

10 INTRACRANIAL PRESSURE MONITORING

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10.1 Introduction

Intracranial pressure (ICP) measurement is an extremely important part of the neurosurgical armamentarium. Not only is raised ICP the commonest cause of death in neurosurgical patients, it is extremely common in patients suffering from head injury. In this latter group, 40% of patients who are admitted in an unconscious state have raised ICP, and in 50% of those who die, raised ICP is the main cause (Miller *et al.*, 1977). Numerous investigations have shown that sustained intracranial hypertension is associated with a poor prognosis (Becker *et al.*, 1977; Johnston and Jennett, 1973; Langfitt, 1969; Narayan *et al.*, 1982; Marshall, Smith and Shapiro, 1979a; Miller *et al.*, 1981). The effective treatment of high ICP has been shown to decrease mortality (Marshall, Smith and Shapiro, 1979a, b). Even so, ICP must be measured before a diagnosis of raised ICP can be made.

Obviously, an understanding of the principles of ICP measurement is an important prerequisite to considering the disturbances of brain function that follow head injury.

The quest for developing the ideal method of recording ICP has been a difficult exercise. The first requirement for any method is that it is accurate; and it should also be safe and simple (North and Reilly, 1990). The search is still incomplete, since all current methods are invasive. The necessity to breach the skull to record ICP has resulted in a significant number of neurosurgeons being reluctant to embrace this technique. It took at least 15 years before ICP monitoring became fully accepted into clinical neurosurgical practice in more than a few centers. Even now, opinions vary as to the value of the technique, from those who claim that it makes no difference to the outcome of any neurosurgical disease to those who assert that it is an indispensable part of neurosurgical practice, without which many patients would surely die. The truth lies somewhere between these two

extremes and it depends on the facilities and personnel available in any given neurosurgical unit (Miller, 1987).

10.2 Historical aspects

10.2.1 LUMBAR PUNCTURE

Lumbar puncture was introduced into clinical medicine in 1897 (Quincke, 1897) and following this, the spinal CSF pressure was used as an indirect measure of ICP. CSF pressure is defined as the pressure just necessary to prevent escape of fluid into a needle introduced into the lumbar subarachnoid space.

Sharpe published a monograph on head injury in 1920 and stated that his principal indication for the operation of subtemporal decompression was a spinal fluid pressure above 15 mmHg (Sharpe, 1920). Jackson also advocated the use of lumbar puncture and pressure measurement in head injury in 1922 (Jackson, 1922), but there was much disagreement on the place and dangers of lumbar puncture, and the reliability of the procedure in accurately measuring ICP. Most authors did agree that a pressure in excess of 200 mmH₂O was definitely abnormal.

The two principal objections to lumbar puncture in the diagnosis of intracranial hypertension have been the danger of inducing brain-stem compression through tentorial or tonsillar herniation and the contention that spinal fluid pressure is not always an accurate reflection of ICP. Langfitt's work was particularly important in demonstrating this lack of correlation between ICP and spinal CSF pressure under conditions of high ICP (Langfitt *et al.*, 1964).

10.2.2 VENTRICULAR PUNCTURE

Ventricular puncture for the relief of increased ICP is one of the oldest practices in neurosurgery. Pressure measurements during this procedure were often done

but prolonged pressure measurements were performed infrequently because water and mercury manometers were cumbersome and also because of the risk of intracranial infection.

10.2.3 INTRACRANIAL PRESSURE MONITORING

The development of strain gauges allowed ICP measurement to be performed directly using a ventricular catheter and an external transducer. The pioneering neurosurgeons in its development were Janny (Guillaume and Janny, 1951) and Lundberg (1960). Since then, the technique has been widely adopted, with some variations which will be discussed later.

10.3 Transducers

Transducers for measuring pressure are based on strain gauges, which were originally developed by engineers who needed to be able to measure the effects of tension and compression in beams. The applied force (per unit area) is called the stress and the resulting increase in length (per unit length) is called the strain. The operation of a wire strain gauge depends on the fact that if a length of wire is stretched, its electrical resistance will increase, and *vice versa*.

