Dynamic measurement of the flow rate in cerebrospinal fluid shunts in hydrocephalic patients

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Abstract. We compared clinical outcomes in hydrocephalic patients and observed variation in the rate of flow in ventriculoperitoneal shunts with changes in posture in 231 separate examinations of shunt flow in 148 patients. A small cadmium telluride detector was placed over the shunt reservoir, and clearance of radioisotope injected into the reservoir was recorded as a measure of flow. Flow rate tended to increase during head elevation. Four patterns of radioisotope clearance were seen: type I, no flow; type II, adequate flow with moderate opening pressure; type III, adequate flow with low opening pressure; and type IV, excessive flow. This categorisation reflected clinical shunt function. Our method effectively assesses flow rate with the patient in a variety of postures or during movement, yielding useful information for adjustment of shunt valve pressure.

Keywords: Hydrocephalus – Ventriculoperitoneal shunt – Programmable valve – radioisotope – Flow rate

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Introduction

Ventriculoperitoneal (VP) shunt placement, a well-established, frequently performed neurosurgical procedure, is the most effective treatment for hydrocephalus. The shunt system includes a valve that controls the flow rate of cerebrospinal fluid (CSF). Despite the effectiveness of these shunts, complications have been reported, including excessive drainage on the one hand and shunt obstruction or stenosis on the other. In treating hydrocephalus, the goal is to establish and maintain a favourable flow rate of CSF through the shunt system. However, what constitutes appropriate shunt flow can differ from moment to moment during a patient's daily activities. Information is therefore needed concerning flow rate fluctuations that reflect changes in the patient's posture.

Many investigators have described methods to determine the patency of a shunt system in vivo as an indication of its clinical efficacy. However, most of these methods have involved static measurements with the patient lying immobile on a table. In 1987, Matsumae et al. [1] described a newly designed method that can determine dynamic flow rate during changes in posture using a small cadmium telluride detector with a radioisotope tracer. We assessed this method by measuring flow in nearly 150 implanted VP shunts in hydrocephalic patients and recording variation in flow rate with changes in posture.

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Materials and methods

Subjects were 148 consecutive hydrocephalic patients who had undergone VP shunt implantation at our hospital. Patients ranged in age from 13 to 81 years (mean, 52). Table 1 shows the aetiology

Table 1. Aetiology of hydrocephalus

Underlying disease	No. of patients
Subarachnoid haemorrhage	87
Tumour	19
Trauma	14
Idiopathic	7
Intracerebral haemorrhage	7
Meningo-encephalitis	5
Cerebellar haemorrhage	3
Idiopathic aqueduct stenosis	1
Others	5
Total	148

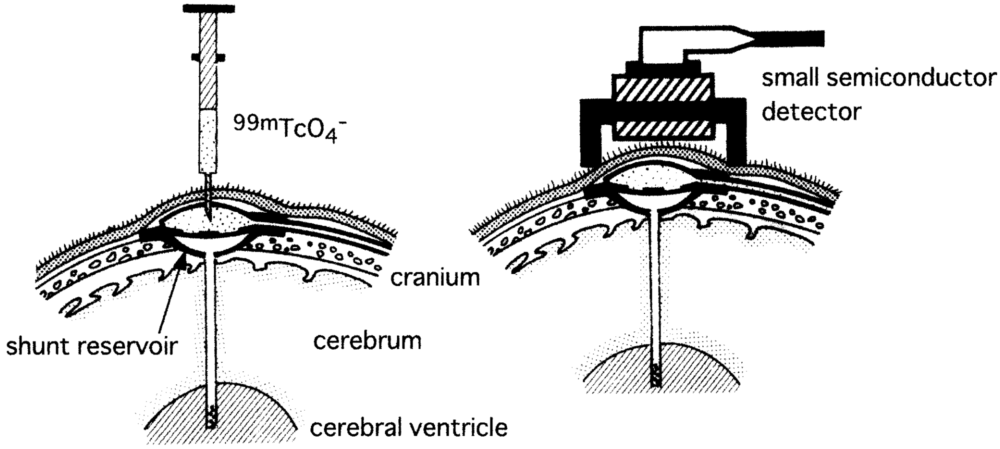

Fig. 1. The radioisotope $^{99m}TcO^{4-}$ (3.7 MBq in 0.01 ml) is injected into the reservoir of the shunt system percutaneously using a 27-gauge needle. A cadmium telluride detector 2 cm in diameter is mounted over the reservoir

