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CSF DYNAMIC DIAGNOSIS OF SPINAL BLOCK II:

The Spinal CSF Pressure-Volume Curve

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In a previous paper (*Gilland* 1962) the block aggravating effect of lowering the CSF pressure was systematically studied. This effect has been assumed to depend on a further narrowing of the spinal subarachnoid space at the obstruction, due to a CSF volume reduction.

The main purpose of the present study was to determine the relation between spinal CSF pressure and the volume of the spinal CSF space. This relation might be termed "the spinal CSF pressure-volume (P-V) curve". The determination was intended to elucidate the block aggravating effect noted above. It would also allow for an estimate of the magnitude of the spinal CSF flow induced by jugular compression. This estimate, in turn, was of interest as part of the background for a theoretical study of CSF dynamics in spinal block (*Gilland* 1965 b).

PREVIOUS WORKS

The spinal CSF P-V curve does not appear to have been previously investigated. In a study by *Schaltenbrand* (1947) concerning CSF production and reabsorption, however, one case with transverse myelitis and complete block on jugular compression is of interest. On withdrawal of 5 ml CSF the lumbar pressure, as determined with an open end water manometer, fell from 11 to 4 cm H_2O and remained at this level for 30 min. Thereafter 10 ml of fluid was injected whereupon the pressure rose to 18 cm H_2O and remained at this level during a 20 min observation period. The cisternal CSF pressure was not recorded, neither was the level of the lesion indicated, and no myelographic findings were reported.

Cranio-spinal CSF P-V relations and membrane elasticity problems have been fundamentally examined by, amongst others, the following investigators. Weed and coworkers studied these problems in a series of papers, *e.g. Weed, Flexner & Clark* (1932), *Weed & Flexner* (1932; including the observation that the meningeal elasticity coefficients in the macaque and the cat decrease with age), *Flexner & Weed* (1933; including cisternal but not lumbar CSF pressure recordings in dogs with spinal block produced by extradural ligature), and *Weed & Flexner* (1933). A critical comment on these works was given by *Davson* (1956) in a general survey. Among the later works cited by him, those of Ryder and coworkers (especially 1953 a) deserve particular attention. Of relevant works not included in Davson's survey should be mentioned those of *Bender, Kehrer & Knebel* (1951), *and Bender & Knebel* (1953). A more recent survey was presented by *Bowsher* (1960) including experiments of his own. The works cited above are not further commented on here, since none of the authors have studied the isolated spinal canal.

Spinal CSF flow induced by jugular compression is a concept agreed on by most authors; for details see *Gilland* (1965 b). The magnitude of the induced CSF flow, however, has never been numerically estimated. *Poppen & Hurxthal* (1934), employing an open-end water manometric technique, judging from model experiments and clinical experiences, evidently considered the CSF flow past an incomplete obstruction to correspond to the outflow of CSF in the open-end manometer. *Ferris* (1941) studied the outflow of CSF through a wide bore lumbar needle into a reservoir on jugular compression, in order to estimate cerebral blood flow. He considered the CSF pressure increase to cause "slight changes in volume due to compression of the spinal veins and to distention of the dural outpockets where the nerves emerge from the bony system". Neither Poppen & Hurxthal's nor Ferris' experimental set-up, however, seemed to allow for more precise conclusions concerning the compliance of the spinal CSF sac.

MATERIAL AND METHODS

Spinal CSF P–V curves were determined in 3 patients with complete spinal block, as evidenced by manometric studies at combined cisterno-lumbar puncture. The patients' data, type of lesion and lower level of the block, as determined by myelography, appear in Table 1. CSF electromanometric studies on jugular compression for the detection of spinal block were made in more than 300 patients. Preliminary findings on the first part of this continuous clinical puncture series have been presented previously (*Gilland* 1962).