In a commonly used transducer such as the Statham P23 series, four strain-sensitive wires are connected to two frames, one of which fits inside the other. The wire frame is attached to the diaphragm of the transducer (upon which the pressure acts) and the outer frame is fixed (Figure 10.1). The set of wires form a Wheatstone bridge network (Figure 10.2), which is energized by a direct current (e.g. 10 V DC). A stable DC amplifier is used to detect the imbalance of the DC bridge, and this signal can then be used to drive a pen recorder or be displayed on an oscilloscope. It goes without saying that the staff in an intensive care unit must be familiar with calibrating and maintaining pen recorders.

10.4 Methods of measuring ICP

Intracranial pressure varies widely from minute to minute, particularly when it is raised, so that single observations can be misleading. Therefore it is important to examine a continual record of ICP, so that waves of raised ICP are not missed. Nevertheless, achieving this ideal poses problems – not least in storing large quantities of chart paper. Marmarou found that the ICP level recorded by the ICU nurses at the end of each hour ('end hour' recording)

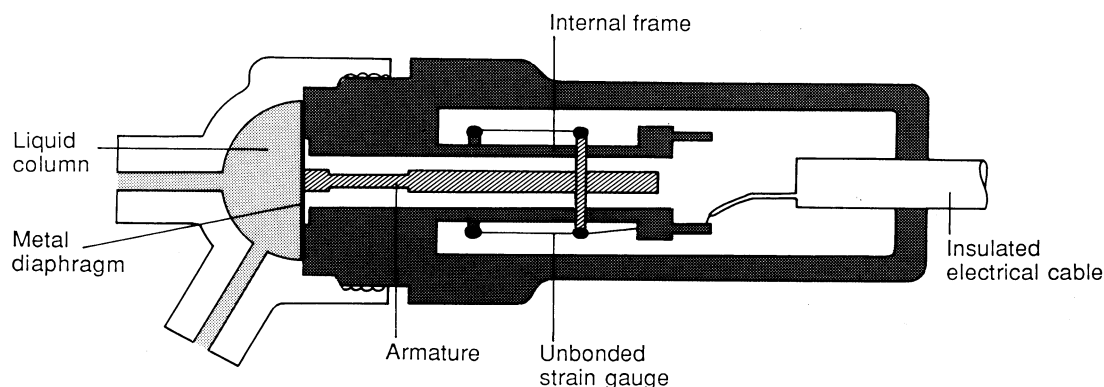


Figure 10.1 A Statham pressure transducer.

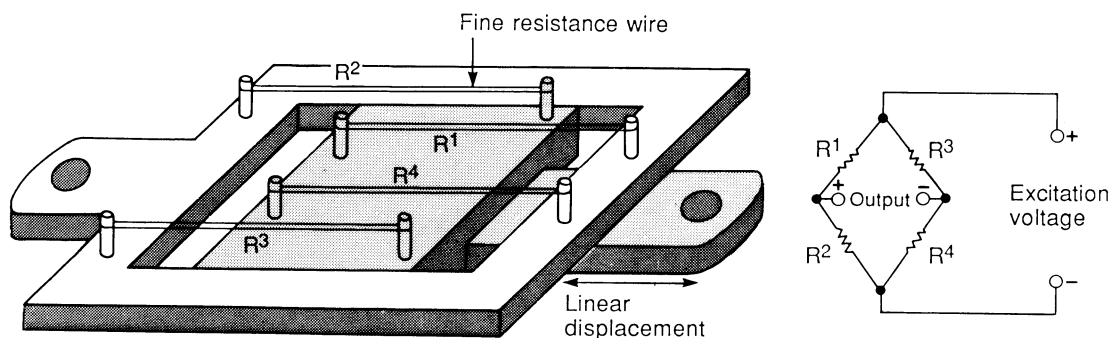


Figure 10.2 An unbonded strain gauge; four active elements.

of ICP was a good estimate of ICP for the entire hour, finding that 83% of the paired observations of computer- and nurse-recorded ICP values differed by less than 6 mmHg (Marmarou *et al.*, 1991). We use the 'end hour' recording for data entry in research projects and visual scanning of the chart output in routine cases.