Table 2. Number of examinations for each valve type

Valve type	No. of examinations
Pudenz, low pressure	81
Pudenz, medium pressure	55
Pudenz, high pressure	5
Sophy valve	90
Total	231

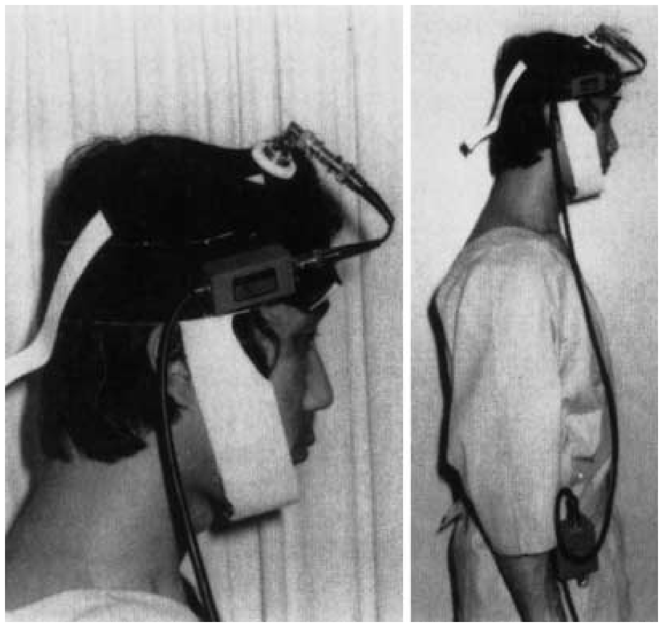

Fig. 2. A small cadmium telluride detector is held in place over the reservoir using a headband. The patient can move freely

of hydrocephalus in each case. Implanted shunts included a low-pressure Pudenz valve (Baxter, Deerfield, USA) in 40 patients, a medium-pressure Pudenz valve (Baxter) in 59 patients, a high-pressure Pudenz valve (Baxter) in three patients and an SU8 Sophy programmable pressure valve (Sophysa, Orsay cedex, France) in 46 patients.

Pudenz valves are standard valves with a single preset pressure indicated as high, medium or low. The desired pressure and corresponding valve must be chosen preoperatively. Sophy valves represent a single model that accommodates variable pressure settings, obviating a surgical procedure when adjustment of pressure is needed. Precise pressure adjustments can be made postoperatively by placing a special magnet over the skin. A detailed description of Sophy valves is given in another report [2].

We carried out 231 separate examinations of shunt flow (Table 2). In patients with an implanted Sophy valve, flow was examined at low, medium and high pressure settings to the extent patients gave prior informed consent. Of the 46 patients with a Sophy valve, 17 consented to undergo examination at all three pressure settings.

Flow examinations were carried out 1–2 weeks after the shunt implantation procedure. Details of the examination method and system used have been described in a previous paper [1]. Briefly, $^{99m}TcO_4^-$ (3.7 MBq in 0.01 ml) was injected percutaneously into the reservoir of the shunt system with a 27-gauge needle. For accurate placement of radioisotope in the centre of the reservoir, we punctured the skin and reservoir at right angles. Immediately after injection, a cadmium telluride detector 2 cm in diameter was positioned over the reservoir and held in place by a headband (Figs. 1, 2) [1]. Data were acquired at 1-s intervals and a clearance curve was generated. Clearance was indicated by a downward curve that reflected CSF flow through the reservoir. Next, the rate of shunt flow was computed with this clearance curve. The relationship between flow rate (F, ml/min) and half-time ($T_{1/2}$) is expressed on the basis of phantom experiments [1] as: $\log F=3.66–(1.01 \log T_{1/2})$.

