

Hydrocephalus. A Practical Guide to CSF Dynamics and Ventriculoperitoneal Shunts

Hydrocephalus is defined and the mechanisms of CSF hydrodynamics discussed. Supplementary tests used in the investigation of idiopathic normal pressure hydrocephalus are reviewed with a detailed explanation of constant flow CSF infusion tests. The principles governing valve selection are illustrated.

Hydrocephalus is the abnormal accumulation of CSF within the cranium due to defective CSF production, flow or absorption. The CSF usually accumulates within the ventricular system, however 'external hydrocephalus' with widening of the subarachnoid spaces is described. Hydrocephalus can be due to **obstructive** causes preventing normal CSF flow through the CSF pathways, or due to abnormal absorption of CSF: **communicating** hydrocephalus. CSF flow studies frequently show a complex picture with contributions from both mechanisms. Overproduction of CSF that exceeds the absorption capacity of the arachnoid granulations is rare.

CSF physiology

CSF is mainly produced by passive ultrafiltration of plasma with some active electrolyte transport from the ventricular choroid plexus. The rate of CSF production is around 20ml/hour, although MRI evidence suggests that this may increase significantly during sleep. To maintain equilibrium, CSF is normally absorbed into the major venous sinuses by a passive mechanism through the one-way valves of the arachnoid villi. The normal CSF pressure at the reference level (the foramen of Monro) in the recumbent adult is 100-200mm H₂O (7-15mmHg) with mean pressures of 20mmHg regarded as elevated. Pressures from 0-7mmHg do not usually signify any pathology. The CSF pressure fluctuates with the arterial pulse wave and respiratory excursions.

Symptomatic patients with obstructive hydrocephalus continue producing CSF. CT and MRI scans identify the site of obstruction. The definitive treatment for most of these patients is removal of the obstructive cause. If CSF diversion is required and the outlet of the IIIrd or IVth ventricle obstructed, a IIIrd ventriculostomy is usually the first choice treatment, particularly in newly diagnosed patients with aqueduct stenosis.

Communicating hydrocephalus occurs when the laterals, IIIrd and IVth ventricles appear to communicate freely. The absorption capacity of the arachnoid villi is exceeded or obstruction of CSF flow occurs within the subarachnoid space. This condition is usually managed with a ventriculoperitoneal shunt system and provides the focus for this paper.

Normal pressure hydrocephalus

In the pre-CT scan era Adams et al. reported three cases of ventriculomegaly associated with gait disturbance, dementia and incontinence.¹ All three patients had normal CSF pressure (140-50, 160 and 175mmH₂O) on lumbar puncture but improved with either a ventriculo-atrial shunt (two cases) or a Torkildsen (lateral ventricle to cisterna magna) diversion (one case). Two cases were idiopathic and one due to a cyst in the IIIrd ventricle. The condition is now classified as (i) Primary or **Idiopathic Normal Pressure Hydrocephalus (INPH)** and (ii) **Secondary Normal Pressure Hydrocephalus**. In the latter group of patients a well-established cause is evident (eg. subarachnoid haemorrhage, traumatic brain injury, meningitis). Whilst the primary pathology may increase the certainty of diagnosing hydrocephalus, the results of

treatment may be confounded by the original brain insult.

Even in the presence of a classic triad of symptoms the response to treatment is often disappointing. Indeed Black reported that 67.2% of patients with gait, cognitive and urinary symptoms and signs improved with a shunt.² The outcome was significantly worse in patients with only dementia and gait disturbance (31.6% improved). Overall, 35.4% of the 62 patients studied suffered complications, including subdural haematomas and fits. The challenge therefore lies in increasing diagnostic accuracy and timely management at a point when symptoms and signs are retrievable.

Clinical feature of INPH

The Symptomatic Triad

The **gait** disturbance in INPH includes at least two of the following features: wide based stance, out-turned feet, decreased step height, decreased step length, decreased speed, increased trunk sway, *en bloc* turning requiring three or more steps for 180°, and poor heel-toe walking. **Cognitive features** are wide-ranging and include attention deficits, psychomotor retardation, impaired recall and memory deficits, executive dysfunction, behavioural and personality changes. Such features can be quantified using a summative mental state examination. **Urinary dysfunction** is characterised by nocturia, urgency, frequency or incontinence reflecting a low capacity neurogenic bladder.