10.4.1 INTRAVENTRICULAR PRESSURE RECORDING

The methodology for measuring ICP has evolved progressively, with many workers preferring a fluid coupled system using a ventricular catheter and an external transducer, considering it to be the 'gold standard' of ICP measurement (Miller, 1989). Ventricular ICP recording is the most reliable method in current use and it has the advantage of minimal expense and maximal accuracy, since the external transducer can be calibrated against an external reference at any time. The equipment required is commonplace in any intensive care unit.

The reference point for an external transducer should be the foramen of Monro, because it is close to the center of the head – 2 cm above the pterion is a rough guide to its surface marking. The midpoint of a line joining the two external auditory meati is another suitable reference point, although somewhat posterior to the interventricular foramen. Other workers use the external auditory meatus (Kosteljanetz, 1987). Whatever reference point is used, the level of an external transducer needs to be altered with each change in head position.

The ventricular method obviously requires placement of a catheter into a lateral ventricle, and this may be a technically difficult procedure because of a narrow or displaced ventricle. Injury of the basal ganglia can occur with ill directed or over enthusiastic attempts at ventricular cannulation. The infection rate in our hands is 3.6%, reaching a potentially serious level after three days (North and Reilly, 1986). Other quoted infection rates range from less than one per cent to more than 5% (Rosner and Becker, 1976; Sundbarg *et al.*, 1972). A big advantage of the ventricular method is that CSF can be withdrawn to lower ICP.

All joints in the recording system must be watertight. If they are not, 'micro-leaks' will invalidate the pressure recordings. Each portion of the system must be tested periodically by isolating the external system from the patient temporarily and subjecting it to a pressure head of about 50 mmHg. After being isolated, the external system should maintain its intraluminal pressure and if not, the connections must be tightened or the system discarded and replaced with a water tight system (Shields, McGraw and Garretson, 1984).

Sometimes, ventricular catheters block and this can

be overcome by flushing a small amount of sterile saline through the system. However, repeated flushing should be avoided because of the real risk of infection.

10.4.2 OTHER METHODS

The hollow skull bolt ('Richmond screw') has been widely used in many centers (Vries, Becker and Young, 1973; Figure 10.3). There have been many modifications to achieve a lower profile, CT compatibility, more side holes ('Leeds screw'), and a pediatric version (Coroneos *et al.*, 1973; James, Bruno and Schut, 1975; Landy and Villanueva, 1984; Mann and Yue, 1988). These devices are simple to insert but they have a tendency to block and so produce a damped, inaccurate trace. At high pressures, the subdural bolt tends to read lower than a ventricular catheter (Mendelow *et al.*, 1983; Miller, Bobo and Knapp, 1986). This question of accuracy presents a major problem and is the main reason why the hollow bolt method has declined in popularity (Miller, 1987). Subdural catheters can be useful where the ventricle cannot be cannulated, but they are also likely to underestimate the true ICP.

The extradural site for monitoring has been used and has the advantage avoiding penetration of the dura. However, there are technical problems associated with the inelasticity of the dura and the need for the transducer to lie flat (co-planar) on the dura. Unfortunately, irregularities of the dura and inner table of the skull are common. If co-planarity is not achieved, stresses and strains in the dura can distort the measurements and falsely record high pressure (Dorsch and Symon, 1975; Coroneos *et al.*, 1973). For these reasons concerning accuracy, the extradural method is now used very infrequently.