Radioisotope present in the peritoneal shunt tube and radioisotope diffusion within the abdominal cavity were imaged using a gamma camera equipped with a low-energy parallel-hole collimator.

With the patient initially supine on the examination table, the head and torso were gradually elevated from a recumbent to a seated position at 1.5-min intervals, and clearance of radioisotope in the reservoir was recorded continuously during changes in posture. If radioisotope cleared with a high flow rate from the reservoir during the course of elevation, measurement at a higher elevation continued with one more injection. In this manner, the pattern of radioisotope clearance was determined in a variety of postures. Finally, the pattern of clearance was assessed relative to clinical outcome.

Table 3. Cerebrospinal fluid flow rates in implanted shunt systems (mean ± standard deviation, ml/min)

Shunt system	Patient head elevation					
	0°	15°	25°	35°	45°	90°
Pudenz, low pressure	0.12±0.18	0.24±0.35	0.41±0.49	0.44±0.50	0.40±0.29	0.68±0.69
Pudenz, medium pressure	0.13±0.21	0.22±0.39	0.33±0.54	0.42±0.40	0.63±0.57	1.2±0.65
Pudenz, high pressure	0.020±0.030	0.020±0.040	0.040±0.050	0.11±0.10	0.37±0.39	
Sophy, low pressure	0.12±0.27*	0.19±0.31*	0.32±0.54*	0.39±0.41	0.43±0.55*	0.70±0.51
Sophy, medium pressure	0.060±0.18	0.16±0.28	0.25±0.38	0.23±0.29	0.39±0.32	0.61±0.58
Sophy, high pressure	0.026±0.060*	0.058±0.14*	0.11±0.25*	0.22±0.36	0.20±0.27*	0.28±0.39

n=231 cases; age, 13–81 years (mean, 52)
*P<0.05 between Sophy valve set at low pressure and Sophy valve set at high pressure

Results

Shunt flow rates are shown for each type of valve in Table 3. Rates tended to increase with head elevation, and lower rates were associated with higher pressure valves. However, large standard deviations indicated a wide variability in rates among patients. A comparison of the different valves and settings demonstrated a significant difference only between low-pressure and high-pressure Sophy valves.

Clearance curves during head and torso elevation were classified into four patterns (Fig. 3). Pattern I was defined as complete absence of shunt flow; pattern II, by gradual onset of CSF flow during late stages of head elevation; pattern III, by gradual onset of CSF flow during early stages of head elevation; and pattern IV, by rapid onset of CSF flow in response to head elevation. Patterns II and III reflect favourable CSF flow. As the absolute value for flow rate cannot be used to adequately evaluate shunt function, we evaluated flow using these four clearance curve patterns. Table 4 indicates the number of cases showing each pattern.

Eight of 15 cases showing pattern I, including five with a Pudenz valve and three with a Sophy valve, did not improve clinically. Neither clearance of radioisotope nor diffusion within the abdominal cavity was observed. Complete blockage of the peritoneal tube was diagnosed in these cases (Fig. 4B), and the shunts were reconstructed. The remaining seven cases showing pattern I had the Sophy valve and were examined at a high pressure setting. We concluded that the pressure required to open the implanted system was too high; as a result, the pressure setting was reduced from high to medium or from high to low. These seven patients improved clinically after the adjustment.

Pattern III cases showed an increase in the flow rate with head elevation and favourable radioisotope clearance. Pattern II was characterised by a slightly higher opening pressure than pattern III. No differences in clinical improvement were observed between pattern II and pattern III cases.