Evidence-based clinical diagnostic criteria for the diagnosis of INPH have only recently been developed. A consensus panel recommends that INPH candidates be categorised into 'probable' and 'possible' groups based upon history, examination, brain imaging and CSF opening pressure.³

Probable INPH

This requires a gait disturbance and either cognitive and/or urinary disturbances in a patient over 40 years old. In addition the history, imaging and lumbar puncture opening pressures must be consistent with the diagnosis. The imaging findings are characterised by ventriculomegaly not due to atrophy or obstructive hydrocephalus, associated with one or more of the following: temporal horn enlargement, a callosal angle of 40° or more (due to bowing of the corpus callosum), periventricular lucency not due to ischaemia and a flow void in the aqueduct or IVth ventricle. The accepted range of CSF opening pressure for probable INPH is 70-245mmH₂O (5-18mmHg).

Possible INPH

This group may have a more acute history in a younger patient with only one of the triad of symptoms and an opening CSF pressure outside the guidelines above. The imaging findings may appear to be consistent with atrophy.

Imaging

CT and MRI scans provide useful information that helps support a diagnosis of normal pressure hydrocephalus. Ventriculomegaly is an essential finding (Evans ratio >0.3; Widest inter-frontal horn distance / Internal skull distance at level of frontal horn). Other findings such as large temporal horns and sulcal obliteration are inconsistent. Although periventricular and deep white matter lesions



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are commonly observed in T2-weighted MRI they are also associated with hypertension and cerebrovascular disease and are therefore not pathognomic of hydrocephalus.⁴ Post-shunting MRI scans do show an improvement in the frontal horn periventricular changes but such pre-operative features are not required to predict a good outcome.⁵ Calculation of the 'stroke volume' of CSF moving in a craniocaudal direction during systole using phase contrast CSF velocity MR imaging has shown that a volume greater than 42µL correlated with a favourable response to shunting.⁶ This is characterised by a signal flow void. PET cerebral blood flow (CBF) studies have shown that pre and post-shunt assessments of haemodynamic reserve using a carbonic anhydrase inhibitor to stimulate increased PaCO₂ indicate that shunt responders show an improvement in their cerebrovascular reserve compared with non-responders.⁷ This suggests that altered CBF dynamics are important in the pathogenesis of INPH and in determining the success of treatment. Unfortunately specific thresholds for low CBF have not been identified as pre-operative predictors of treatment success.

Due to the diagnostic conundrum and the difficulties in determining shunt responsive cases several other tests have been developed to aid management. These include intracranial pressure monitoring, CSF infusion tests, the tap test and a period of CSF drainage. The main drawback of these tests is the low sensitivity and poor predictive value of some tests (see Table 1). The additional tests that are often used are detailed below.

Table 1: Predictive value of additional tests in the assessment of idiopathic normal pressure hydrocephalus (data derived from Marmarou et al¹⁰).

Test	Sensitivity	Specificity	PPV	NPV	Positive likelihood ratio
Tap	26-62%	33-100%	73-100%	23-42%	0.93 - infinity
CSF Drainage	50-100%	60-100%	80-100%	36-100%	2.5 - infinity
Calculation of R _{csf}	44-92%	46-100%	75-92%	27-92%	0.88 - 12.5

ICP monitoring

Patients with INPH frequently have normal ICP. However, 24 hour monitoring may reveal several abnormalities that indicate poor cerebral compliance (Figure 1). An ICP recording shows systolic and diastolic pulsations. Plateau (A) waves with elevations exceeding 50mmHg for periods of 5-20 min are not normally seen in patients with idiopathic hydrocephalus. However, careful analysis of the ICP trace – using computer software with threshold filters – reveals low amplitude (commonly 1-