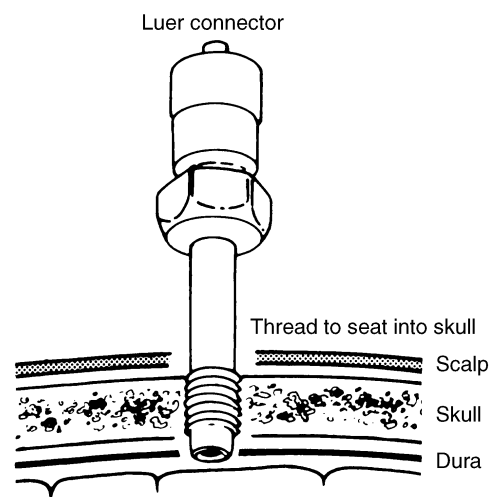


Figure 10.3 A subarachnoid screw.

10.4.3 CATHETER-TIP TRANSDUCER

We have used catheter-tip transducers for several years and this is currently our preferred method of recording ICP. Miniature implantable transducers have been developed from intravascular transducers, of which the Camino transducer is an example (Figure 10.4). Pressure is measured at the tip of a narrow fiberoptic catheter where there is a flexible diaphragm. Light is reflected off the diaphragm and these changes in light intensity are interpreted in terms of pressure. The outside diameter of the device is only 4 FG (1.3 mm). The system is not dependent on a fluid column, or on an external transducer where the height needs constant readjustment depending on the level of the patient's head. Ostrup *et al.* (1987) and Crutchfield *et al.* (1990) have reported excellent results but cost is still a problem. There is a close correlation between ICP measured by the Camino catheter-tip transducer and the intraventricular method (Gambardella, d'Avella and Tomasello, 1992). The Innerspace transducer is a similar type of a fiberoptic catheter-tip transducer, but the physical principle uses spectral frequency. Marmarou has reported both experimental (Yoshihara *et al.*, 1993) and clinical (Marmarou *et al.*, 1994) tests on this transducer.

The main limitation of a catheter-tip transducer is that it is not possible to calibrate it *in situ* and it should be replaced if monitoring is to be continued for longer than 5 days, because of possible drift. They are simple to insert and we place the tip in the brain at a depth of

1–2 cm. The fiberoptic cable can be damaged by restless patients or if it is bent acutely, and this fragility is a practical problem and is one that limits the usefulness of the method.

10.4.4 IMPLANTED MICROCHIP TRANSDUCER

Implanted microchip sensors have now been developed and an example is the Codman MicroSensor transducer. It consists of a miniature solid state pressure sensor (Figure 10.5) mounted in a very small titanium case (diameter 1.2 mm = 3.6 FG) at the tip of a 100 cm long flexible nylon tube (diameter 0.7 mm = 2.1 FG). The transducer tip contains a silicon microchip with diffused piezoresistive strain gauges which are connected by wires in the nylon tube to complete a Wheatstone bridge type circuit. When the transducer is energized and pressure is applied, the silicon diaphragm deflects a small amount (less than 0.001 mm^3 for 100 mmHg applied pressure), inducing strain in the embedded piezoresistors. This resistance change is reflected in the form of a differential voltage which is then converted into units of pressure, i.e. millimeters of mercury. The bottom layer of the silicon diaphragm is vented to the atmosphere along the nylon tube, while the top layer is exposed to the applied CSF or brain tissue pressure.

The microsensor transducer can be inserted directly into the brain parenchyma but is also fine enough to be passed through a catheter into the lateral ventricle. Narayan and his colleagues found that this device had