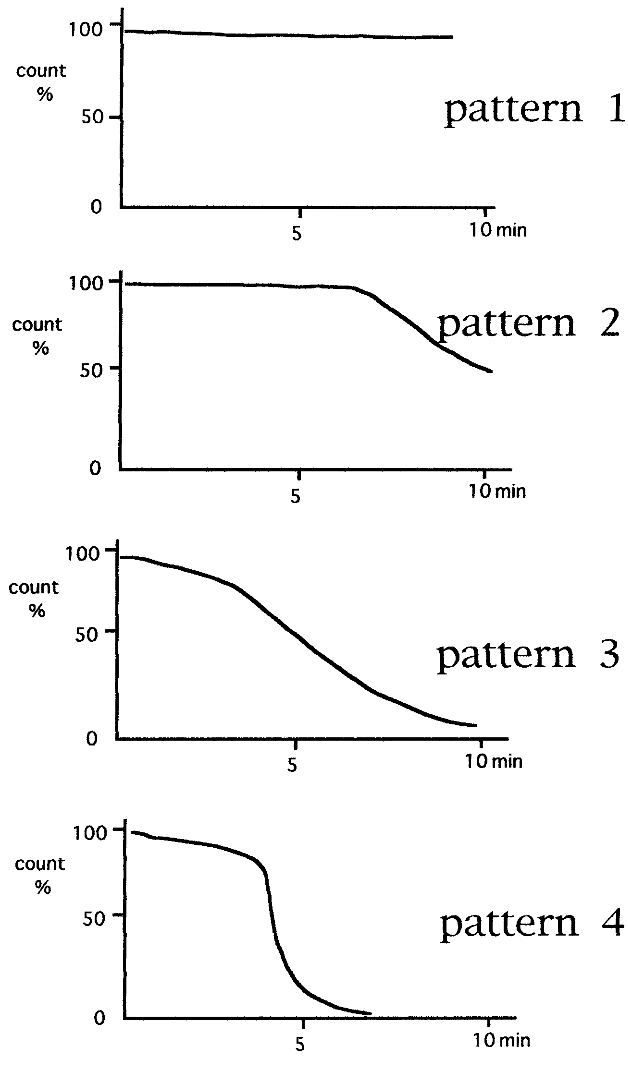

Fig. 3. Patterns of radioisotope decrement in the reservoir as the patient's head is elevated

