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Non-invasive ICP monitoring in infants: the Rotterdam Teletransducer revisited

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Abstract Measurement of intracranial pressure (ICP) is important in patients at risk of raised ICP, as in hydrocephalus. Ideally, it should be non-invasive, thus avoiding the risk of infection and other complications. Such is provided by measurement of ICP through the anterior fontanelle. There are several methods of measuring anterior fontanelle pressure (AFP); those most frequently used are based on the applanation principle. An evaluation of AFP measurement devices resulted in the choice of the Rotterdam Teletransducer (RTT) to be used in our study of children with hydrocephalus. The literature contains little information on the accuracy or validation of the AFP measurements using the RTT. Therefore, the physical qualities of the RTT were reassessed, using a specially developed calibration device. The results of this study demonstrate that membrane temperature does not have any effect on the measured pressure. The thermal stabilization time of the RTT was found to be 3 h after switching on. Insufficient thermal stabilization results in a pressure underestimation of up to 3 mmHg. Furthermore, a maximum inaccuracy of 2.6 mmHg, after calibration and readjustment of the transducer, was calculated. Validation of the equipment was achieved by simultaneous AFP/ICP measurements in hydrocephalic patients showing high correlations ($r = 0.96-0.98$). The discussion suggests a measurement protocol as a means of increasing the reliability of RTT measurements.

Key words Intracranial pressure
Ventricular fluid pressure
Fontanelle pressure
ICP monitoring · Fontanometry
Hydrocephalus · Infant

Introduction

Intracranial pressure (ICP) monitoring in young infants can be useful in a variety of neurological conditions (hydrocephalus, intraventricular haemorrhage, birth injuries, meningitis, encephalopathies, etc.). Ideally, the monitoring should be non-invasive, avoiding the risk of infections and other complications. Because the anterior fontanelle in infants gives access to the intracranial compartment, several fontanometers for measuring ICP have been designed [11, 21]. These non-invasive techniques can be applied over a longer period of time and allow frequent intermittent measurements. However, ICP monitoring is only of clinical importance when the measurement equipment is accurate and completely reliable. Measurement should show high correlation with the actual ICP. Although several studies suggest a close relation with simultaneously measured intraventricular pressure, a serious criticism of fontanometers has been that non-invasive ICP measurements are not sufficiently reliable to be useful in clinical practice [6, 11, 14, 17, 21]. The inaccuracy is partly caused by externally exerted pressure when the transducer is applied to the fontanelle [4, 10]. Attention has also been drawn to problems with calibration and zero drifts [11].

Most anterior fontanelle pressure (AFP) measurement techniques are based on the applanation principle, described by Wealthall and Smallwood [21]. This involves the application of a transducer with a sensing surface surrounded by a non-sensitive outer ring. These are positioned so that they are coplanar with the fontanelle. In this way, the skin is flattened and stretching forces are dissipated at the peripheral non-sensitive outer ring. The non-invasive AFP measurements are performed in either a direct or an indirect manner. The indirect (or pneumatic) AFP measurement technique uses air as a medium for transmitting the AFP to the pressure measurement device. With the direct AFP measurement technique, the pressure is measured directly on the fontanelle.

Indirect (pneumatic) AFP measurement devices

The pressure applied to the coplanar membrane is actively kept in equilibrium with the AFP using an external air-pump. There are two principles commonly used to detect the equilibrium between external generated pressure and AFP. The first principle uses optically controlled pressure regulation, in which a beam of light is reflected on a mirror mounted on the coplanar membrane. The intensity of the reflected light is influenced by the deformation of the membrane due to the difference between AFP and external generated pressure. Of the optically controlled devices, the LADD, first introduced by Vidyasagar and Raju [20], is the one most commonly used.

The second principle uses a valve to control the externally generated pressure, first developed by Whitelaw and Wright [22]. A continuous but slow air flow is supplied to the device which results in pressure on the coplanar membrane. The valve opens and keeps the externally generated pressure equal to the AFP.

