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ORIGINAL ARTICLE

Factors Affecting Cerebrospinal Fluid Flow in a Shunt

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Abstract

Nineteen hydrocephalic patients were studied to determine factors affecting cerebrospinal fluid (CSF) flow through shunts. This study was based on our previously reported method by which fluctuations in CSF flow through a shunt of from 0.01 ml min⁻¹ to 1.93 ml min⁻¹ were identified, each having its own rhythmic pattern.

While CSF flow in a supine position was less than 0.01 ml min⁻¹, head elevation to 60° led to increases in CSF flow from 0.12 ml min⁻¹ to 0.17 ml min⁻¹. Sudden respiratory changes such as coughing also affected CSF flow. CSF flows were higher than average between 10 pm and 7 am, and changes in CSF flow were related to slight increases in ICP during REM sleep. There is no relationship between CSF flow in a shunt and daily fluid intake which varied from 27 ml kg⁻¹ to 103 ml kg⁻¹, and no significant changes in CSF flow resulting from rapid intravenous injection of Glycerol and Ringer's solution.

Key words: *Hydrocephalus, shunt, CSF hydrodynamics, in-shunt flowmeter, intracranial pressure.*

Introduction

Shunt systems have been generally adopted in the treatment of hydrocephalus, but have not always proven satisfactory. The effects of shunting are evaluated by improvements in neurological symptoms and signs, changes in CT findings and intracranial pressure (ICP). The hydrodynamics of cerebrospinal fluid (CSF) flowing through the shunt system after the operation, and what factors affect this CSF flow have not been fully clarified.

We have, therefore, developed a new non-invasive method to determine the CSF flow through the shunt intermittently^{13,15,29}. We have previously reported fluctuations in the CSF flow through the shunt in hydrocephalus¹⁴, and also on the relationship between the CSF flow through the shunt and neurological improvement^{16,19}. In the present study, the

factors which are assumed to be affecting the CSF flow in the shunt system are evaluated.

Methods and Materials

The method of measuring CSF flow has previously been reported^{13,15,19,29}. This consists of inducing electrolysis of the CSF in the in-shunt bubble generator with a high-frequency transmitter, using a Doppler flowmeter above the skin to detect the movement of the bubbles in the fluid as they flow through the shunt, and then calculating CSF flow on the basis of the results obtained.

Nineteen adult patients with either communicating or non-communicating hydrocephalus were studied all of whom had received a ventriculo-peritoneal shunt with the Raimondi peritoneal catheter of medium pressure (Heyer

TABLE I. Cases of hydrocephalus

Case	Age/Sex	Etiology	CSF flow max/min(ml min ⁻¹)
1	54 F	HICH	0.06/0.01
2	64 F	SAH	0.07/0.01
3	67 M	Contusion	0.07/0.02
4	42 F	HICH	0.08/0.01
5	43 F	SAH	0.08/0.01
6	67 M	NPH	0.12/0.01
7	63 M	SAH	0.13/0.01
8	42 M	SAH	0.17/0.01
9	38 F	Aqueductal stenosis	0.20/0.01
10	50 F	SAH	0.21/0.01
11	51 F	SAH	0.23/0.02
12	65 F	Contusion	0.27/0.01
13	66 M	SAH	0.33/0.01
14	65 F	SAH	0.43/0.01
15	18 M	Aqueductal stenosis	0.52/0.03
16	58 M	HICH	0.55/0.12
17	55 M	SAH	0.64/0.01
18	70 M	SAH	0.78/0.06
19	20 M	Contusion	1.93/0.07

HICH: hypertensive intracerebral hemorrhage

SAH: subarachnoid hemorrhage

NPH: normal pressure hydrocephalus

Schulte Corp.) They included 9 males and 10 females aged from 18 to 70 years (mean:53). Ten cases were due to ruptured aneurysm, 3 to hypertensive intracerebral hemorrhage, 3 to cerebral contusion, 2 to aqueductal stenosis and one to idiopathic normal pressure hydrocephalus (Table I).

