imum deviation of the 0 point was measured when the transducer was just above the sample (0°) or just below the sample (180°), of 45 mmH₂O (0.10 mm) depending on the angle of the transducer. In practice, the angle is limited from immediately above (0°) to a lateral position (90°), and the deviation of the 0 point in this clinical situation is less than 15 mm H₂O with the 0.10 mm spring plate. The 0.2 mm spring plate has the largest deviation, 25 mmH₂O.

The basis for selecting a spring plate was: 1) amplification capability, 2) linearity, and 3) relative stability. The 0.20 mm plate seemed the most suitable.

Next, the size (diameter) of the plunger is discussed. To obtain an accurate measure of the ICP, the appplanation area should be as small as possible and a linear relationship should also exist, even when the

anterior fontanelle is 1 cm in diameter. Plungers, 3, 6, and 9 mm in diameter, were produced, and examined in regard to the balance between the size of plunger and the thickness of the spring plate as well as the linearity. A linear relationship was not observed when a 3 mm plunger was used.

On the contrary, a linear relationship was found when a 6 mm plunger was used with any spring plate. With the 9 mm plunger, only a spring plate of 0.20 mm

thickness was used. Because the gain is narrow with the amplifier, sufficient adjustment could not be made. The baseline pressure was 140 mmH₂O rather than the conventional pressure of 100 mmH₂O, but otherwise the linearity was satisfactory (Fig. 4).

It was ascertained that sufficient linearity and sensitivity were obtained when plungers with a diameter of 6 mm or more were used. In addition, the non-linear relationship with the 3 mm plunger was

Fig. 4a. The pressure in a 1 liter flask was raised by 100 mmH₂O increments from 0 to 500 mmH₂O to compare the values recorded from an artificial "fontanelle" with a transducer having a 9 mm plunger and a 0.20 mm spring plate. The results demonstrate that an inner pressure of 100 mmH₂O, was recorded as 140 mmH₂O by the transducer. A linear relationship was obtained as the inner pressure was increased.

Fig. 4b. Results using a transducer with a 6 mm plunger and a 0.20 mm spring plate. The pressure were identical.

TABLE 1
Transducer characteristics

transducer size	diameter	32 mm
	height	12 mm
	diameter of plunger	6 mm
gauge resistance	120 ohms	
gauge factor	approximately 2	
electric configuration	4 active arm bridge	
recommended excitation	6 V (p-p) at 1 kHz	
sensitivity	10 μ V output per	
drift of temperature	10 mmH ₂ O/°C	
	mmH ₂ O applied pressure	
linearity	$\pm 1\%$ FSD*	
frequency response	DC - 200 Hz	

* Tested at full-scale deflection (FSD) with applied pressure of 500 mmH₂O

considered to be due to the small contact area between the plunger and the sample, the pressure transmission to the strain gauge was unstable, because a small change of intracranial pressure would not be accurately transferred to the plunger.

Therefore the 6 mm plunger and 0.2 mm spring plate which gave the best balance, were used in the present study.

The internal structure of the F.P. sensor had 4 paper strain gauges (PSG; 120 Ω) of the temperature corrected type. Two were mounted in parallel on each side of the core, the center of spring plate, and the other two were mounted on the back of spring plate. The 4 PSGs were used to construct a bridge which was connected to an amplifier. The multiple strain gauge system with 4 PSGs was used to increase the pressure and reaction sensitivities and to minimize the drift from each PSG with an increase in temperature. The sensitivity of the F.P. sensor was 2.7 V/g/cm². The characteristics of this apparatus are summarized in Table 1.

Results

1. Experimental results with a skull model

A 1 liter flask filled with water was

Fig. 5. A hole (3 cm diameter) was made in the top of a 1 liter round flask which was filled with water. The hole was covered by a membrane, such as a surgical glove with a mouse skin. This served as a model for the scalp and underlying fontanelle. The internal pressure (P) was adjusted by changing the level of water in the reservoir (H).

used as a model for the skull. A round opening was made in the top of the flask, and covered with a rubber membrane to imitate the "anterior fontanelle". The inner flask pressure was changed by changing the fluid level in a connecting reservoir (Fig. 5).