Inherent to both techniques are certain drawbacks, such as a slow frequency response, temperature instability and motion artefacts due to movements of the connecting air tube (both devices) and optic fibres (optically controlled devices) [1, 11]. Furthermore, one has no means of making baseline corrections to the LADD, and in situ calibration of this device on the fontanelle is problematic [1, 11].

Direct AFP measurement devices

The pressure sensor is mounted on the membrane and converts the AFP into an electrical impedance. The coupling between the sensor and the impedance measuring device can be either galvanic or telemetric. An example of a galvanic coupled device is the strain gauge transducer with the gauges placed in a Wheatstone bridge [2, 3, 18]. An example of a telemetric device is the Rotterdam Teletransducer (RTT), a telemetric high frequency tuning device based on modulation of the resonance frequency of a passive coil capacitor circuit [8, 16].

These devices generally have a fast frequency response [3, 16, 18]. A drawback of the strain gauge transducers is their possible temperature dependency [3, 18]. During measurement, energy dissipated in the gauges can alter the temperature of the transducer, resulting in a pressure drift. Within the RTT, little energy is dissipated inside the sensor, and this has a positive effect on the thermal stability of the device. In both techniques, the wiring between the sensor and the impedance measuring device is very flexible; they are, therefore, less sensitive to motion artefacts.

According to Leggate and Minns [11], an ideal pressure transducer should have a flat frequency response from zero up to about 30 Hz. Additionally, the relationship with the actual ICP should be linear. It should be sensitive and not influenced by thermal changes.

The indirect (pneumatic) AFP measurement devices cannot fulfil the frequency response requirement. Therefore, a direct telemetric measuring device, the RTT, is used in this study. The RTT allows in situ baseline correction, and the positioning of the sensor on the fontanelle is such that the application pressure does not interfere with the actual measured AFP. According to previous studies the RTT has a frequency response that exceeds 50 Hz, which allows for AFP pulse wave analysis. Furthermore it has good long-term stability, is accurate and has relatively low thermal instability [6, 13, 16]. Barometric pressure changes are automatically compensated for [12]. Furthermore, the transducer has been developed from an epidural method. It is impermeable to water and will not be affected by perspiration of the skin [5, 12].

However, using the RTT in hydrocephalic infants, we encountered certain drawbacks, such as variable zero drifts and calibration inconsistencies. Previous studies could not explain these findings. The aim of the present study was, therefore, to reassess the physical qualities of the RTT, and to evaluate its validation by relating the measured AFP to the actual ICP, represented by the intraventricular pressure (IVP). In order to be able to interpret future AFP measurements obtained with the RTT in clinical practice, the data variation in different circumstances was examined. The discussion suggests a measurement protocol guaranteeing maximum accuracy.

Materials and methods

The Rotterdam Teletransducer

The RTT is composed of a resonator and an electromagnetic coupled impedance measurement device. The resonator consists of a passive coil capacitor system enclosed within a piston. The location of the capacitor is such that one of the plates forms the flat top of

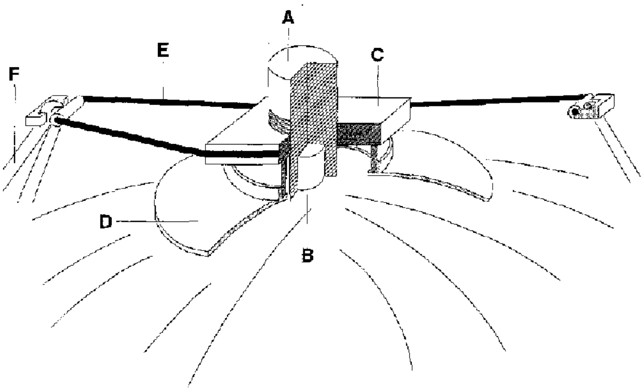


Fig. 1 Mechanical construction of the RTT fixation frame and piston. *A* Piston, *B* transducer, *C* perspex body, *D* adaptor fixation plate, *E* loading spring, *F* rubber band