The influences of the following factors on the CSF flow in the shunt were examined:

(1) Incline of body (with upper half at varying degrees of 0°, 30°, 60° and 80°) and changes in ICP corresponding to each of the above postural changes.

(2) Rapid changes in intrathoracic and intra-abdominal pressures resulting from coughing.

(3) Fluctuations in ICP over a one-day period, especially changes therein during the rapid eye movement (REM) sleep stage.

(4) Daily fluid intake.

(5) Rapid intravenous infusion of hypertonic solution (500ml of 10% Glycerol/30 min) and Ringer's Lactate solution

(500-1000 ml hr⁻¹).

(6) Systemic blood pressure.

Influence of Various Factors Upon the CSF Flow in a Shunt

Fluctuations in CSF Flow Due to Postural Change

Fluctuations in the CSF flow corresponding to postural changes could be determined in three patients observed over the period 10 am to 8 pm. The CSF flow rate were measured more than twice in each case.

With the patient in a supine position, the CSF flow through the shunt was invariably less than 0.01 ml min⁻¹. When the upper half of the body was raised to 30°, the CSF flows increased slightly to 0.04, 0.05 and 0.08 ml min⁻¹, respectively, in the three cases. With a further increase to 60°, there was a further change in CSF flow to 0.12, 0.13 and 0.17 ml min⁻¹, respectively. However, when at 80°,

i.e. nearly a sitting position, the CSF flow increased to 0.24 and 0.43 ml min⁻¹, respectively in two of the cases, but decreased in the third case to less than the value at the 60° position (Fig. 1).

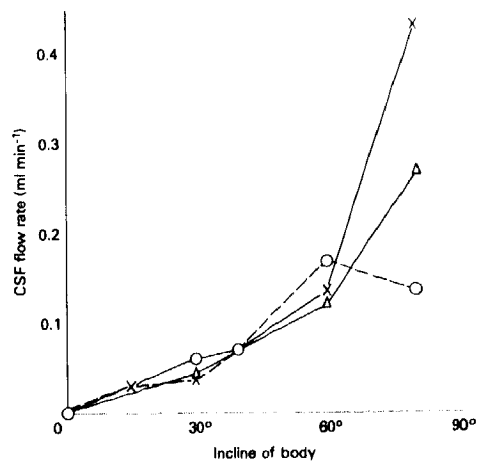


FIG. 1. Changes in CSF flow with head elevation in 3 cases. CSF flows of less than 0.01 ml/min through a shunt in a recumbent position increased to over 0.04 ml/min with head elevation.

The changes in intracranial pressure (ICP) with inclination of the body were examined in two cases. The mean ICP of patient A in the recumbent position was 10 mmHg, which dropped to 5 mmHg when the patient was tilted up to 30°. When the patient was raised up to 60°, however, the pressure rose temporarily showing a large fluctuation, but 5 min later, it returned to a value almost equal to that at 30°. The mean ICP of patient B in a supine position was 20 mmHg, but this rapidly fell to 12 mmHg when the body was raised 30° (Fig. 2).

Fluctuations in the Intrathoracic and Intra-abdominal Pressures Resulting from Coughing

In most cases, transient increases in ICP exceeding 40 mmHg were observed after sharp fluctuations in intrathoracic and intra-abdominal pressures even when the body remained in the same physical position (Fig. 3). In these

