

TECHNICAL NOTES

Quantitative Evaluation of Cerebrospinal Fluid Shunt Flow

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We describe a rigorous method for measuring the flow of cerebrospinal fluid (CSF) in shunt circuits implanted for the relief of obstructive hydrocephalus. Clearance of radioactivity for several calibrated flow rates was determined with a Harvard infusion pump by injecting the Rickham reservoir of a Rickham-Holter valve system with 100 μ Ci of Tc-99m as pertechnetate. The elliptical and the cylindrical Holter valves used as adjunct valves with the Rickham reservoir yielded two different regression lines when the clearances were plotted against flow rates. The experimental regression lines were used to determine the in vivo flow rates from clearances calculated after injecting the Rickham reservoirs of the patients. The unique clearance characteristics of the individual shunt systems available requires that calibration curves be derived for an entire system identical to one implanted in the patient being evaluated, rather than just the injected chamber. Excellent correlation between flow rates and the clinical findings supports the reliability of this method of quantification of CSF shunt flow, and the results are fully accepted by our neurosurgeons.

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Shunt malfunction after extracranial diversion of cerebrospinal fluid (CSF) through a prosthetic valve-regulated shunt is one of many possible problems causing vague symptoms in children with hydrocephalus. Malfunction cannot be confirmed easily by either percutaneous examination or tapping the shunt system; it can be ruled out only after flow determination.

Several qualitative nonradioactive methods for evaluation of shunt function and patency have achieved varying degrees of success. These include percutaneous examination, serial head measurements (which are unreliable in a growing child), and CSF pressure measurements. Earlier methods of measuring CSF flow suffered from inherent problems of discomfort associated with intrathecal injection, leakage of tracer from injection site, and multiple blood sampling. There are certain well-defined settings, such as: (a) in children who become independent of the shunt (5-10%), (b) in children whose ventricles remain large after shunting and thus questions arise about its function, (c) in children who do well even though percutaneous testing of the shunt shows that it is blocked, and (d) in patients with symptoms that mimic shunt malfunction; in these it is important to understand not only whether the shunt is patent but also whether it is functional to its fullest capacity.

The introduction of the TCT scanner has made it possible to chart the response of the brain—or, more specifically, the recon-

stitution of the cerebral mantle—following shunting. Several quantitative radionuclide methods for determining shunt patency and flow have been described but have met with variable success (1-5). This paper offers an improved radionuclide method for quantitating the flow through a ventriculo-atrial-ventriculo-peritoneal shunt, one that obviates many of the difficulties of previously described methods.

MATERIALS AND METHODS

Nine patients with Rickham-Holter shunts,* either ventriculo-atrial or ventriculo-peritoneal, were investigated because of complaints of headache, back pain, stiffness of the neck, lethargy, or seizures. Two of these patients were studied again after revision of their shunts; they were asymptomatic at the time of such study. A Holter-Rickham shunt identical to the one used in all of the above patients was previously calibrated, and a calibration curve was generated as described below. This curve was used to calculate flow rates in the patients' shunts.

The calibrated shunt system must be identical to the one inserted in the patient and must be calibrated for several flow rates within the expected range. The system comprising a Rickham-Holter assembly and the ventricular and distal end catheters was arranged as shown in Fig. 1. The ventricular end was connected to a Harvard pump, and preweighed test tubes were arranged to receive the outflow from the distal end. During the delivery of normal saline by the pump at specific flow rates, the Rickham reservoir was injected with 100 μ Ci of pertechnetate (Tc-99m) in 0.05 ml saline

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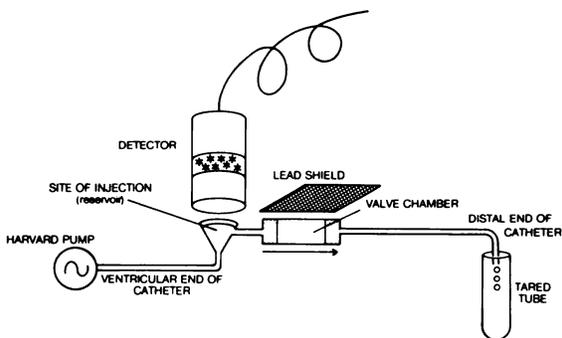