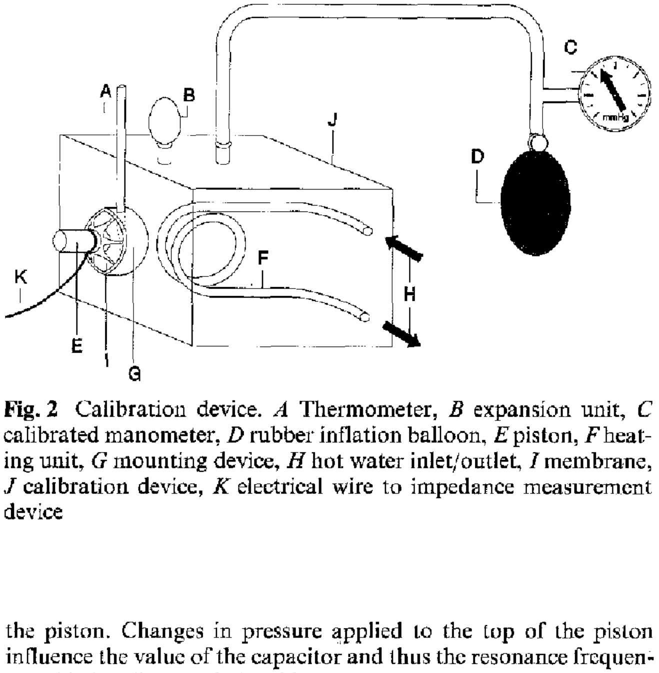


Fig. 2 Calibration device. *A* Thermometer, *B* expansion unit, *C* calibrated manometer, *D* rubber inflation balloon, *E* piston, *F* heating unit, *G* mounting device, *H* hot water inlet/outlet, *I* membrane, *J* calibration device, *K* electrical wire to impedance measurement device

the piston. Changes in pressure applied to the top of the piston influence the value of the capacitor and thus the resonance frequency. This is a linear relationship.

The piston is rotated manually into the thread of a lightweight perspex adaptor (Fig. 1), which rests on the skin overlying the bony structures adjacent to the fontanelle. It is kept in place by means of rubber bands.

Accurate depth positioning of the piston is essential. The pressure depth curve (PD curve) is used to adjust the piston to the fontanelle [17]. This curve is produced by uniformly rotating the piston into the thread of the adaptor. A characteristic plateau occurs in the PD curve when the top of the piston is coplanar with the fontanelle. Optimal depth positioning of the piston is at a point halfway along the plateau [17].

The occurrence of the plateau on the PD curve is independent of the operator, provided the insertion is performed at a constant, slow rate. Hence, the depth ascertained using the PD curve is largely intra- and interobserver-independent and guarantees reproducible AFP measurements [7]. The size and state of the fontanelle do, however, have a great influence on the quality of the measurement.

Evaluation of the RTT

The most important physical modalities were reviewed when evaluating the performance of the RTT. This was done in both in vitro and in vivo experiments. In vitro, the RTT was tested using a specially developed calibration device. In vivo, several AFP and intraventricular pressure (IVP) measurements were carried out simultaneously.

In vitro measurements

A sensitive calibration device was constructed, consisting of a pressure chamber with fixed walls except for an area covered with a Latex membrane (Fig. 2). The piston can be positioned on this membrane by means of a mounting device. Pressure on the membrane of the calibration device can be verified with the Utah Medical Veri-Cal pressure transducer tester, to an accuracy of 0.1 mmHg. The pressure measured by the RTT was recorded on an IBM-compatible personal computer using the Metrabyte DAS16 12-bit analogue-to-digital converter. Multichannel data acquisition recording software (MKR) was used for data storage.

The in vitro measurements of the RTT can be divided into two parts. First of all the performance of the RTT was examined under ideal laboratory conditions. Secondly, as several clinical factors may have a negative effect on the accuracy of the calibration, these were investigated in simulated clinical situations.