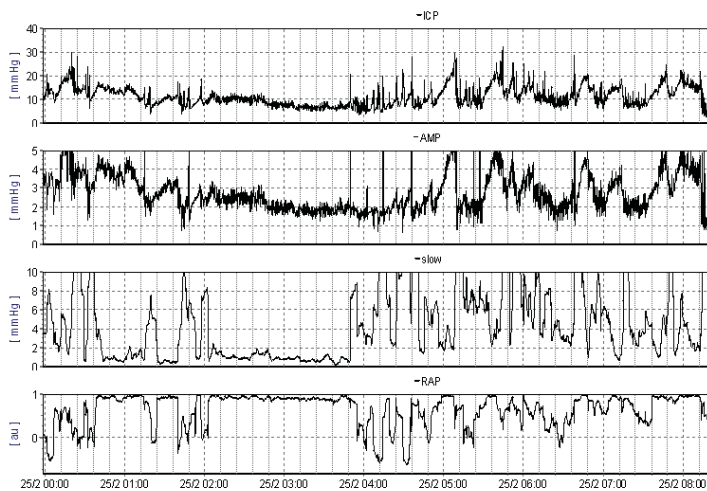


Figure 1: Overnight ICP monitoring in a normal pressure hydrocephalus patient who responded to subsequent VP shunt insertion. Graphs show ICP; Amplitude; Slow B waves and RAP coefficient. The baseline pressure was normal (8-10mmHg) with many vasogenic waves exceeding 20mmHg. The pulse amplitude of the ICP waveform was elevated, especially during the vasogenic waves. The averaged amplitude of the slow B waves was above 5mmHg and the derived RAP coefficient was above 0.7 most of the time, signifying poor compensatory reserve.

5mmHg) superimposed B waves with a period of 30 seconds to 2 minutes.⁸ The prevalence of B waves appears to increase during normal REM sleep and with rises in intracranial pressure. A recent detailed analysis in patients with communicating and non-communicating hydrocephalus indicates that B waves are commonly observed but have a poor correlation to clinical outcome.⁹

Tap test

Many authors have reported the withdrawal of 40-50ml of CSF as a useful test, with responders benefiting from shunt insertion. However the test has a low sensitivity (26-62%) and should not be used to rule out a diagnosis of idiopathic normal pressure hydrocephalus.¹⁰

External Lumbar CSF Drainage

This test developed from the concept that a trial of controlled CSF removal (10ml/hr) for 72 hours might predict shunt responders. The sensitivity of

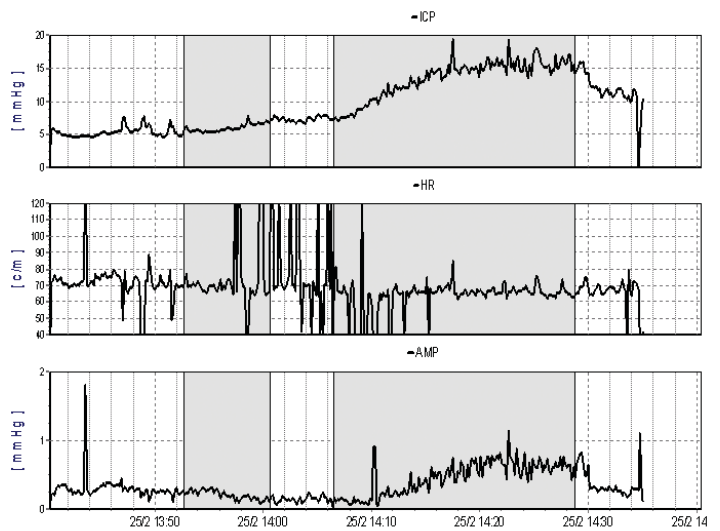


Figure 2A: CSF infusion study performed via a ventricular access device – normal result showing ICP, heart rate and ICP pulse amplitude; infusion rate 1.5ml/min. The opening pressure (5mmHg) and amplitude were normal. During infusion the ICP increased to a plateau of 15mmHg, enabling calculation of resistance to CSF outflow (7mmHg/ml/min). The low pulse amplitude and absence of vasogenic waves are characteristic of a normal study. Measurement of the heart rate from the pulse amplitude enables the technical quality of the recording to be assessed.