FIG. 1. Experimental setup for calibration of shunt system. Valve chamber is shielded from detector with lead shield in order to restrict counting to reservoir alone. Flow rates are determined in triplicate at each flow rate setting. Shunt system should be identical to one used in patient.

with a 25-gauge hypodermic needle, taking care to avoid introducing air into the system. The Holter valve was shielded with a piece of lead, and an external detector was placed over the reservoir. Counts during a 6-sec period were obtained at 15-sec intervals over a period of 6 min, and count rates were plotted against time on semilogarithmic graph paper. Each $t_{1/2}$ and clearance ($0.693/t_{1/2}$) was determined from visual fit of the plotted curve. The collected fluid at the distal end of the catheter was weighed to determine the actual flow rate. The process of injecting, recording the disappearance of radioactivity, and collecting the flow at the distal end was repeated eight to ten times for each of the six flow rates calibrated between 0.02 and 0.33 ml/min. The mean clearance values were plotted against the respective mean flow rates and a regression line was drawn connecting these points. This line was then used as a reference for the determination of CSF flow rate in patients with the same shunt system.

In vivo CSF flow rate determination. The patient's scalp over the shunt reservoir was shaved and after surgical preparation with povidone-iodine and antiseptic solution, the Rickham reservoir was injected with 100 μ Ci of pertechnetate in 0.05 ml saline, using a 25-gauge needle. The injection site was wiped gently with sterile gauze. A circular lead shield, 10 cm in diameter and 0.16 cm thick, with a 1-cm-diam circular hole in the center, was placed over the injection site, exposing only the injected Rickham reservoir to the external detector for counting. A 6-sec count was recorded every 15 sec for 6 min, and the patient was then placed under a gamma camera for imaging. The recorded counts were plotted against time and the $t_{1/2}$ for clearance determined. The actual flow rate in the patient's shunt is determined by interpolation from the reference

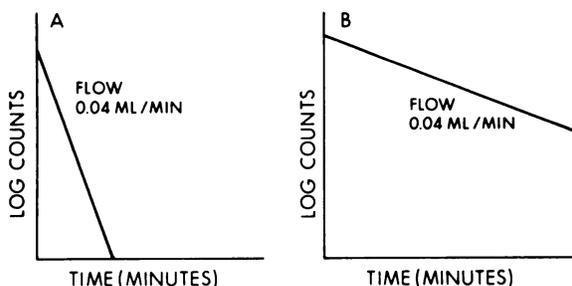


FIG. 2. Clearance curves for Rickham reservoir: A: without Holter valve attached to reservoir; B: with shielded Holter valve attached to reservoir. Indicated clearances differ markedly for same flow rate, emphasizing necessity of evaluating clearances in entire system that is identical to patient's.

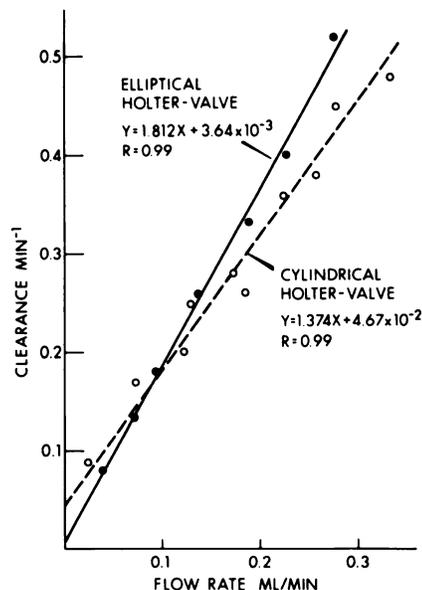


FIG. 3. Reference curves for shunt system with cylindrical and elliptical valves attached. Regression lines are drawn through experimental points.

curve for clearance plotted against flow rate, previously generated in vitro.