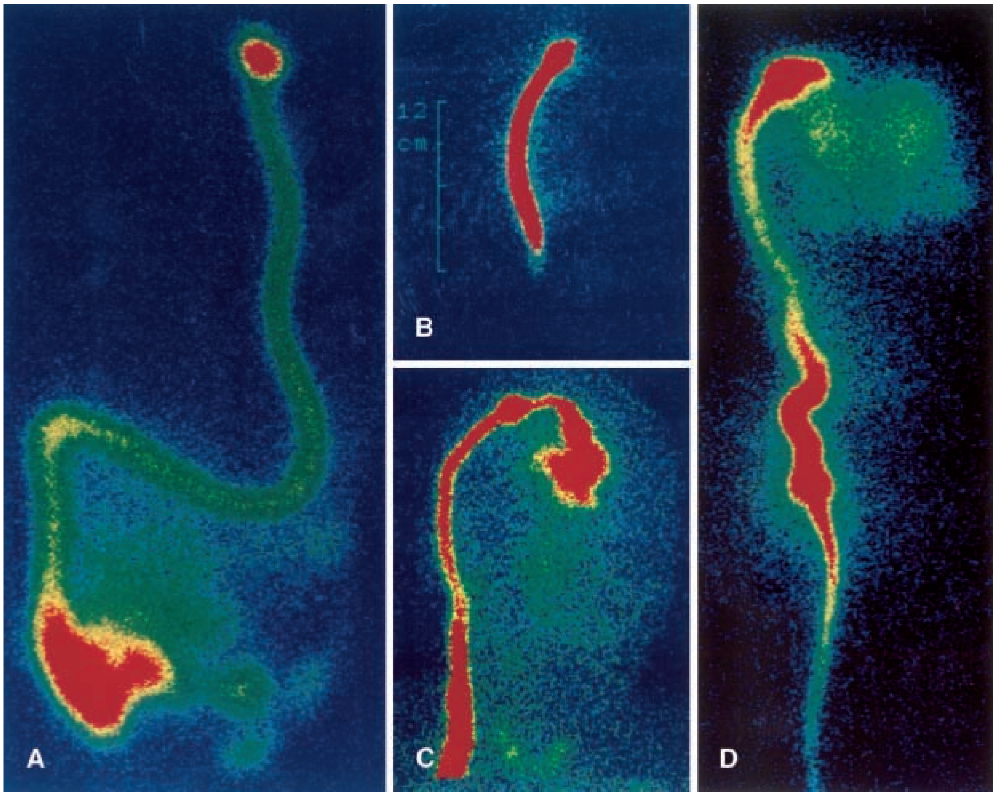

Fig. 4A–D. Images of radioisotope diffusion generated by a gamma camera. **A** Good diffusion into abdominal cavity. **B** Blockage of flow in shunt tube. **C** Reflux into cerebral ventricle. **D** Leakage into the subcutaneous peritubular sheath

Table 4. Number of cases by clearance pattern

Clearance pattern	No. of cases
Pattern I	15
Pattern II	78
Pattern III	106
Pattern IV	32
Total	231

Table 5. Causes of unfavourable outcome in cases with proper shunt function

Cause of unfavourable outcome	No. of cases
Abnormal low density on imaging	29
Increase in tumour size	3
Progression of parkinsonism	3
Sequela of encephalitis	3
Depression	1
Diffuse brain injury	1
Vascular dementia	4
Total	44

In two of the subjects showing pattern III, false clearance was observed because of either reflux into the lateral ventricle (Fig. 4C) or leakage into the subcutaneous peritubular sheath (Fig. 4D). We diagnosed blockage due to obstruction and a tear in the peritoneal tube, and the shunts were reconstructed. The gamma camera images were useful in detecting abnormal radioisotope location in these cases.

Of 32 patients showing pattern IV, six had the low intracranial pressure syndrome, manifest as headaches when patients were in an upright position. Four of these six patients had a Sophy valve, and all four improved after the pressure of the valve was increased. Two of the six patients had a low-pressure Pudenz valve, and both underwent surgery for valve replacement with a Sophy valve. In all six patients, a high shunt flow rate was noted. None of the remaining 26 pattern IV cases showed signs of low intracranial pressure syndrome.

Of 106 patients showing pattern III, four developed subdural hygroma or haematoma following shunt placement, as did four of 32 patients showing pattern IV. All eight patients had a Pudenz valve. One of four patients showing pattern IV developed bilaterally enlarging subdural haematomas and underwent re-operation to exchange the valve for a Sophy valve, which was set for high pressure. Another patient showing pattern IV had a low-pressure Pudenz valve and developed a large unilateral subdural hygroma; this patient subsequently underwent re-operation to substitute a high-pressure Pudenz valve. A high shunt flow rate was recognised in these two cases. The remaining six patients were followed up conservatively because the hygroma was smaller and not enlarging.

Forty-four patients showing pattern II, III or IV had an unfavourable outcome after the shunt placement procedure despite demonstrating appropriate diffusion of radioisotope within the abdominal cavity. These patients were retrospectively diagnosed as having irreversible lesions, such as severe parenchymal damage due to extensive subarachnoid haemorrhage, severe head injury, malignant brain tumour, deterioration of parkinsonism or progressive vascular dementia (Table 5).

Discussion

Many methods have been used to assess patency of shunt systems. Methods have also been described for measuring rate of flow in a CSF shunt system as an absolute value. The first such method was described in 1973 by Rudd et al. [3], who injected a small amount of $^{99m}TcO_4^-$ into the shunt reservoir and calculated half-life according to clearance of tracer. Harbert et al. calculated flow rate using a clearance formula [4]. Similar methods have been described for use in nuclear medicine [5, 6, 7, 8, 9, 10].

Rudd et al. [3], Chervu et al. [5] and Ohya et al. [6] reported isolated shunt flow measurement in patients in an immobile posture. Several other studies have reported flow rates or intracranial pressure as a combination of two values, with subjects in a supine position and either sitting or standing [4, 7, 8, 9, 10, 11, 12, 13, 14, 15]. Thus, flat clearance curves observed in some patients while in a supine position did not always indicate a shunt obstruction, given that flow resumed once the patient stood or sat, or when the examiner applied pressure to the reservoir.