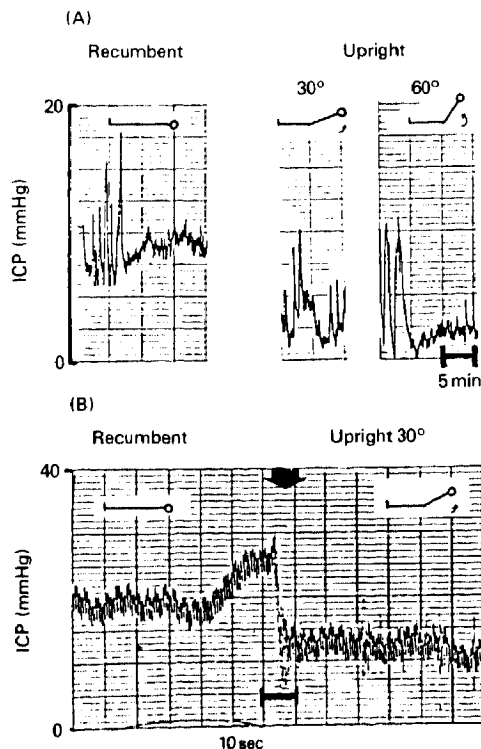


FIG. 2. Changes in ICP with head elevation in 2 cases. The mean ICP value of 10 mmHg in case A (top) in the recumbent position dropped to 5 mmHg when tilted up to 30°. The mean ICP value of 20 mmHg in case B (bottom) in the recumbent position dropped rapidly to 12 mmHg when tilted up to 30°.

cases, bubbles passed through the shunt in an instant, indicating a transient and very rapid increase in CSF flow.

Fluctuations in ICP Over 1 day

CSF flow through the shunt over a 24 h period was intermittently determined in 16 patients. In the supine position, CSF flow fluctuated in each case with peak CSF flows of between 0.06 ml min⁻¹ and 1.93 ml min⁻¹, and individual fluctuations over a day with 1-3 peaks for each of the patients (Fig. 4).

The correlation between the CSF flow through the shunt and ICP was also evaluated

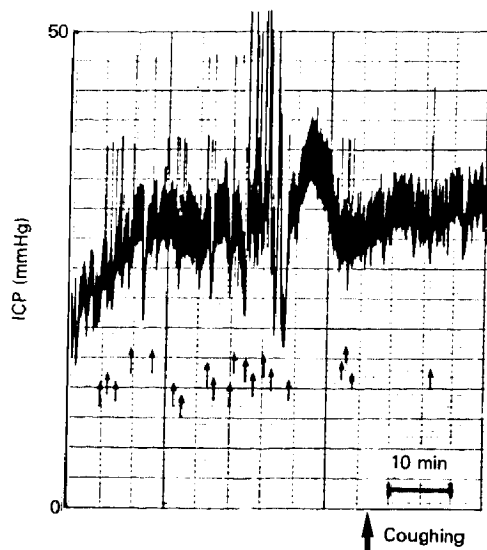


FIG. 3. Transient increases in ICP accompanying coughing.

in three cases of which the following is representative.

Case 4, a 42-year-old female, showed changes in the CSF flow and ICP over the 15 h period from 9 pm to 12 am as shown in Fig. 5. The CSF flow through the shunt fluctuated from a maximum of 0.77 ml min⁻¹ down to a minimum of 0.05 ml min⁻¹ with 3 peaks at 10 pm and 4 and 9 am. The mean ICP also fluctuated with a peak of 18 mmHg and a minimum of 2 mmHg, and was thought to be related to the CSF flow. Both the CSF flow and ICP showed almost similar fluctuations in the other 2 patients.

In addition, paragraphic monitoring of ICP, electroencephalogram (BEG), respiratory movements, electrooculogram and swallowing movements with the patient in the supine position all day revealed transient rises in ICP coinciding with respiratory movements, eye-ball and swallowing movements during the rapid eye movement (REM) sleep stage in three out of four patients studied. Fluctuations in the CSF flow for Case 4 at 9.30 pm are illustrated in Fig. 5 and correspond to movements of the eyes, respiration and swallowing. Coinciding with these fluctuations, ICP rose transiently.