Laboratory conditions. Dissipation of energy by electrical components increases the temperature inside the measurement device. This influences the (electrical) characteristics of the RTT and its performance. The *thermal stabilization time*, defined as the time needed for the output of the system to stabilize after being switched on, has to be specified. After calibration, the pressure measured by the RTT was registered over a period of 5 h. The membrane of the calibration device was at room temperature (21 °C).

In addition, prior to measurement, the RTT has to be *calibrated*. The performance of the RTT was investigated using a stabilized system, with the insertion depth of the transducer set at the plateau of the PD curve. Calibration was performed at 0.0 and 40.0 mmHg. After each measurement, gain and offset were randomly altered, prior to readjusting the piston to the membrane and to the subsequent recalibration.

Simulated clinical conditions. In clinical measurements, the RTT is calibrated on the membrane (21 °C) of a calibration device and subsequently transferred to the fontanelle (37 °C). When the electrical qualities of the resonator show temperature dependency, measurement errors are possible. In order to determine *temperature dependency*, the resonator, after thermal stabilization, was calibrated on the membrane at room temperature (21 °C). Next, the temperature of the membrane was increased to 37 °C and an AFP measurement repeated without recalibrating the RTT.

In clinical measurements, the piston with the *transducer is moved* from the calibration device and readjusted to the fontanelle. This could influence calibration qualities and thus the accuracy of the measurement. To assess this, the piston was put into position on the calibration device using the PD curve and a calibration performed. After removing the piston from the membrane and subsequently reinserting it in the mounting frame, the offset was adjusted to 0.0 mmHg just prior to the point at which the piston touched the membrane. The relation between generated and measured pressure was subsequently determined, with the membrane at room temperature (21 °C).