The CSF pressures were recorded through 21 gauge (= ID 0.80 mm) needles with pressure transducers, Elema® models EMT 458 and 490 B, connected via electromanometers, Elema® model 460, to a 4-channel ink jet writer, Mingograph® 42. For a detailed description of recording equipment, see *Gilland* (1965 c). The volume displacement in the hydraulic system was less than 0.2 ml within the measurement range (—25 to +70 cm H_2O). The patients were examined in the lateral recumbent position with the center of the head and the vertebral column on the same horizontal level, chosen as pressure reference level. On analyzing the charts, respiratory CSF pressure variations were compensated for by free-hand smoothing of the curves, to obtain mean pressures. The chart reading error corresponded to 1–2 cm H_2O.

TABLE 1

Patients with Complete Spinal Block in whom the Spinal Pressure-Volume Curve was Determined.

Case no. sex, age in years	Date investigated	Symptoms and type of lesion	Lower margin of block at myelography	Verification
No. 38 ♀ 55	23 III 59	Paraparesis and parahyp-aestesia. Recurrrent meningioma or postop. scar formation.	T 3	Operated 1951, re-operated 20 XII 1957
No. 53 ♂ 74	30 VII 59	Paraparesis. Disc protrusion.	T 5	Operated 15 I 1960
No. 190 ♂ 42	15 V 63	Paraparesis and parahyp-aestesia. Focal myelopathy with cord swelling.	T 6	No operation, subsequently improved

Procedure.

For the purpose of investigating the occurrence of spinal block jugular and abdominal compression were performed with simultaneous recording of the cisternal and lumbar pressures, as previously described (*Gilland* 1962). For the determination of the spinal CSF P–V curve in cases no. 38, 53, and 190, a second lumbar puncture needle was then inserted in an adjoining lumbar interspace. Through this needle sterile saline solution at 37° C was injected while a simultaneous cisternal and lumbar pressure recording was made. The record was marked for each ml injected. A total amount of 9 ml, 10 ml, and 9 ml, respectively, were injected at a rate of 0.25–0.5 ml per sec. A typical recording is illustrated in Fig. 1. After a pause of 0, 7, and 60 seconds respectively, the amount of fluid injected was aspirated. In case no. 38 after a 5 min. pause additional fluid was aspirated until a pressure of —25 cm H_2O was reached. This occurred after 16 ml of fluid had been aspirated at a rate of 0.25 ml/sec. This fluid was reinjected without intervening pause.

The cisternal pressure remained stable throughout these procedures, indicating complete manometric spinal block. The cisternal pressure recording was considered compulsory, when determining the spinal CSF P–V curve, because complete block on jugular compression in some patients was found to co-exist with an incomplete block on abdominal compression, the blocking process acting similar to a non-return valve.

The clinical puncture routine procedure was modified during the course of the series to avoid the risky combined cisterno-lumbar puncture, when initial lumbar

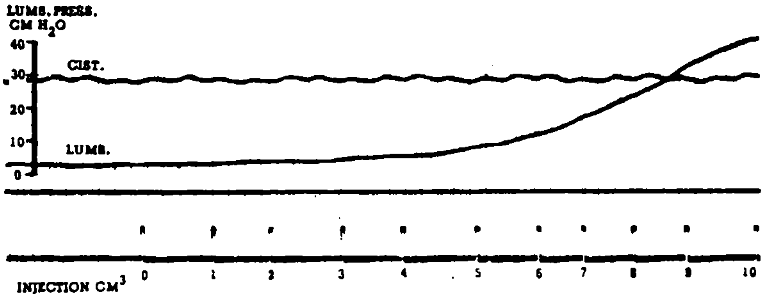

Fig. 1.
Recording of lumbar CSF pressure increase on injection of saline through a separate lumbar needle, in a case with complete spinal block (case no. 53). The time for injection was 19 sec.

recording demonstrated unequivocal block. This implied a self-imposed limitation on the number of patients in whom the spinal P–V curve could be determined.

Estimation of Method Errors.

The CSF pressure at the start of injection does not represent the patient's steady state, due to a probable leak of fluid during the preceding part of the examination. This, however, does not interfere with the conclusions drawn from the curves.