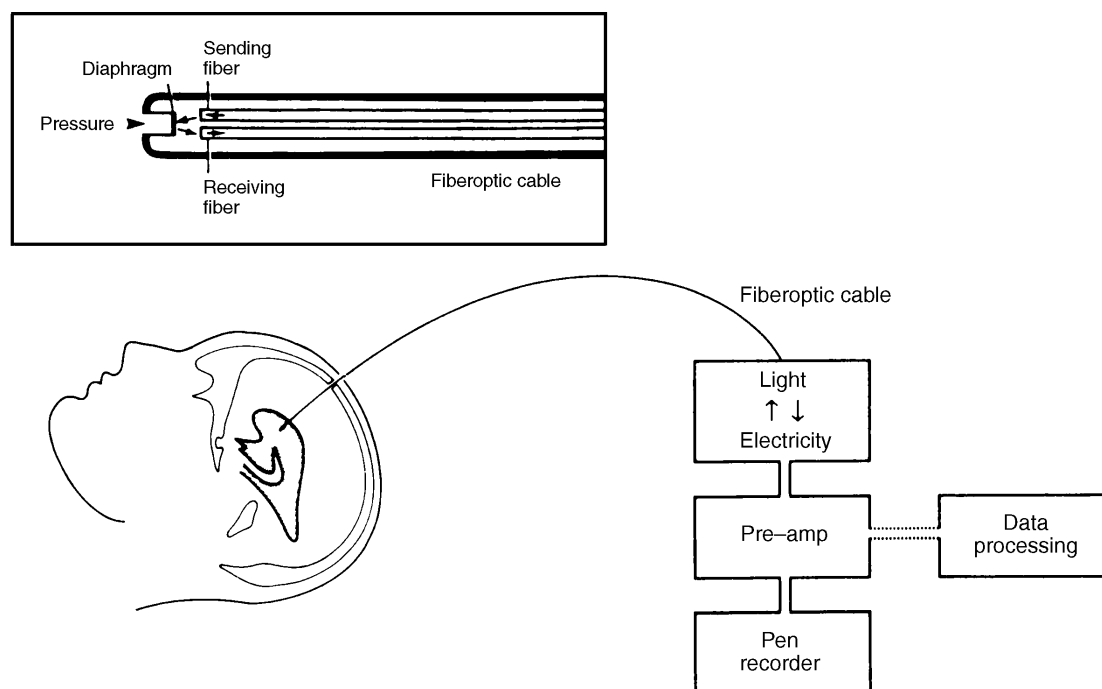


Figure 10.4 A catheter-tip transducer.

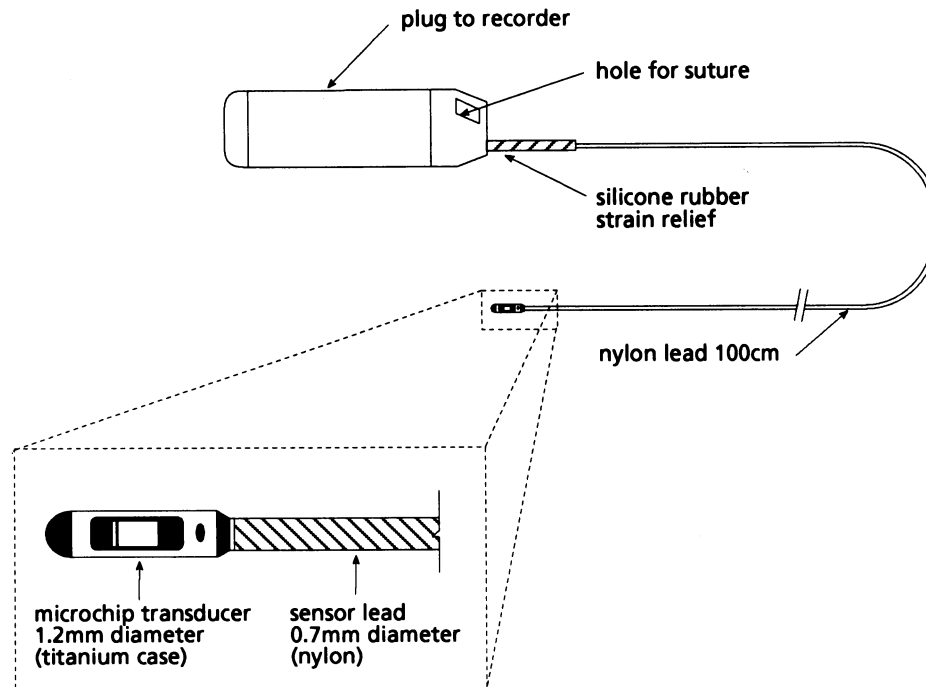


Figure 10.5 A microchip transducer.