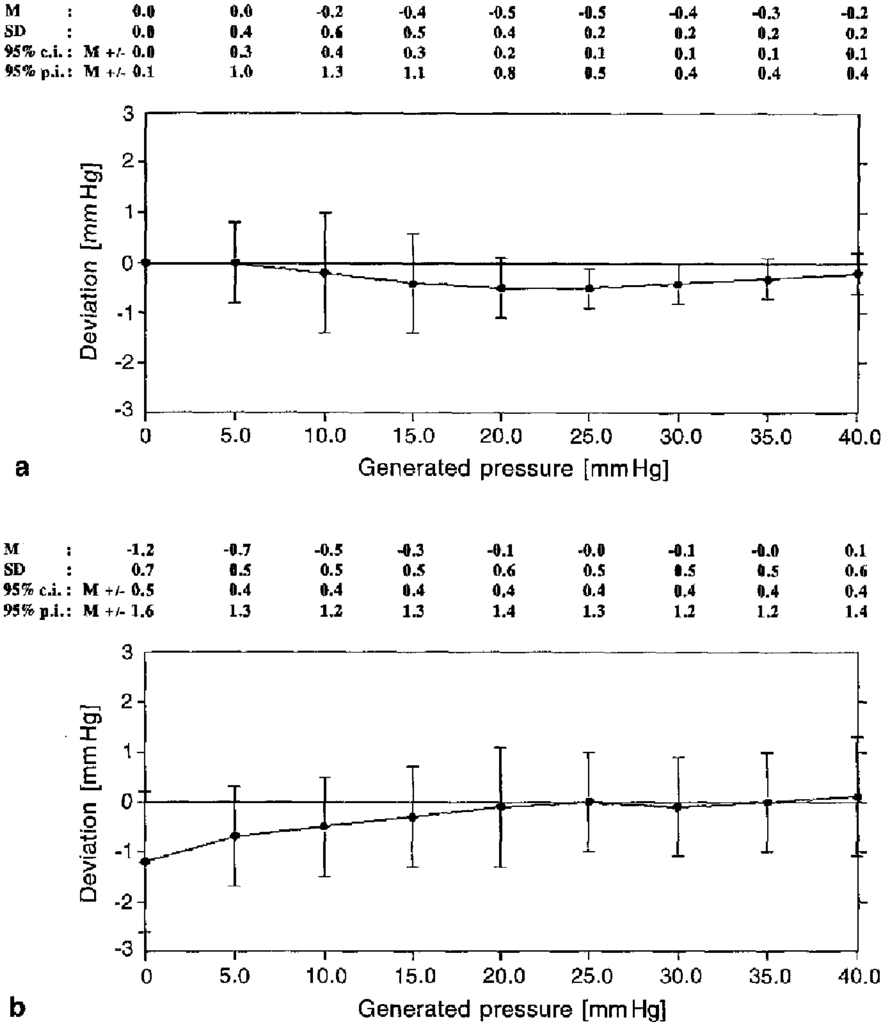


Fig. 3 Deviation between generated pressure and measured pressure. For each class of generated pressure $n=10$. Numerically presented: Mean (*M*), standard deviation (*SD*), 95% confidence interval (*c.i.*) for the mean, 95% prediction interval (*p.i.*) for new observations [15]. Graphically presented: mean +/−2 SD. **a** Calibration, **b** manipulation of the transducer and subsequent zero adjustment

In vivo measurements

The method of measuring the AFP must always guarantee that the results bear a close relation to the actual ICP. To validate the RTT, several long-term measurements of AFP and IVP were performed simultaneously, in order to verify the relationship between the pressure measured by the RTT and the actual IVP. The IVP is used as a standard reference for the ICP. For the IVP measurements, a ventricular drain was connected to an HP1290A probe and HP78205D pressure unit. During the measurement, the child was in a supine position. AFP and IVP were continuously recorded on a computer for several hours and correlated off-line.