Part of the fluid injected can be assumed to leave the subarachnoid space by different routes (see *e.g. Seiro* 1943, and *Foldes & Arrowood* 1948). It can leak out through the perforation beside the needle (for recent aspects on this problem, see *e.g. Tourtellotte et al.* 1964, and *Lundberg & West* 1965). It can seep past a block which is undetectably not complete. It can also seep out through the root sleeves (*Thorsén* 1947), through the arachnoid itself, and through the vein walls in the subarachnoid space. For a discussion including the latter aspect see *e.g. Bowsher* 1960.

The rate of fluid escape is probably largest at peak pressure, *i.e.* during the pause between injection and aspiration of fluid. By referring the pressure fall during this pause to the corresponding volume decrease in the P–V curve obtained, an estimate can be made of the volume loss. Thus in case no. 190 the CSF pressure during the 1 min. pause between injection and aspiration of fluid fell from 51 cm to 30 cm of H_2O, corresponding to a volume loss of 2.5 ml. As the preceding injection of 9 ml took 16 sec., the leakage error should be less than 0.6 ml, *i.e.* less than 7 per cent.

Fluid escape can also be estimated by determining the difference ("hysteresis") between the P–V curve obtained on injection of fluid and that obtained on aspiration. Thus in case no. 53 when 7 ml of fluid had been injected the pressure was 17 cm H_2O, whilst on aspiration when 7 ml remained to be aspirated the pressure was 10 cm. This pressure difference, according to the P–V curve, corresponds to a volume of 1.5 ml. This estimated volume loss refers to a period of 30 sec. and as the complete injection of 10 ml took 20 sec. the volume error should be less than 1/10, *i.e.* less than 10 per cent. Any lag of the subarachnoid vessels and the arachnoid and dura in adjusting to a temporary steady state at different pressure levels has not been taken into consideration, but would tend to reduce the volume error, as determined.

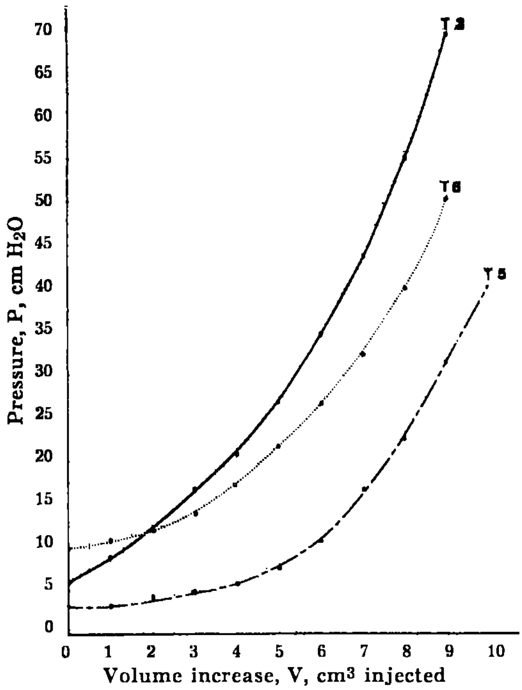

Fig. 2.
Relation between lumbar CSF pressure and volume of fluid injected lumbarly in three cases with complete spinal block at the thoracic levels indicated.

RESULTS

The relation between the amount of fluid injected and the lumbar CSF pressure, in the three patients with complete spinal block, appears in Fig. 2. The relation between the amount of fluid injected and aspirated and lumbar CSF pressure in case no. 38 is plotted semi-logarithmically in Fig. 3. This representation transforms the P-V relation into a fairly straight line, showing the exponential character of the curve. The same appearance of the positive and negative phases of the P-V curve was obtained in a fourth case (no. 55) in whom the block, caused by a meningeoma at T 2, was complete only at pressures below + 30 cm H_2O.