The properties of this "fontanelle" model system were studied. Several ma-

terials were used, including a condom, a surgical rubber glove, a rubber sheet with little elasticity, a rubber glove with mouse skin, and a rubber glove with infant's back skin. The flask pressure was measured with a F.P. sensor via the "fontanelle". The results are shown in Fig. 6. Even with a rubber sheet and mouse skin, which is far from ideal, Y was equal to $1.006X + 0.597$ this nearly corresponds to a straight line, $Y = X$. The correlation was 0.993. With a relatively elastic condom or surgical glove, the error of measurement was negligible (Fig. 6). From these results, when the human anterior fontanelle scalp has a certain degree of elasticity, the measurement of pressure with the F.P. sensor over the scalp probably reflects the absolute ICP.

The size of round window in the flask was changed from 3 cm to 5 cm. In both cases, a rubber sheet with little elasticity was used for the "fontanelle". The measurement was very accurate (Fig. 7). This suggested that a difference in size

of the anterior fontanelle is unlikely to cause an error in measurement.

Next, the inner pressure was measured simultaneously, with the fontanelle pressure. The fontanelle pressure was measured with the APT-16 transducer or F.P. sensor, and the inner pressure was measured directly with a Satham P-36 pressure transducer. Both the APT-16 transducer and F.P. sensor produced the same pressure values as the Satham P-36. However, when a sudden change of pressure occurred, the APT-16 and F.P. sensor tended to generate slightly higher amplitudes than the Satham P-36 transducer (Fig. 8). This is probably attributable to a difference in the frequency-response characteristics. 1) A decrease in the frequency-response of the system, including compliance at 20-30 Hz, occurred with the Satham P-36 transducer, and 2) an enhancement of the frequency-response of the system at approximately 100 Hz occurred due to the high resonance frequency with the APT-16 or F.P. sensor.

Fundamental experiment (I)

Correlation in two artificial fontanelle materials

Fig. 6. Relationship between the inner flask pressure and the output from the F.P. sensor with two membranes, a surgical glove (●) and a mouse skin (○).

Fundamental experiment (II)

Correlation in two sizes of artificial fontanelle

Fig. 7. Pressure relationship for artificial fontanelles, 3 cm (■) and 5 cm (▲) in diameter.

Fig. 8. Simultaneous recording with an F.P. sensor (above) and a Statham pressure transducer (below). The F.P. sensor detects the inner flask pressure and pressure fluctuations more accurately.

Fig. 9. Simultaneous recording with a needle transducer (above) and an F.P. sensor (below) in a hydrocephalic patient, 1 month of age. Note that the F.P. sensor detects the ventricular pressure and pressure fluctuations more accurately.

Fig. 10. Tracings from a 13 month-old patient with hydrocephalus using an F.P. sensor (above) and an intraventricular needle connected to a Statham transducer (below). Note the excellent reproduction of the intraventricular tracing with the F.P. sensor.

2. Results of simultaneous measurement of ventricular pressure

To evaluate the reliability of the F.P. sensor clinically, ventricular pressure was measured with a Statham P-36 transducer by ventricular puncture and the ICP was

simultaneously determined with an F.P. sensor via the anterior fontanelle in a patient with hydrocephalus. The subjects were hydrocephalic patients, 1 and 13 months of age. There were differences in the elasticity of the scalp over the anterior

Fig. 11. Polygraphic recordings of ICPs measured with an F.P. sensor during non-Rem (above) and REM periods (below) of sleep in a patient with meningocele and hydrocephalus. The height and amplitude of the ICP increased during REM sleep.

fontanelle and in the size of the fontanelle. The anterior fontanelle was relatively hard and $4\text{ cm} \times 3.3\text{ cm}$ in the 13 month old patient. The size was $3\text{ cm} \times 2.2\text{ cm}$ in the one month old patient.