an average drift of less than 1 mmHg over a 9-day period (Gopinath *et al.*, 1993, 1994). This group (Gopinath *et al.*, 1995) also tested the Codman transducer in 25 patients, comparing it against a ventricular catheter and an external transducer. Encouragingly low levels of baseline drift were found and it showed no tendency to under-read or over-read. Piper and Miller (1995) evaluated the wave-form analysis capability of this transducer against a fluid coupled transducer. They found that there were no significant differences between the two transducers. Actually the microchip transducer has a superior frequency response, although this may not be clinically important for wave form analysis.

A variation of a ventricular catheter with a pressure measuring transducer located at the tip of the catheter is the Ventcontrol MTC (Piek and Raes, 1996). This technology represents the direction in which ICP monitoring will evolve.

10.5 Which system?

It is not easy to decide which system of ICP measurement is the best, because of the large number of variables, including cost. If access to the ventricle is required, then a ventricular catheter and external transducer is both cost-effective and reliable; it is the 'gold standard'. However, most patients now being monitored for ICP are likely to be suffering from head injury and they will usually have narrow ventricles, making cannulation potentially difficult for a young

neurosurgeon. In the head-injury situation, the preferred method is either a fiberoptic catheter-tip transducer (e.g. Camino or InnerSpace) or an implantable transducer (e.g. Codman) inserted into brain parenchyma, and this can be done at the bedside very simply. The choice between these two types of transducer largely comes down to a question of cost, which varies from country to country and is an individual decision. The Camino and InnerSpace transducers require a more expensive control monitor (\approx US\$5000) whereas the Codman control unit is less expensive (\approx US\$500). At the present time, the disposable transducer kit costs about the same for each of these three products.

Pickard and his colleagues have examined the Camino, Codman and InnerSpace transducers in a pressure-flow test rig designed for the assessment of hydrocephalus shunts (Czosnyka, Czosnyka and Pickard, 1996). They measured long-term and temperature zero drifts, frequency response characteristics, the accuracy of measurement of static and pulsatile pressures and the slew rate. All three transducers scored satisfactorily during bench testing, and performed according to the manufacturer's specifications, giving high quality readings in testing conditions. The Codman transducer scored best overall. Pickard's ranking is shown in Table 10.1.

I believe that the time has come to recommend that implantable and catheter-tip transducers should replace fluid coupled systems. The main disadvantage of catheter-tip transducers is that they cannot be

Table 10.1 Results of testing ICP measurement transducers (1 = better; 2 = average or as good as another having the same score; 3 = worse; –these values were measured relative to the Camino transducer)

| | Camino | Codman | InnerSpace |
|---|--------|--------|------------|
| 24-hour zero drift at 0 mmHg | 2 | 2 | 1 |
| 24-hour zero drift at 20 mmHg | 2 | 2 | 2 |
| Temperature drift (27–40°C) | 3 | 2 | 1 |
| Accuracy in static measurement | 1 | 2 | 3 |
| Accuracy in measurement of pulse pressure | – | 2 | 3 |
| Bandwidth | – | 2 | 3 |
| Slew rate | 2 | 2 | 3 |

calibrated *in vivo*, but this deficiency appears to be of little practical importance.

10.6 Interpretation of ICP monitoring

It is conventional to calibrate ICP monitoring apparatus in units of mmHg to permit a direct comparison of ICP with blood pressure and to enable the difference between the two pressures (CPP) to be calculated.

ICP records offer two main kinds of information, the baseline level and variations of the pressure, i.e. waves. In other words, raised ICP may be steady or periodic.