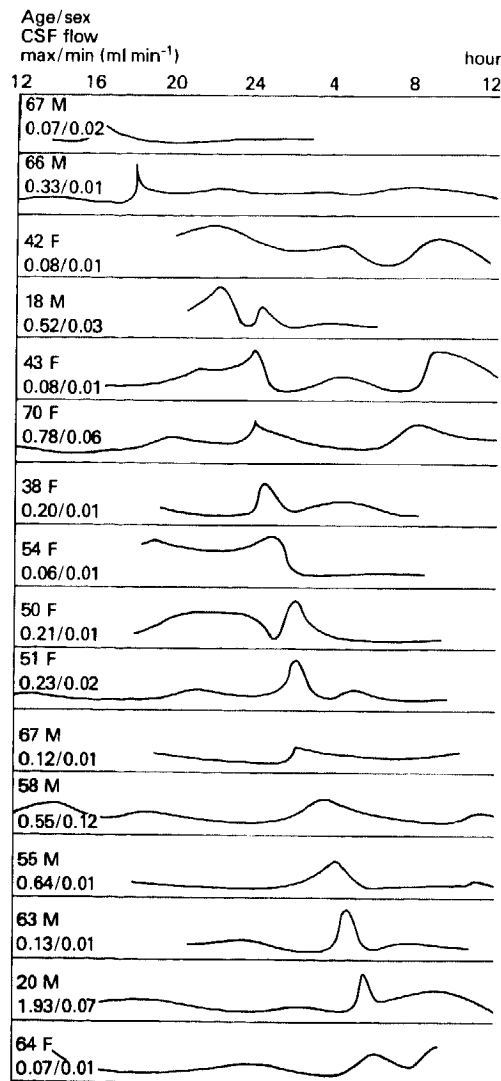


FIG. 4. Daily patterns of CSF flow through shunts in 16 cases. In supine position, the flow fluctuated in each case, with 1-3 peaks between 0.06 ml/min and 1.93 ml/min.

Daily Total Volume of Fluid Ingested

The water intake in a day of the 16 patients ranged from 27 ml kg⁻¹ up to 103 ml kg⁻¹, with a mean of 50 ml kg⁻¹. The CSF flow rates varied greatly. The linear regression between the CSF flow and total daily intake was $y = 0.593 - 0.004x$, with a correlation coefficient of 0.18. There was no correlation between the fluid intake and the CSF flow through a shunt (Fig. 6).



FIG. 5. CSF flow rate (ml min⁻¹) and ICP (mmHg) over the 15 h period. The CSF flow rate fluctuated from a maximum of 0.77 ml min⁻¹ down to a minimum of 0.05 ml min⁻¹ with 3 peaks at 10 pm and 4 and 9 am. The mean ICP also fluctuated with a peak of 18 mmHg and a minimum of 2 mmHg, and was thought to be related to the CSF flow. Both the CSF flow and ICP showed almost similar fluctuations in the other 2 patients. In addition, paragraphic monitoring of ICP, electroencephalogram (BEG), respiratory movements, electrooculogram and swallowing movements with the patient in the supine position all day revealed transient rises in ICP coinciding with respiratory movements, eye-ball and swallowing movements during the rapid eye movement (REM) sleep stage in three out of four patients studied.

Rapid eye movement (REM) sleep stage in three out of four patients studied. Fluctuations in the CSF flow for Case 4 at 9.30 pm are illustrated in Fig. 5 and correspond to movements of the eyes, respiration and swallowing. Coinciding with these fluctuations, ICP rose transiently.