RESULTS

The rate of clearance of radioactivity from the injected chamber is affected by the presence of the other components of the system. The striking difference between the clearance curves for the Rickham reservoir with and without the shielded Holter valve is shown in Fig. 2. The accidental introduction of air into the system, or choice of the Holter valve as injection site, yields erratic clearance values for identical flow rates, whereas air-free reservoir injection yields highly reproducible clearance values. Figure 3 shows the reference curves generated in vitro for a standard Rickham reservoir attached to a cylindrical and an elliptical Holter valve. Each point on the reference curve is the mean of eight to ten clearance values, with a coefficient of variation of 5% to 8% over the range of flow rates calibrated.

The clinically determined in vivo flow rates derived from the reference curves, together with flow rates derived by Harbert's method (5), are given in Table 1. The latter values are obtained by multiplying the clinically determined clearance values by a constant factor of 0.06, which represents the experimentally derived volume for the Rickham reservoir. Figure 4 shows the clearance curve for an indwelling shunt in a patient who was evaluated after the shunt was tapped and flushed because of suspicion of intermittent shunt obstruction. The clinical presentation of headaches and lethargy resolved following flushing, and the patient was asymptomatic at the time of study. The scintiphoto was taken over the abdomen following the clearance study and shows the passage of activity from the Rickham reservoir into the distal end of the catheter. The clearance curve of an obstructed shunt, and the scintiphoto of the injected Rickham reservoir 30 min after injection of activity, are shown in Fig. 5. The scintiphoto shows slight reflux of activity into the ventricle, indicating a patent proximal end. Total obstruction of the distal end, with no flow of CSF, was confirmed at surgery. Figure 6 presents clearance curves for a shunt system evaluated in both supine and upright positions following a single injection. The striking change in $t_{1/2}$ between

TABLE 1. VENTRICULO-PERITONEAL SHUNT EVALUATION

Patient	Age (yr)	TCT evaluation	Clinical evaluation of shunt	Clearance (min ⁻¹)	CSF flow rate (ml/min)* present method	CSF flow rate (ml/min) Harbert's Method†
1	9	Moderate hydrocephalus	Distal end of shunt blocked‡	0.063	<0.02 (reflux)	0.0038
2	12	Moderately enlarged ventricles	Good function‡	0.141 0.462	0.06 (supine) 0.30 (upright)	0.0085 0.028
3	38	Normal sized ventricles	Ventricular end of catheter blocked‡	0.081	0.026	0.0049
4	5	Normal sized ventricles	Good function	0.33	0.20	0.020
5	6		Good function after tapping and flushing. Intermittent shunt obstruction.	0.99	>0.50 ml (after flushing)	0.059
6	35	Obliteration of third ventricle	Shunt intact, with possible decreased CSF production	0.067	<0.02	0.004
7	4		Difficult to tap	0.079	0.03	0.005
8	6		Good function	0.182 0.385	Reflux and variable flow into to distal catheter (0.10 to 0.25 ml/min) Technically poor study.	0.011 0.023
9	55		Good function—rhinorrhea	0.34	0.23	0.02

* Lower limit of detection 0.02 ml/min.

† Flow rates based on $F = 0.06 \lambda (5)$. The multiplication factor 0.06 is an experimentally derived volume for the Rickham reservoir.

‡ Surgical proof.

the supine and upright positions, and continued complaints of headache and stiffness, resulted in the surgical replacement of the medium-pressure valve with a low-pressure valve. While intra-abdominal pressures could possibly affect the flow through the

shunt, our technique measures the CSF flow rate through the shunt during the period of our examination.