Results

In vitro measurements

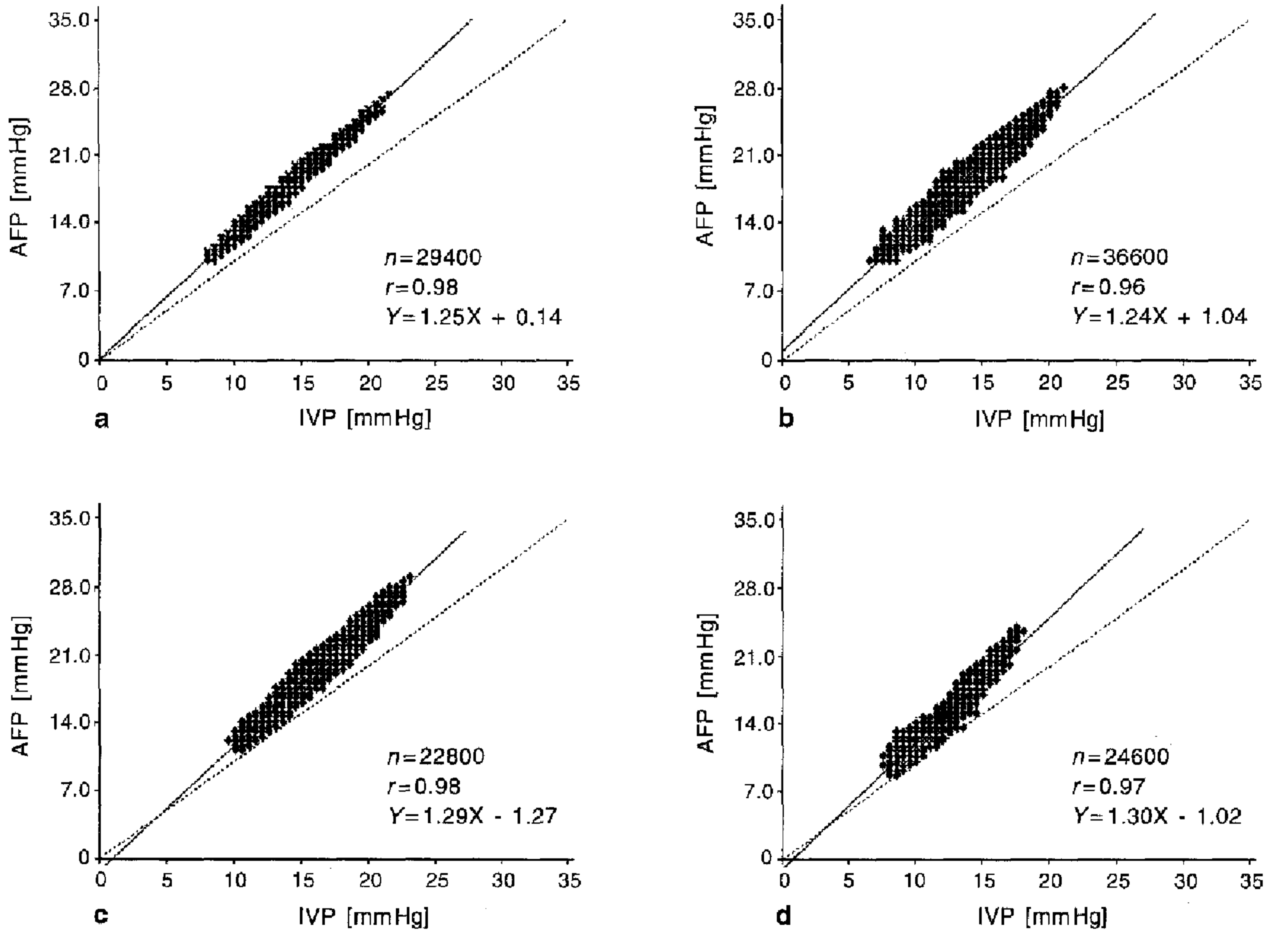
Laboratory conditions

Thermal stabilization time. The results show a rapid decrease in measurement output during the 1st h, and after 3 h there was no output drift. Thermal stabilization time is, therefore, considered to be 3 h. The difference between measured pressure at the start and 3 h later is at least 3 mmHg.

Calibration. The results of 90 calibration measurements (Fig. 3a) show an overall mean pressure difference of −0.3 mmHg. The largest mean pressure deviation occurs between 10 and 20 mmHg, with maximum deviation limits (mean ± 2 SD) ranging from −1.4 up to 1.0 mmHg.

Simulated clinical conditions

Membrane temperature. The results show that the difference in membrane temperature during measurement (37 °C), compared to the membrane temperature during calibration (21 °C), has no significant effect on the AFP measurement.



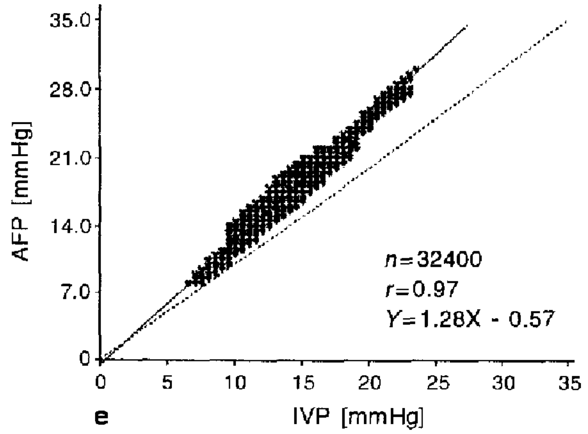


Fig. 4a–e Simultaneous AFP/IVP measurements. *N* Sample size, *r* correlation coefficient

Simulation of transducer manipulation in clinical practice. The results show that the manipulation of the piston and subsequent zero adjustment apparently has an effect on the accuracy of the measurement (Fig. 3b). Below 20 mmHg the deviation between measured pressure and generated pressure increases, as the generated pressure decreases. The deviation limits (mean ± 2 SD) range from −2.6 up to 1.3 mmHg.

In vivo measurements

The measurements show high correlations ($r = 0.96$–0.98) between the AFP measured with the RTT and the IVP (Fig. 4). AFP measurements exceed the IVP values. The difference between AFP and IVP values increases with increasing pressure. By means of linear curve-fitting the slope of each curve was calculated, and found to vary between 1.24 and 1.30.