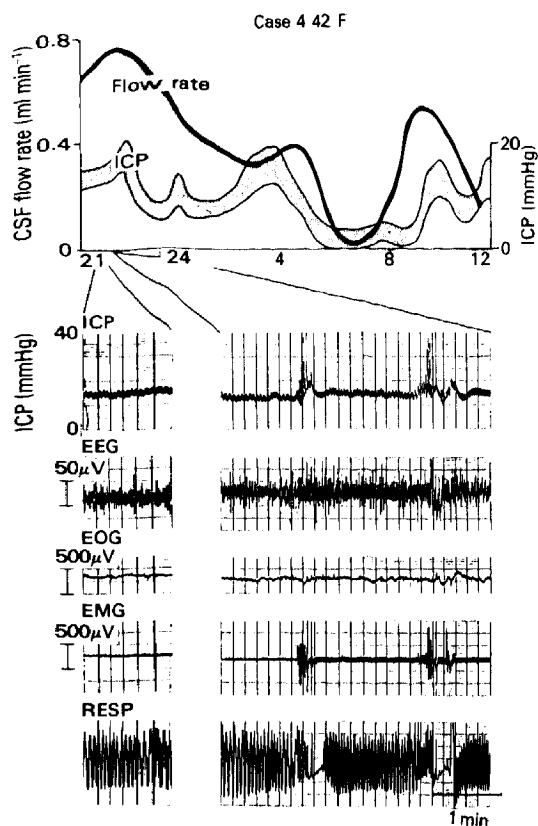


FIG. 5. Changes in CSF flow and ICP over a 15-hour period. CSF flow fluctuated between 0.01 ml/min and 0.077 ml/min with 3 peaks. Mean ICP fluctuated between 2 mmHg and 18 mmHg, and was thought to be related to the changes in the CSF flow. Paragraphic monitoring revealed transient increases in ICP with respiratory movements, eyeball and swallowing movements during REM sleep.

Rapid Intravenous Infusion of a Hypertonic Solution and Ringer's Lactate Solution

Changes in the CSF flow through the shunt were examined after rapid intravenous infusion of hypertonic solution in case 14. 500 ml of 10% Glycerol was administered intravenously within 30 min when the patient was tilted to 45°. The CSF flow through the shunt, which had been 0.077 ml min⁻¹ before admin-

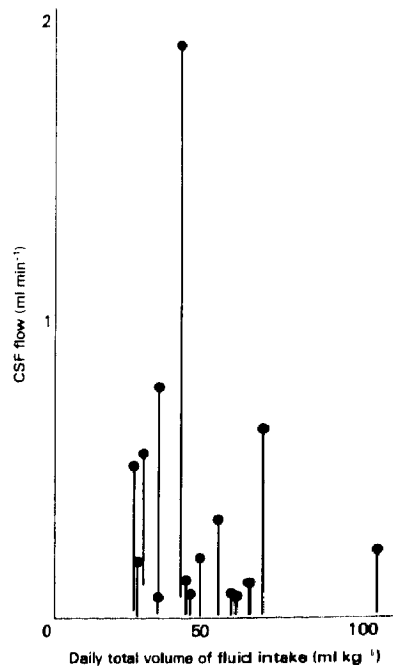


FIG. 6. Lack of correlation between CSF flow through a shunt and daily total volumes of fluid intake.

istration, decreased slightly to 0.073 ml min⁻¹ after administration (Fig. 7).

Cases 8 and 14 received infusions of 500 or 1000 ml respectively of Ringer's Lactate solution within one hour. In case 8, the CSF flow increased slightly from 0.141 ml min⁻¹ to 0.162 ml min⁻¹ when tilted to 30°, while in case 14 showed only a marginal change from 0.073 ml min⁻¹ to 0.071 ml min⁻¹ when tilted to 45°. Thus, there were no significant changes in the CSF flow through the shunt after these rapid intravenous injections.

Systemic Blood Pressure

Seven of the 19 patients had systemic hypertension both pre and postoperatively, and antihypertensive drugs were administered to five of them. The remaining 12 patients stayed within normal range of systemic blood pressure. There was no significant correlation between the systemic blood pressure and the fluctuations in, or mean values of, the CSF flow through the shunt.