DISCUSSION

The method of measuring CSF flow described here is a refinement of the method developed by Harbert et al. (5). The latter procedure has been modified to correct a serious source of error arising from the assumption that the clearance characteristic of the Rickham reservoir is the same with and without the Rickham-Holter valve assembly. In our detailed evaluation of the Rickham-Holter shunt system, striking differences in clearance characteristic of the Rickham reservoir were observed depending on whether the shielded Holter valve was attached or not. This difference in clearance can be appreciated easily in a study with a typical flow rate of 0.04 ml/min. The $t_{1/2}$ of the Rickham reservoir alone was 1.7 min, contrasting with a $t_{1/2}$ of 8.7 min when it was connected to a totally shielded Holter valve. The shunt system for extracranial diversion of CSF generally consists of a proximal and a distal catheter and a reservoir connected to a one-way valve. Several variations of this system are used, as determined by the neurosurgeon at the time of operation. The system may have only the reservoir with or without a one-way valve, or the distal catheter may be fitted with a valve. The clearance of radioactivity from the reservoir with a finite volume was found to vary greatly, depending on the presence of the various components in the system, even though the injected chamber was viewed exclusively.

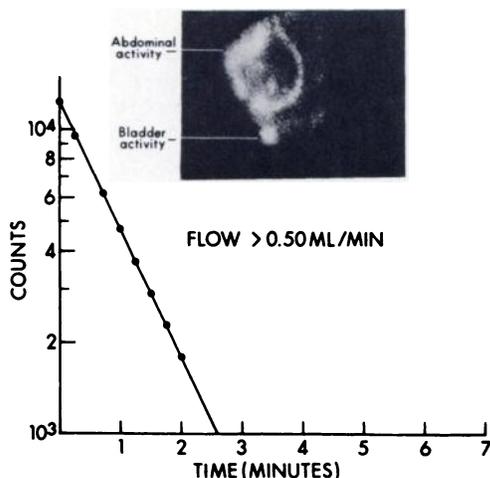


FIG. 4. Clearance curve for satisfactorily working shunt. Insert is scintiphoto of abdomen, showing collection of activity in distal end of catheter at 10 min after injection of tracer into Rickham reservoir. No activity was detected at site of injection, indicating rapid clearance from reservoir.

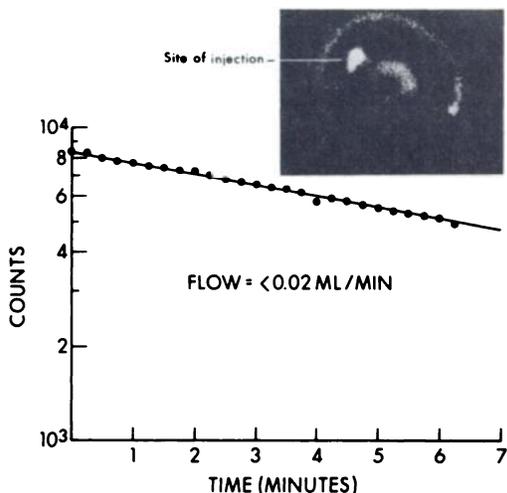


FIG. 5. Clearance curve for obstructed shunt, showing delayed clearance of activity. Scintiphoto (insert) of head at 30 min shows injected activity within Rickham reservoir, with some reflux of activity into ventricle. No activity was observed in upper chest or abdominal region.

The volumes of the valve and reservoir combination, as derived from the regression equation of the calibration curves, are 1/1.374 and 1/1.812, respectively, for the cylindrical Holter-Rickham and the elliptical Holter-Rickham combination. The true measured volumes for the individual reservoir (0.14 ml) and valve (0.26 ml) do not add up to the calculated volume obtained from the exponential equation for the cylindrical valve and reservoir combination (0.72 ml). This points out the likelihood of eddy currents or recirculation within the system. The hydrodynamics of the fluid through the valve and reservoir system are highly complex and one can only simplify the system by arriving at an effective volume as determined for different experimental flow rates.