In both cases the baseline pressure was nearly the same with the Satham P-36 and the F.P. sensor. However, during a sudden change of ICP accompanying a body movement, e.g. cough, the amplitude of each pulse tended to be slightly higher with the F.P. sensor than with the Satham P-36, similar to the model experiment (especially with the 0.15 mm spring plate in the F.P. sensor). In the older infant with the hard anterior fontanelle, the baseline pressure was measured with an F.P. sensor via the anterior fontanelle and compared with the intraventricular pressure from a needle tap. The difference in baseline pressure between the two systems reached a maximum of 60 mmH₂O depending on the degree of force needed to fix the F.P. sensor onto the anterior fontanelle. Further each pulse had a shorter duration, approximately 0.1 msec, with the F.P. sensor than with the Satham P-36. This is probably due to differences in the sizes of transducer transmission area, in the medium for transmission, in the frequency-response characteristics, and in the specific factors of each measurement system (Fig. 9, 10).

3. Clinical application

ICPs were recorded with a polygraph from 14 infants with hydrocephalus, 8 normal infants (less than 2 months) and newborns, and 25 infants with other types of intracranial diseases. During sleep, especially during REM and non-REM periods, the ICP was $283.8 \pm 106.6\text{ mmH}_2\text{O}$ and $157.5 \pm 19.1\text{ mmH}_2\text{O}$ in hydrocephalus, and $88 \pm 16.1\text{ mmH}_2\text{O}$ and $76.1 \pm 23.0\text{ mmH}_2\text{O}$ in normal infants and newborns, respectively. Fig. 11 is a polygraphic recording of REM and non-REM periods from a patient with meningocele compli-

cated by hydrocephalus. Since this recorder has a range beyond 550 mmH₂O, 1/2 gain was used (Fig. 11).

Discussion

Many measurements of ICP via the anterior fontanelle or the scalp defect have been described, and the methods of measurement are summarized in Table 2. The characteristics have been already reported in detail by Hayashi (1975). Wentzler (1922) measured the anterior fontanelle pressure by improving Schiötz's tonometer. This method is simple, but is limited to use in the sitting position, which leads to extremely low and incorrect values. The method of Purin (1964), using Marey's tambour, is theoretically accurate and can be applied clinically, but some training is necessary for measurement. Also, the anterior fontanelle must be relatively large, and continuous measurement for long durations is impossible, even though necessary to determine the ICP. The reproducibility is poor. Weathall and Smallwood (1974) used the APT-16 transducer, an applanation transducer based on Imbert-

TABLE 2
*Classification of ICP measurement
via fontanelle*

I. Improved schiötz's tonometer Wentzler (1922) Davidoff and Chamlin (1959) Edwards (1974)
II. Marey's tambour with pressure transducer Purin (1964) Barashnev and Leontiv (1965) Picton-Warlow and Robinson (1970) Hayashi (1975)
III. Applanation transducer Weathall and Smallwood (1974) Robinson et al. (1977) Shojima et al. (1977) Salmon et al. (1977) Honda et al. (1978)

Fick's principle, to measure the ICP non-invasively via the anterior fontanelle of the infant. This method is simple, and can measure ICP accurately. Furthermore it can measure the ICP continuously. Robinson et al. (1977) used similar methods in clinical cases, mainly with newborns. Shojima (1980) and Salmon et al. (1977) have reported in detail on the accuracy of the APT-16 transducer. An APT-16 transducer is an electromagnetic type transducer in which an, AC current is passed through the primary coil to produce a magnetic field. A metallic core is connected to the plunger and responds to the pressure by moving through the magnetic field, inducing an electric current. The movement is used to calculate ICP, based on a proportional relationship with electric current. The disadvantages of this transducer are the height of coil required to produce the magnetic field, an unstable fixation of the transducer on the anterior fontanelle due to the weight of the coil, and also the possibility of other resultant forces, such as strain on the X or Y axes, by the central core.