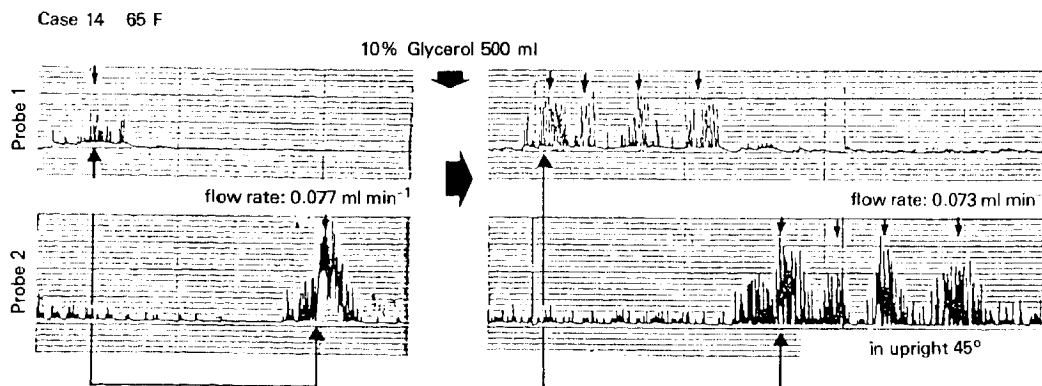


FIG. 7. Case 14. Changes in CSF flow with intravenous infusion of 50g of Glycerol within 30 min. CSF flow of 0.077 ml/min through the shunt at 45° prior to infusion, decreased slightly to 0.073 ml/min after infusion. Small arrows indicate Doppler flowmeter signals of bubbles in CSF flowing through the shunt.

Discussion

In clinical practice it is extremely important to examine the function of shunts implanted in cases of hydrocephalus and in particular to examine the fluctuations in the CSF flow through the shunts. Various methods have so far been adopted to this specific purpose. These methods include: (1) injection of radioisotope ($^{99m}\text{TcO}_4^-$, $^{131}\text{I-HSA}$, $^{99m}\text{Tc-DTPA}$, etc.) into the shunt and with calculation of the CSF flow rate by analysing the disappearance curve^{4,7,17,18,20,25,27,32,38,39}. (2) calculating the CSF flow rate based on the changes in temperature of the cooled CSF using body surface thermometers^{1,9,10,11,12,22,41,42,43}. (3) calculating the CSF flow rate based on the changes in the temperature of the cooled CSF using the Cameleon print⁴⁶. However, it is difficult to determine the CSF flow rate repeatedly with any one of these methods over a short period of time. Also, the results obtained have a fairly large margin of error. Thus, no satisfactory results have been obtained to date using these methods.

As previously reported, we have developed and adopted an in-shunt CSF flowmeter in clinical practice in attempt to clarify the CSF hydrodynamics in cases of hydrocephalus. Lorenzo *et al.*²³, Cutler *et al.*³ and Rubin *et al.*³⁷ earlier reported that the CSF formation rate was 0.30 ml min⁻¹, 0.35 ml min⁻¹ and

0.37 ml min⁻¹. Our results revealed that the CSF flow through the shunt did not always coincide with the amount of CSF produced and was not constant, but varied from 0.01 ml min⁻¹ to 1.93 ml min⁻¹. Furthermore, even when several patients were subjected to the same conditions, the flow rate varied with each patient, showing an individual rhythmic pattern in each case^{14,19}.

Therefore, we examined our patients under varying conditions to determine what factors would influence the CSF flow in a shunt. The results showed that the factors directly influencing the CSF flow are changes in the physical attitude of the body, transient increases in ICP because of rapid changes in pressure within the thorax and the abdomen after coughing, and rises in ICP during the REM sleep stage.

Changes in CSF Flow Because of Changes in Posture and ICP

In the recumbent position, the CSF flow was less than 0.01 ml min⁻¹, but increased as the upper half of the body was raised incrementally to 30° and then 60°, although the degree of the increase varied with each patient. Kadoya *et al.*²⁰ reported that the CSF flow rate in the sitting position was more than 0.1 ml min⁻¹, whereas it was less than 0.1 ml min⁻¹ in the recumbent position. Matsuoka