The relationship $F = \lambda V$ predicts that the introduction of air into the injection chamber should decrease the volume of the mixing chamber and therefore exaggerate the clearance. This was not found to be the case. In actual measurements, the introduction of air produced erratic clearance curves ranging from greatly decreased clearance to total blockade of the flow, depending on the location of the air bubble and the extent to which it impeded the flow at the exit. These observations once again point out the inadequacy of using static volumes for the dynamic process encountered in the flow system.

Reflux into the ventricles occurred in two cases. In one patient the distal end was blocked and the reservoir had been pressed hard after the injection of the tracer. In the second case, the patient had a bulging fontanelle with exaggerated pulsation, and the clearance curve was unreliable and reported as such. We found that in the presence of a positive flow through the shunt valve, excess injected volume flows out of the distal catheter and does not affect the clearance curve. A similar finding has been reported by Harbert (5). We could reproduce the clearance values reported by Harbert et al. (5) for a Rickham reservoir in vitro when it was not connected to the Holter valve, which is rarely the case in a patient. In vivo flow rates computed for the same clearance using our method and Harbert's are shown in Table 1. The lower computed flow rate is a result of the influence of the valve on the clearance of the injected chamber. Other parameters that have been shown to distort the clearance values are the site of injection, contamination of the overlying tissues with radioactivity at the injection site, and the introduction of an air bubble into the system.

The advantage of the method described here is its accuracy, based on extensive bench work to calibrate a shunt system that is

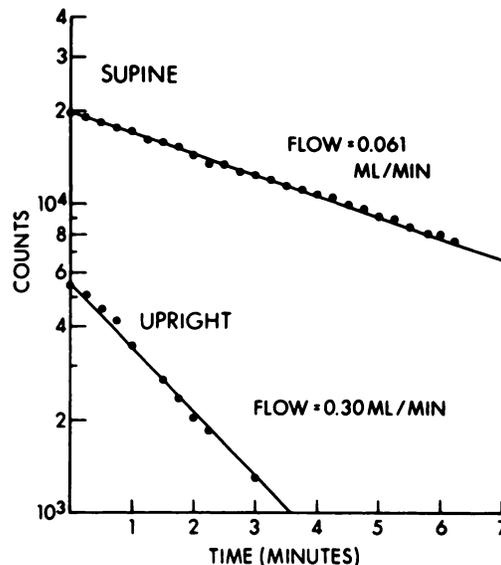


FIG. 6. Clearance curves from patient shunt, studied with single injection in upright and supine positions. In upright position $t_{1/2} = 1.5$ min, compared with 4.9 min in supine position, indicating postural effect on rate of flow. After this study medium-pressure valve was replaced by low-pressure valve.

identical to the system in the patient. The clinical evaluation of the shunt patency itself can be done in a few minutes, and the reliability of the values makes this method valid for comparison of serially determined values. The single disadvantage is the extensive work involved in calibrating an identical shunt system and the generation of a calibration curve to be used in determining the in vivo flow rates. Fortunately, the neurosurgeons at any particular institution usually limit themselves to the use of one or two types of shunt systems, making it possible for only one or two calibration curves to suffice.

The method described above is simple and yields accurate information about CSF shunt flow in a noninvasive manner. Relatively minor problems are involved in obtaining the reference curve that is necessary for arriving at the CSF flow rates in patients. The reference curves reproduced here could be used at any other center as long as the patient to be studied has an identical indwelling shunt.

The amount of activity injected into the reservoir is very small ($\sim 100 \mu\text{Ci}$) and the radiation dose is minimal. The technique has been in routine use at our center for evaluation of patients in whom CSF diversionary shunt systems have been placed, and is well accepted by the neurosurgery department.

FOOTNOTE

* Various models used depending on requirements. Obtained from Codman and Shurtleff Comp., Randolph, MA.

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