The F. P. sensor is similar to the APT-16 transducer in principle of operation and accuracy, however the F. P. sensor is 12 mm high and weighs 15 g. This is less than half the height and weight of the APT-16 transducer (24 mm and 36 g). Thus it is easily fixed on the anterior fontanelle and seems most suitable for continuous measurement of ICP over several hours. Also it is less expensive than the APT-16 transducer.

Wealthall and Smallwood (1974) compared the ICP via the anterior fontanelle and the intraventricular pressure by ventricular puncture. Only a small difference was noted which was expressed by $Y = 0.97X + 7.6$ ($p < 0.001$). This small error in measurement should not be a problem. A small pressure from fixing the transducer on the anterior fontanelle could produce this error. Measurements of the extra-

dural ICP, utilizing the coplanar measurement theory by Imbert-Fick's principle, also involves a problem at the point of measurement, apart from the difference between the scalp and the dura mater. Major et al. (1972) described the relationship between the tonometer depth and the ICP from a model experiment in which there was 3 stages, i.e. (1) a flattened membrane surface, (2) point of coplanar attachment, and (3) region producing an increase of inner pressure with increasing depth of the tonometer. It was decided that the point of coplanar attachment was the most suitable point for measurement. Ikeyama et al. (1976) stated that the artificial increase of the ICP was not due to the pressure buffer system of the blood vessels or cerebrospinal fluid cavity, if the depth of compression by a tonometer is small. Therefore measurement is possible even in region 3 as defined by Major et al. (1972). Schettini (1975) determined the relationship between the depth of the tonometer and the ICP in animals, and regarded the measurement possible in the region producing a sudden increase of pressure with relatively stable amplitude. The F. P. sensor was fixed to the anterior fontanelle by the tension of a rubber ring. This should correspond to stage 2 or 3. This method of fixation does not result in an increase of the ICP by movements made during measurement. However, if the ICP is greatly increased, the buffering actions of the intracranial vein and cerebrospinal fluid cavity are small, and fixation of sensor by compression may increase the ICP artificially.

In clinical practice, the pressure of fixation has little influence in newborns with elastic anterior fontanelles. As the anterior fontanelle hardens with age, or as the ICP is increased markedly, the elasticity of the anterior fontanelle is lost, the area applanated by the transducer is irregular, and the conditions are no longer appropriate for use of the appplanation method.

Fig. 12a. View of the F.P. sensor from the side.

Fig. 12b. View of the F.P. sensor from below. The foot plate of the F.P. sensor is stationary. When the sensor is placed on the anterior fontanelle, the plunger is displaced

Fig. 12c. View of the F.P. sensor from above.

Fig. 12d. This picture demonstrates the placement of the F.P. sensor on the anterior fontanelle. The guide ring is fixed by cyanoacrylate directly to the scalp over the anterior fontanelle, and the sensor is easily attached to the guide ring with a three-flanged spring.

Consequently, the intracranial pressure is markedly influenced by the fixation pressure. The error in the steady state pressure may be as large as 60 mmH₂O.

Measurement of the ICPs in older infants and infants with extremely high pressures must be investigated further in the future. The appplanation method of fixation may be improved by using different adhesives (Fig. 12). In addition, the height and weight of transducer have been reduced as much as possible to make it suitable for continuous recording of the ICP. Instead of the electromagnetic type APT-16 transducer, an F.P. sensor using strain gauges has been developed, but the

temperature characteristics of the strain gauge is still a problem. Although this sensor has a 4 gauge system to compensate for the temperature drift, the drift is still as large as 10 mmH₂O/C°. Since the F.P. sensor is attached to the human body, the drift due to changes of body temperature becomes a problem during continuous measurement for many hours. If the body temperature changes by 0.3°C in an infant, a drift of 3 mmH₂O is produced, although this degree of change is not a problem. When the F.P. sensor is used for continuous measurement, it is necessary to warm the sensor up for 20-30 minutes at the body temperature of the subject before it is attached.