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*et al.*²⁷ reported that the CSF flow rate clearly increased with the raising of the patient head. Portnoy *et al.*³⁴⁻³⁶ reported on the hydrodynamics of the shunt and concluded that perfusion pressure (PP) = [intraventricular pressure (IVP) + hydrostatic pressure (HP)] - [distal cavity pressure (DCP) + closing pressure (CP)]. They suggested that as HP was 0 in the recumbent position changes in PP depended upon changes in IVP. Fluctuations in PP, however, depend mainly upon HP which is increased by raising the head, even though IVP turns negative. Durward *et al.*⁵, reporting on changes in ICP due to the inclination of the body, concluded that ICP reduced by -4.5 ± 1.6 mmHg $\sim -6.1 \pm 3.5$ mmHg when the patient was tilted 15° to 30° from lying position. Kito *et al.*²¹ also reported that ICP decreased with elevation of the head. In our patients also, ICP was reduced by 40-50% when the body was raised 30° from the supine position. Thus the fact that the CSF flow through the shunt increased, despite the decreased ICP on raising the head, can be ascribed to the siphon effect or increase of hydrostatic pressure in the shunt caused by the inclination of the body, as reported by Fox *et al.*⁸ and by Yamada *et al.*⁴⁵.

Based on these findings it is evident that, in cases of hydrocephalus, the CSF flow through the implanted shunt is dependent upon the fluctuations in IVP in the recumbent position, i.e. where HP is close to zero, but that when the head is raised, i.e. where HP is larger than CP, the CSF flow through the shunt is highly dependent upon the fluctuations of HP in the shunt.

Matsuoka *et al.*²⁷ recommend that an anti-siphon valve be installed in the shunt to prevent increases in the CSF flow resulting from head elevation. While in none of our 19 patients was an anti-siphon valve employed, complications such as slit ventricles and acute subdural hematoma were not observed. This finding suggests that although the CSF flow through the shunt temporarily increases immediately after postural change, ICP drops to zero, accompanied by a drop in PP and there is a gradual decrease in the CSF flow.

On the other hand, when there is no change in posture, despite the presence of HP, the CSF flow through the shunt closely correlates to the fluctuations in ICP as illustrated in Fig. 5.

REM Sleep, ICP and CSF Flow Interactions

Cooper *et al.*² reported that ICP increased during sleep in 15 out of 24 cases. Ogashiwa *et al.*^{30,31} reported that, in normal pressure hydrocephalus (NPH), the increases in ICP during sleep were only observed during the REM sleep stage. In our patients also, the rises in ICP, as shown in Fig. 5, could be seen coinciding with the movements of eyeballs, respiration and swallowing during the REM sleep. These changes are closely related to increases in the CSF flow through the shunt. Matsuoka²⁶ earlier reported that ICP increased 100-240% in REM sleep. In our patients, however, the ICP increased only slightly. This could be attributed to the increase in the CSF flow through the shunt following the rise in ICP.

Other Factors

The CSF flow through a shunt possibly increases because of the sharp and transient rise in ICP accompanying coughing. Yamada *et al.*⁴⁵ observed that the pressure within the thorax and abdomen rose with coughing, but this potential change in hydrostatic pressure does not prevent an increase in the CSF flow through the shunt.

Zoghbi *et al.*⁴⁷ reported that, in animal experiments, the CSF production decreased with administration of Glycerol (3 g kg⁻¹). In our present study, there was no distinct change in the CSF flow through the shunt following the administration of Glycerol. As explained above, the CSF flow through the shunt was not directly affected by administration of Ringer's lactate solution or fluctuations in systemic blood pressure.

Conclusion

As previously reported, the CSF flow through the shunt varies in individual cases within a range of 0.01 ml/min up to 1.93 ml min⁻¹. Furthermore, it is clear from the results in our nineteen hydrocephalics that the following factors influence the fluctuations in the CSF flow through the shunt.

(1) Postural changes: in a recumbent position, the CSF flow through the shunt was less than 0.01 ml min⁻¹, but rose to 0.04–0.08 ml min⁻¹ with head elevated at 30°, and to 0.12–0.17 ml min⁻¹ at 60°.

(2) Transient rises in ICP associated with fluctuations in pressure within the thorax and abdomen after coughing.

(3) Rises in ICP during the REM sleep stage.

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