Ikeda et al. [8] defined four distinct types of outcome: no flow, low flow, excessive flow and normal flow. Patients showing one of the first three outcomes often required surgical replacement of the shunt system.

While the above investigators quantitatively assessed outcome as rate of flow, Kadoya et al. [9] qualitatively classified clearance curve patterns with subjects in an immobile posture (either supine or seated). However, the patterns were not assessed in relation to clinical outcome.

In nuclear medicine practice, a large scintillation detector is commonly positioned over the shunt reservoir. This positioning permits only measurements in an immobile posture such as supine, sitting while resting on the elbows, sitting upright or a fully upright position. Thus, continuous measurements during changes in posture have been unobtainable.

We reported the present method in detail in a previous article [1]. Our method is similar to past techniques in terms of use of a radioisotope, but it is unique in using a small semiconductor detector placed directly on the patient's head (Fig. 2). The patient is thus allowed to move freely, and variations in flow rate with changes in posture are recorded continuously. Even abrupt pattern IV clearance in response to head elevation is graphically shown without lag. This method is simple, and measurements require 10 min or less to complete.

We measured flow rate in four different shunt valves (low-, medium- and high-pressure Pudenz valves and the Sophy valve). All four types of valve showed increases in the flow rate with head elevation because of a change in the pressure difference between the cranial cavity and the abdominal cavity. However, observed standard deviations were large, with wide variability in rates between patients. Accordingly, measurements with subjects in an immobile position do not fully reflect shunt function. For this reason, we evaluated shunt function not only according to the absolute flow rate in each position, but also according to the clearance curve pattern recorded as the head and torso were elevated.

In cases where a Sophy valve had been set at a high pressure and showed a pattern I response, reducing the pressure setting resulted in a pattern II or III response. In patients with low intracranial pressure syndrome who showed a pattern IV response, increasing the pressure setting of the Sophy valve allowed for a pattern II or III response, and improvement of symptoms. Combining a programmable pressure valve with shunt flow examination allows the pressure to be reset at any time while identifying the best pressure according to clearance pattern.

Improvement of hydrocephalic symptoms and reduction in ventricular size on computed tomographic images were achieved in all cases in which no brain parenchymal lesion was present. No difference in clinical outcome was observed between patients showing patterns II and III. The difference between patterns II and III is the opening pressure, which differs between individuals according to the hydrostatic pressure in the shunt tube as determined by intracranial pressure, patient height, abdominal cavity pressure and degree of outlet resistance from contact between the abdominal tube and the intestinal serosa.

A false-positive response can occur with our flow measurement method. A clearance curve is obtained even when reflux flow to the lateral ventricle or leakage to the subcutaneous space around the shunt tube is present, because the shunt flow rate is calculated by determining the degree of radioisotope decrease in the reservoir. Although absolute values were small in two cases, indicating a false-positive response, no difference in clearance pattern was observed between these cases and normally responding cases. A gamma camera image is necessary to confirm radioisotope dispersion into the abdominal cavity, without subcutaneous or intraventricular pooling of radioisotope (Fig. 4). This confirmation provides information similar to that obtained from conventional shunt radiography with contrast media.

Patients with low intracranial pressure syndrome and marked subdural fluid collection following shunt placement showed pattern IV, and were diagnosed as having excessive shunt drainage. Four patients with a Sophy valve required an increase in pressure setting, while four with a Pudenz valve underwent re-operation to exchange the valve for one with a higher pressure setting.

In 44 cases, disturbances of consciousness and dementia did not improve with shunting, despite proper shunt function. Such outcome variables, then, were not accurate indicators of shunt function. Brain lesion representing the primary disease can limit the effectiveness of a VP shunt in alleviating hydrocephalus, relatively contraindicating shunt implantation in retrospect. However, an intracranial lesion does not necessarily predict ineffectiveness of shunting.