Conclusion

An APT-16 transducer was used to measure the ICP via the anterior fontanelle. The advantages and disadvantages of this applanation transducer were analyzed. A transducer (F.P. sensor) using paper strain gauges (PSG) was manufactured and was found to be useful for continuous measurement of the ICP via the anterior fontanelle. Mechanical problems and temperature characteristics of the F.P. sensor were discussed.

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References

- BARASHNEV, Y.I. and LEONTIV, A.F. (1970). Cerebrospinal fluid pressure in premature infants with and without intracranial birth injury (Russian). *Rediatriya*, **44**, 507.
- DAVIDOFF, L.M. and CHAMLIN, M. (1959). The "Fontanometer" adaptation of Schiötz tonometer for the determination of intracranial pressure in neonatal and early period of infancy. *Pediatrics*, **24**, 1065-1068.
- DORSCH, N.M.C. and SYMON, L. (1975). A practical technique for monitoring extradural pressure. *J. Neurosurg.* **42**, 249-257.
- EDWARDS, J. (1974). An intracranial pressure tonometer for use on neonates preliminary report. *Dev. Med. Child Neurol.* **16**, 38.
- HAYASHI, T. (1975). Studies on early diagnosis of infantile central nervous system disorder, especially, for hydrocephalic infant. *The Journal of the Kurume Medical Association*, **38**, 401-449.
- HONDA, E., HAYASHI, T., HIKITA, T., SHOJIMA, T. and KURAMOTO, S. (1978). Clinical analysis of chronic subdural effusion-relationship between CT findings and ICP via fontanelle. *Nervous System in Children*, **3**, 113-122.
- IKEYAMA, J., MAEDA, N., NAGAI, H., KOGA, K., IGARASHI, I. and INAGAKI, D. (1976). Measurement of intracranial pressure - (5) - problems on epidural measurement of intracranial pressure-. *Brain and Nerve*, **28**, 1289-1295.
- MAJOR, R., SCHETTINI, A., MAHIG, J. and NERIES, A.H. (1972). Intracranial pressure measured with the coplanar pressure transducer. *Med. Biol. Eng.* **10**, 724-733.
- PICTON-WARLOW, C.G. and ROBINSON, R.J. (1970). Evaluation of a method of indirect measurement of intracranial pressure in infants. *Dev. Med. Child Neurol.* **12**, 507.
- PURIN, V.R. (1964). Measurement of the cerebrospinal fluid pressure in the infant without puncture. *A New Method Rediatriya*, **43**, 82-85.
- ROBINSON, R.O., ROLFE, P. and SUTTON, P. (1977). Non-invasive method for measuring intracranial pressure in normal new born infant. *Dev. Med. Child Neurol.* **19**, 305.
- SHOJIMA, T. (1980). Studies on non-invasive method of intracranial pressure (ICP) measurement in infants. *The Journal of the Kurume Medical Association*, **43**, 408-459.

- SALMON, J. H., HAJIAR, W. and BADA, H. S. (1977). Fontogram; A non-invasive intracranial pressure monitor. *Pediatrics*, **60**, 721-725.
- SCHETTINI, A. and WALCH, E. (1975). Simultaneous pressure depth measurement of the intracranial system made epidurally, in Lundberg N, Ponten U, Brock M. *Intracranial Pressure II*. Berlin, Springer, 409-415.
- WEALTHALL, S. R. and SMALLWOOD, R. (1974). Method of measuring intracranial pressure via fontanelle without puncture. *J. Neurol. Neurosurg. Psychiatry*, **37**, 88-94.
- WENTZLER, P. (1922). Ein Apparat zur Messung des Schadel innenendruckeres an der Fontanelle des Sauglings. Vorl Mitteilung *Arch Kinderhk*, **70**, 24.