10.6.1 BASELINE PRESSURE

Normal ICP is pulsatile due to intracranial arterial pulsations reflecting the cardiac and respiratory cycles. Based on largely intuitive considerations, the normal level of mean ICP is 0–10 mmHg and it is abnormal over 15 mmHg. Lundberg suggested that mean levels above 20 mmHg are moderately elevated and that sustained levels above 40 mmHg are severely increased (Lundberg, 1960). In head injury, it is more common to observe a rise in baseline pressure, rather than waves of raised ICP. If the bone flap has been removed surgically, pressure readings can be unreliable.

10.6.2 PRESSURE WAVES

Lundberg identified three different types of ICP variations, 'A', 'B' and 'C' waves (Lundberg, 1960). Plateau waves ('A' waves) are clinically very important because they indicate dangerously reduced intracranial compliance. They rise steeply from near normal or slightly raised ICP to 50 mmHg or more and persist for 5–20 minutes before falling precipitously, even to below the original level. Although named for their rather flat tops, there may be irregularities and peaks.

The most frequent type of pressure wave, although of less adverse clinical significance than the plateau wave, is the 'B' wave. These are rhythmic oscillations, sharply peaked and occurring once every 1–2 minutes, in which mean ICP rises in a crescendo manner

from a variable baseline to a level 20–30 mmHg higher, and then falls abruptly with no intervening period of sustained intracranial hypertension. 'C' waves seem to be of little clinical significance.

10.6.3 PULSE AMPLITUDE

As ICP increases above the resting level, the amplitude of the cardiac pulse component increases while the relative magnitude of the respiratory component may decrease. Thus ICP pulse amplitude increases linearly with increases in ICP, an observation made by Cushing over 90 years ago (Cushing, 1902). Pulse pressure may also increase before mean ICP rises. This has clinical importance as it may allow prediction of deterioration before ICP rises. In other words, a widening pulse amplitude in the absence of an increased ICP indicates an impairment of intracranial compliance or reserve.

10.6.4 INTRACRANIAL PRESSURE WAVE FORM

The ICP wave has a pulsatile quality at two different frequencies – one synchronous with the arterial pulse while the other is slower, in time with breathing (Figure 10.6).

The vascular waves are caused by arterial pulsations in the large vessels within the brain, producing an oscillation in the volume of the ventricular system (Bering, 1955). The shape of the CSF pressure wave is similar to that of systemic blood pressure and it has three fairly consistent components, the 'percussion wave' (P_1), 'tidal wave' (P_2) and 'dicrotic wave' (P_3 ; Figure 10.7). The dicrotic notch between P_2 and P_3 corresponds to the dicrotic notch of the arterial pulsation. The respiratory wave is synchronous with alterations in central venous pressure, reflecting intrathoracic pressure. They are seen prominently in patients on ventilators. Normally, the amplitude of the cardiac pulse is about 1.1 mmHg, and the combined cardiac and respiratory variation is approximately 3.3 mmHg (Bradley, 1970).

Analyzing cerebrovascular pressure transmission by applying Fourier analysis to both the arterial and