The block provoking effect of lowering the CSF pressure becomes evident on examining the P-V curves. It appears that a pressure reduction of a fixed magnitude will imply the largest volume reduction at CSF pressures around 0. At extreme high or low CSF pressures a pressure reduction of the same fixed amount will result in a smaller volume reduction. Accordingly, the main block-provoking effect of lowering

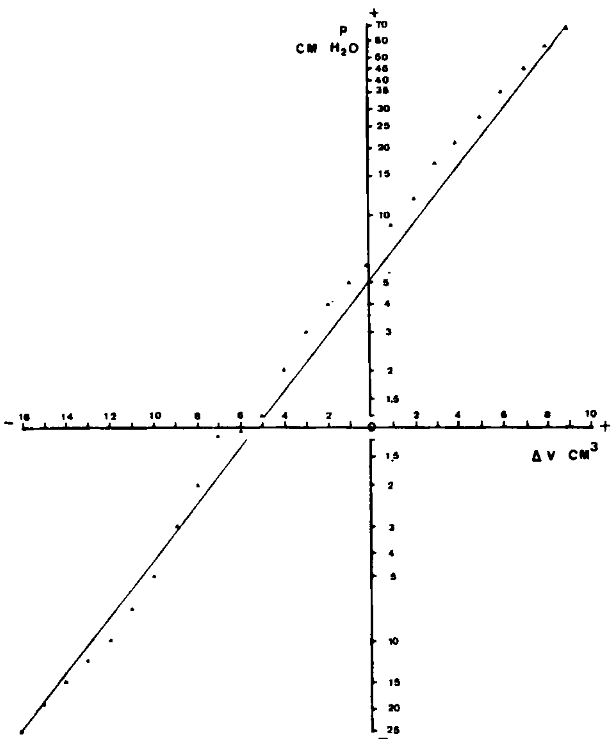

Fig. 3.
Semilogarithmic representation of relation between lumbar CSF pressure and the fluid volumes injected and aspirated lumbarly in case no. 38 with complete spinal block at T 3. The fluid injection portion is identical with the T 3 curve in Fig. 2. The logarithmically infinite gap between + and — pressure has been arbitrarily drawn to allow the positive and negative phase curves to join.

the CSF pressure should be obtained in the neighbourhood of zero, making clinical block investigation procedures at sub-atmospheric pressures less important. This agrees well with the author's clinical experiences of dynamic spinal block diagnostics (*Gilland* 1962).

The magnitude of CSF flow induced on jugular compression can be appreciated from the P-V curves as follows: A typical pressure recording of jugular compression in a patient (case no. 86) with incomplete block at T 5 is reproduced in Fig. 4. The CSF flow necessary to bring about this lumbar pressure increase can be considered to be of the same magnitude as the amount of fluid which had to be injected in the patients with complete block in the same region, in order to obtain a corresponding pressure rise. The pressure rise from 16 to 37 cm H_2O on jugular compression in case no. 86, according to the P-V curves established, would correspond to a CSF flow past the midthoracic level

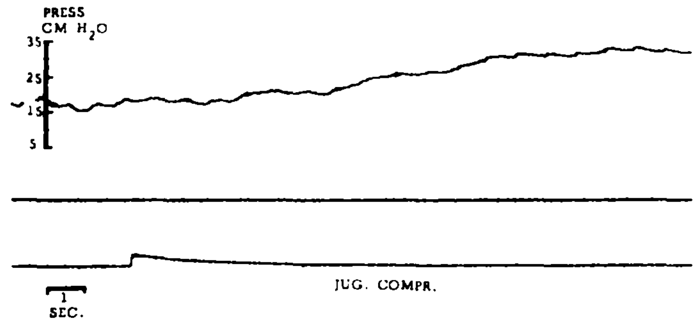

Fig. 4.
Lumbar pressure response on jugular compression in a patient with incomplete block at T 5. (Case no. 86, ♀, age 63 years, with paraparesis and parahypaestesia caused by a meningeoma, which was subsequently removed).

of about 3 ml. In the puncture series in general, on jugular compression the CSF pressure rose from 10–15 to 30–60 cm H_2O, corresponding to a CSF flow past the midthoracic level within the range 2–7 ml.

If lumbar pressure had been measured with an open-end water manometer with ID 2 mm (*i.e.* accomodating 0.3 ml of fluid per 10 cm pressure increase), the CSF flow past the midthoracic level should have been increased to the approximate range 2.5–8.5 ml. Evidently the hydraulic capacity of the spinal CSF sac supervenes that of a narrow-bore open-end water manometer in determining spinal CSF flow on jugular compression.