In conclusion, our method can evaluate the function of a shunt system by identifying four distinct patterns of shunt flow. Pattern I, an elevated opening pressure or a shunt blockage detectable by a gamma camera, requires resetting of the pressure activating the valve, or a surgical valve substitution. Cases showing pattern II or III, and all pattern IV cases aside from those showing excessive drainage, represent effective function, provided that examination with the gamma camera rules out leakage and reflux. Hydrocephalic symptoms in these cases improved. Patients with excessive drainage following shunt implantation, manifest as either low intracranial pressure syndrome or subdural fluid collection, typically show pattern IV. Visual confirmation of rapid flow was possible in these cases by inspection of the clearance curve. Such patients require a higher valve pressure setting.

The present flow examination method is particularly useful in combination with reprogrammable valves. Examination of CSF flow using a small portable scintillation counter is a promising assessment tool in the management of hydrocephalus that should improve outcomes.

References

1. Matsumae M, Murakami T, Ueda M, Suzuki Y, Sato O. Dynamic changes of cerebrospinal fluid shunt flow in patients' daily life. *Childs Nerv Syst* 1987; 3:30–34.
2. Matsumae M, Sato O, Itoh K, Fukuda T, Suzuki Y. Quantification of cerebrospinal fluid shunt flow rates. Assessment of the programmable pressure valve. *Childs Nerv Syst* 1989; 5:356–360.
3. Rudd TG, Shurtleff DB, Loeser JD, Nelp WB. Radionuclide assessment of cerebrospinal fluid shunt function in children. *J Nucl Med* 1973; 14:683–686.
4. Harbert J, Haddad D, McCullough D. Quantitation of cerebrospinal fluid shunt flow. *Radiology* 1974; 112:379–387.
5. Chervu S, Chervu LR, Vallabhajosyula B, Milstein DM, Shapiro KM, Shulman K, Blaufox MD. Quantitative evaluation of cerebrospinal fluid shunt flow. *J Nucl Med* 1984; 25: 91–95.
6. Ohya M, Tsugane R, Ito M, Nojiri K, Sato O, Ikei K. Quantitative measurement of CSF shunt flow and evaluation of shunt function in hydrocephalic patients. *Nerv Syst Child* 1981; 6: 255–263.
7. Brendel AJ, Wynchank S, Castel JP, Barat JL, Leccia F, Ducassou D. Cerebrospinal shunt flow in adults: radionuclide quantitation with emphasis on patient position. *Radiology* 1983; 149:815–818.
8. Ikeda K, Itoh H, Someya S, Yamamoto S. Relationship between cerebrospinal fluid flow through the ventriculo-peritoneal shunt and computed tomographic images of hydrocephalic patients. *Nerv Syst Child* 1988; 13:123–128.
9. Kadoya S, Ito S, Kubota N, Maeda T. Flow rates of cerebrospinal fluid shunts – evaluation on normally functioning shunts. *Neurol Med Chir (Tokyo)* 1981; 21:565–571.
10. Matsuoka Y, Hashi K, Kawarazaki A, Ohkawa N. Quantitative flow measurement of cerebrospinal fluid shunt. *Neurol Med Chir (Tokyo)* 1979; 19:909–915.
11. Foltz EL, Blanks J, Meyer R. Shunted hydrocephalus: Normal upright ICP by CSF gravity-flow control – a clinical study in young adults. *Surg Neurol* 1993; 39:210–217.
12. Higashi S, Futami K, Matsuda H, Yamashita J, Hashimoto M, Hasegawa M, Tokuda K, Hassan M, Hisada K. Effect of head elevation on intracranial hemodynamics in patients with ventriculoperitoneal shunts. *J Neurosurg* 1994; 81:829–836.
13. Czosnyka Z, Czosnyka M, Richards HK, Pickard JD. Posture-related overdrainage: comparison of the performance of 10 hydrocephalus shunts in vitro. *Neurosurgery* 1998; 42:327–334.
14. Barami K, Sood S, Ham SD, Canady AI. Postural changes intracranial pressure in chronically shunted patients. *Pediatr Neurosurg* 2000; 33:64–69.
15. Miyake H, Ohta T, Kajimoto Y, Nagao K. New concept for the pressure setting of a programmable pressure valve and measurement of in vivo shunt flow performed using a microflowmeter. *J Neurosurg* 2000; 92:181–187.