Discussion

This study reassessed the physical qualities of the Rotterdam Teletransducer (RTT) in order to allow performance of reliable pressure measurements for clinical interpretation. The value of the AFP measurements for determining the ICP depends on the relation between these two variables. The main advantages of the RTT, as a fontanometer, are the special fixation frame of the transducer, which means that the pressure applied by the frame does not interfere with the measured pressure, and the ability to perform bedside calibration. Additionally, the fast dynamic response of the RTT allows for ICP pulse wave analysis.

When using the RTT in AFP measurement, proper depth setting of the piston is of primary importance. This is accomplished using the pressure depth curve (PD curve) [17]. If the depth setting procedure is performed accurately, AFP measurements are reproducible and the interobserver error is very small.

The physical qualities of the RTT were investigated in three different ways: (1) in vitro measurements under ideal laboratory conditions, (2) in vitro measurements under simulated clinical circumstances, and (3) several simultaneous in vivo AFP/IVP measurements.

Under ideal laboratory conditions, the warming-up period (thermal stabilization time) after switching on was determined, and found to be at least 3 h. Insufficient thermal stabilization can result in the measured pressure being underestimated by as much as 3 mmHg. After thermal stabilization, the system has to be calibrated. Calibration is investigated using a specially developed calibration device. After calibration, the results show a maximum prediction interval of +/−1.3 mmHg. Therefore, the maximum inaccuracy of pressure measurement is 1.5 mmHg. This is in accordance with previous estimates which state an inaccuracy of less than +/−2 mmHg [16]. Performing calibration on more than 2 points (0.0 and 40.0 mmHg) did not increase accuracy.

In clinical practice, the temperature of the fontanelle differs from that of the calibration membrane. The results of the experiments indicate that this temperature difference does not contribute significantly to the measurement error. However, after sufficient thermal stabilization, calibration and offset correction, manipulation of the piston, such as moving it from the calibration device to the fontanelle, appears to have a considerable effect on the accuracy of the measurement. The results show a maximum prediction interval of +/−1.6 mmHg. Therefore, manipulation of the piston after calibration increases the maximum inaccuracy of pressure measurement to 2.8 mmHg.

The clinical relevance of measurements with the RTT is determined by the relationship between AFP and ICP (or IVP). Simultaneous measurements show correlations between AFP and IVP varying from 0.96 to 0.98. In all these measurements, as pressure increases, AFP exceeds IVP values (offset of 3–4 mmHg). This phenomenon has been recognized in the literature [9, 18, 19]. Suggested explanations are: the effect of the combination of tissues overlying the fontanelle; stretching forces of the skin exerted on the transducer membrane; and the difference in pressure between the subarachnoid space and the brain itself [19].

From the experimental results of the present study, it can be concluded that if certain steps are not taken, a considerable measurement error can occur. Therefore, the following measurement protocol should be carried out to ensure maximum accuracy, assuming no ossification and a sufficient size (preferably no smaller than 2 x 2 cm) of the fontanelle. First of all, allow a stabilization period of at least 3 h. Then adjust the piston to the calibration device on the plateau of the PD curve, and subsequently perform a calibration on the calibration device. Finally, move the piston from the calibration device to the fontanelle and adjust offset (zero), just prior to the moment at which the piston touches the skin.

We conclude that the RTT has been proved to be an accurate and reliable device for determining the ICP by measuring the AFP, if extended operating procedures are observed. However, hardware improvements to reduce thermal stabilization time and improve the gain and offset adjustment procedures might increase its reliability even further.