Patient discomfort on examination. One of the patients on injection experienced a moderate straining sensation in the legs at peak CSF pressure, ceasing on aspiration of fluid. Otherwise there were no untoward effects of the examination.

That the procedure presented in this paper is comparatively safe can partly by inferred from *Ryder et al.*'s (1953 b) experience on investigating the craniospinal CSF pressure mechanisms by inducing CSF pressure variations between −25 to +150 cm H_2O in 157 patients.

DISCUSSION

Spinal CSF sac distensibility is implied by the data obtained. This distensibility can be referred to the arachnoid-dura, the blood vessels and the blocking expansive process. These factors are discussed in turn. The compliance of the arachnoid-dura can be demonstrated on pantopaque myelography, where the lumbar subarachnoid space is seen to enlarge considerably when the patient's position is changed from horizontal to erect (*Taveras & Wood* 1964). That the membranes can not only collapse but also expand from the physiologic steady state position in intact man is probable; however, additional myelographic studies to prove this appear to be required (*Rådberg* 1964).

If it is assumed that venous pressure in the recumbent posture remains comparatively low it seems reasonable that the subarachnoid vein walls will be compressed by the increase in CSF pressure following fluid injection. The compliance of the blocking expansive process is difficult to assess, therefore the curves obtained differ to an unknown extent from the hypothetical curves of normal subjects. A grading of the factors contributing to the compliance found requires additional studies.

The spinal CSF sac is, reasonably, more or less distensible throughout the spinal canal. Thus, on jugular compression in cases with incomplete block the more fluid will flow past the block the higher its level in the spinal canal. All other factors being equal (including the size of the lumen at the block), the higher the level of the block the more delayed will the lumbar pressure rise be. It follows that, in general, blocks located in the upper part of the spinal canal will be the ones most easily detected on lumbar manometrics.

Apart from the influence of spinal sac distensibility on CSF flow, *Bowsher* (1957, 1960) called attention to another factor. Of his experiments, especially those concerning abdominal compression are of interest in the present connection. For the intact cranio-spinal CSF system he found an increased rate of absorption of Na^{24} from the CSF to the blood stream on abdominal compression in the monkey. With additional evidence from model experiments he concluded that on abdominal compression CSF passes rapidly through the expanding venous walls, presumably in a volume equal to the increase in venous volume. In the isotope experiment, however, the scintillation rate meter was placed over the monkey's foot where a scintillation increase might be caused by venous stasis induced by the abdominal compression.

If Poppen & Hurxthal's opinion on CSF flow (see introduction) had been correct, it would be impossible to detect incomplete block with fairly isovolumetric recording techniques. In the clinical series the author has employed electromanometric systems with volume displacements down to less than 1 mm^3 per 100 mm Hg in the complete hydraulic system, without untoward results as to block detection.

SUMMARY

In a previously presented clinical series of electromanometric recordings on combined cisterno-lumbar punctures for the detection of spinal block, 3 patients with complete spinal block as evidenced by

manometrics were further investigated. Through a separate lumbar needle saline was injected under simultaneous cisterno-lumbar electromanometric pressure recording. In one of the patients fluid was aspirated down to a sub-atmospheric CSF pressure of —25 cm H_2O. On myelography the lower levels of the blocks were found to be situated between T 3 and T 6.

The relations found between volume increment and CSF pressure indicated a compliance of the spinal CSF sac. The pressure-volume curves were plotted and it appeared that the CSF pressure, within the range studied, was an exponential function of volume increment. Similar findings were obtained in a fourth case with complete block only at CSF pressures below +30 cm H_2O. From the spinal block diagnostic point of view the compliance found appeared considerable. It was inferred from the spinal CSF pressure-volume curves that the CSF flow past the midthoracic level induced by jugular compression is of the magnitude 2–7 ml. The introduction of a lumbar narrow-bore open-end water manometer should not increase this flow considerably. A study of the literature did not reveal any similar estimates.

It was also found that a CSF pressure reduction of a given magnitude caused the largest volume reduction of the spinal CSF sac at CSF pressures around zero. The implication for the refinement of dynamic spinal block detection by lowering the CSF pressure, as previously described (*Gilland* 1962), is discussed.

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