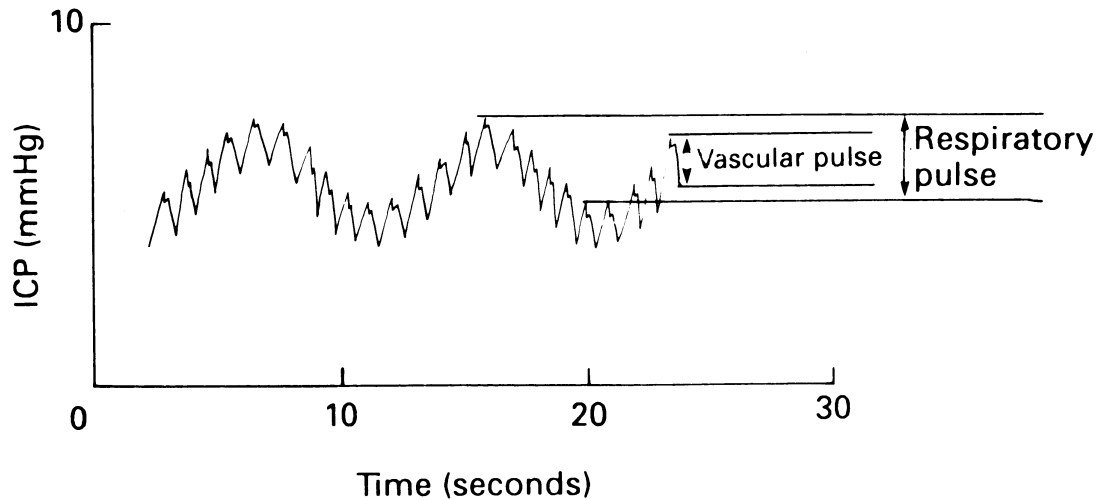


Figure 10.6 ICP waveform.

intracranial pressure waveforms has been examined as a method of assessing cerebrovascular pathophysiology (Chopp and Portnoy, 1980). Experimental studies have determined changes in the low-frequency component of the cerebrovascular pressure transmission spectrum to be associated with vascular mechanisms underlying raised intracranial pressure while non-vascular mechanisms are associated with increased transmission of both low and high frequency components (Portnoy and Chopp, 1981; Takizawa, Gabra-Sanders and Miller, 1986; Kasuga, Nagai and Hasegawa, 1989). Clinical studies have also demonstrated specific patterns of cerebrovascular pressure transmission occurring in patients with severe head injury (Bray *et al.*, 1986; Piper *et al.*, 1990). Although initial studies of the high frequency band (4–15 Hz) demonstrated a correlation with mortality (Robertson *et al.*, 1989), recent work has shown this frequency spectrum to be affected significantly by heart rate (Contant *et al.*, 1993). Analysis of low-frequency pressure transmission may provide a clinically useful indicator of the presence or absence of autoregulation, based on experimental work examining phase shift characteristics between the fundamental of the BP to ICP waveform (Piper *et al.*,

1993). It may also provide a means of identifying optimal CPP thresholds by identifying autoregulatory breakpoints (Takizawa, Gabra-Sanders and Miller, 1987). Although this work is promising further development is required before cerebrovascular pressure transmission analysis becomes a clinically useful analytical tool.

10.7 Conclusion

ICP monitoring has developed into a very useful tool, particularly in patients suffering from head injury. If a decision is made to monitor ICP, then certain standards must be achieved so that reliance can be placed on the data which are obtained. We have much confidence in both the catheter-tip transducer and the implanted microchip transducer, with the output being directed to a slow-moving chart recorder so that the paper trace of ICP is available to all members of the team caring for the patient. Other physiological variables such as arterial BP are also recorded whenever possible. We regard the catheter-tip and implanted microchip transducers as having replaced the ventricular catheter and external transducer as the 'gold standard' in ICP measurement.

ICP monitoring provides the only sure way of confirming or excluding intracranial hypertension. If this is present, ICP monitoring provides the only reliable method of assessing whether therapy works and provides an early opportunity of switching to an alternative therapy should treatment fail. If increased ICP is not present, potentially dangerous treatment can be avoided. If the patient is paralyzed or heavily sedated, conventional neurological observation is useless and ICP monitoring provides a means of determining the patient's cerebral perfusion pressure (CPP) and an index of cerebral function (Sullivan *et al.*, 1977).

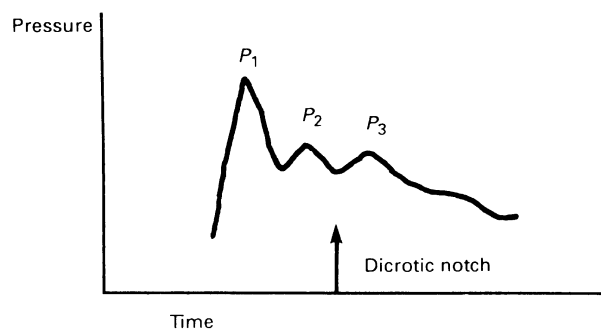


Figure 10.7 CSF pressure wave.

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