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References

1. Bunegin L, Albin MS, Rauschhuber R, Marlin AE (1987) Intracranial pressure measurement from the anterior fontanelle utilizing a pneumoelectronic switch. Neurosurgery 20:726–730
2. Hayashi T, Kuramoto S, Honda E, Anegawa S (1987) A new instrument for non-invasive measurement of intracranial pressure through the anterior fontanel. I. Preliminary report. Child's Nerv Syst 3:151–155
3. Honda E (1984) Measurement of fontanelle pressure. I. A new instrument for noninvasive measurement of intracranial pressure via the anterior fontanelle. Kurume Med J 31:235–247

4. Horbar JD, Yeager S, Philip AGS, Lucey JF (1980) Effect of application force on non-invasive measurement of intracranial pressure. Pediatrics 66:455–457
5. Jong DA de, Berfelo MW, Lange SA de, Maas AIR (1979) Epidural pressure monitoring with the so-called Rotterdam Transducer. Further in vivo results. Acta Neurochir 45:301–309
6. Jong DA de, Maas AIR, Berfelo MW, Ouden AH den, Lange SA de (1982) The Rotterdam Teletransducer. A telemetric device for measuring epidural pressure. Biotelemetry Patient Monit 9:154–165
7. Jong DA de, Maas AIR, Voort E van de (1984) Non-invasive intracranial pressure monitoring. A technique for reproducible fontanelle pressure measurements. Z Kinderchir 39:274–276
8. Jong DA de, Maas AIR, Ouden AH den, Lange SA de (1984) Long-term intracranial pressure monitoring. Med Prog Technol 10:89–96
9. Jørgensen PB, Riishede J (1972) Comparative clinical studies of epidural and ventricular pressure. In: Brock M, Dietz H (eds) Intracranial pressure I. Springer, Berlin Heidelberg New York, pp 41–45
10. Lacey L, John E, McDevitt M, Cassady G, Philips J (1986) Effect of application force and gestational age on transfontanel pressure in healthy neonates. Biol Neonate 50:136–140
11. Leggate JRS, Minns RA (1991) Intracranial pressure monitoring – current methods. In: Minns RA (ed) Problems of intracranial pressure in childhood. McKeith, Oxford New York, pp 123–140
12. Maas AIR (1985) The Rotterdam Teletransducer: state of the device. Z Kinderchir 40 [Suppl I]:19–23
13. Maas AIR, Jong DA de (1986) The Rotterdam Teletransducer: state of the device. Acta Neurochir (Wien) 79:5–12
14. Mehta A, Wright BM, Shore C (1988) Clinical fontanometry in the newborn. Lancet: 754–756
15. Neter J, Wasserman W, Whitmore GA (1988) Applied statistics, 3rd edn. Allyn and Bacon, Boston London Sydney, pp 273–301
16. Overweg-Plandsoen WCG (1990) The Rotterdam Teletransducer. Anterior fontanelle pressure monitoring in infants. Thesis, Rotterdam, pp 28–37
17. Plandsoen WCG, Jong DA de, Maas AIR, Stroink H, Eijndhoven JHM van (1986) The pressure-depth curve in anterior fontanelle pressure monitoring. In: Miller JD, Teasdale GM, Rowan JO, Galbraith SL, Mendelow AD (eds) Intracranial pressure VI. Springer, Berlin Heidelberg New York, pp 193–196
18. Schettini A, McKay L, Majors R, Mahig J, Nevis A (1971) Experimental approach for monitoring surface brain pressure. J Neurosurg 34:38–47
19. Sundbärg G, Nornes H (1972) Simultaneous recording of the epidural and ventricular fluid pressure. In: Brock M, Dietz H (eds) Intracranial pressure I. Springer, Berlin Heidelberg New York, pp 46–50
20. Vidyasagar D, Raju TNK (1977) A simple non-invasive technique of measuring intracranial pressure in the newborn. Pediatrics 59:957–961
21. Wealthall SR, Smallwood R (1974) Methods of measuring intracranial pressure via the fontanelle without puncture. J Neurol Neurosurg Psychiatry 37:88–96
22. Whitelaw AGL, Wright BM (1982) A pneumatic applanimeter for intracranial pressure measurement. J Physiol 336:3–4