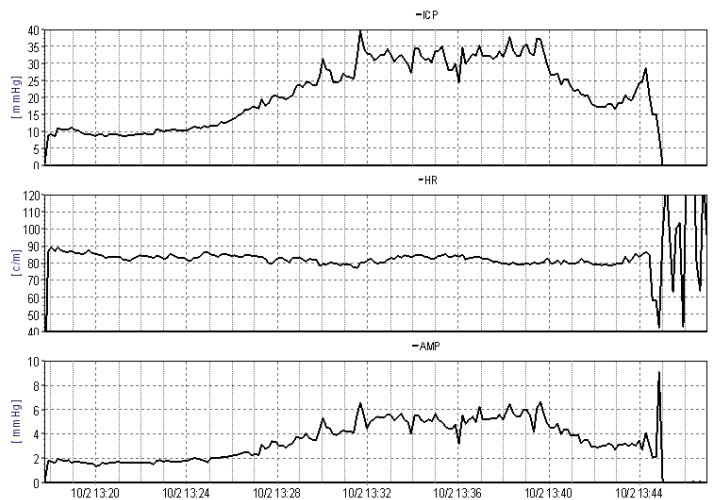


Figure 2B: CSF infusion study performed via a ventricular access device – patient with probable idiopathic normal pressure hydrocephalus, infusion rate 1.5ml/min. The opening pressure is normal (10mmHg) but CSF infusion produces a plateau around 34mmHg enabling the R_{csf} to be calculated (16mmHg/ml/min). This level is just below the 18mmHg/ml/min threshold described by Boon et al.¹² Strong vasogenic waves are also evident at pressures above 25mmHg with an increase in the pulse amplitude. The derived Pressure Volume Index (PVI) was elevated (9.1ml) reflecting poor compensatory reserve.

the test has been reported as 50-100% with a specificity of 60-80% and a positive predictive value of 80-100%.¹⁰

CSF infusion test

The resistance to CSF absorption by the arachnoid villi can be measured and helps predict shunt responsive patients.

The test is commonly performed in the left lateral position using a constant infusion technique. Lumbar puncture needles are inserted at 2 levels; the use of a solitary needle with a three-way tap is not as reliable. A pressure transducer is connected to one needle and the baseline opening pressure recorded. Normal saline is infused at 1.5ml/min through the second needle whilst the pressure is continuously measured. In most patients the pressure rises steadily and then reaches a plateau. The resistance (R_{csf}) to CSF absorption can be calculated using an Ohm's Law analogy:

$$R_{csf} = \frac{\text{Plateau pressure (mmHg)} - \text{Baseline pressure (mmHg)}}{\text{Infusion rate (ml/min)}}$$

The R_{csf} in normal subjects ranges from 6 to 10mmHg/ml/min. It increases in the elderly. In such cases the rate of CSF production probably decreases to prevent hydrocephalus ensuing.¹¹

By using an infusion rate of 1.5ml/min a 30-mmHg increase in CSF pressure provides evidence of the R_{csf} exceeding 20mmHg/ml/min. The use of higher infusion rates (eg. 3ml/min) imposes limitations in that the pressure needs to rise by 60mmHg to confirm an R_{csf} of 20mmHg/ml/min. We recommend aborting the test if CSF pressure exceeds 50mmHg. In this case a minimum value for the R_{csf} can still be calculated using the (peak pressure – baseline pressure) as the numerator in the equation. Boon et al. have reported that in patients with probable NPH (mainly idiopathic but also including some secondary cases) a positive response to shunting was likely if R_{csf} exceeded 18mmHg/ml/min with a PPV of 92% and a likelihood ratio of 3.5 in their series of 95 patients. However, the sensitivity of the test at this threshold was only 46% although the specificity was high at 87%.¹²

Performing the infusion test via a frontal ventricular access device appears to minimise the effect of CSF leakage around lumbar needles and may increase the predictive value of the investigation (Figures 2A and 2B). With sophisticated computer analysis (see www.neurosurg.cam.ac.uk/icmplus) of the pressure waveform further information about the elastance and compliance of the craniospinal axis, including the Pressure Volume Index (PVI), can be derived both in lumbar and ventricular CSF infusion studies. This may assist the decision making process in borderline cases.

Choosing a CSF shunt

Most neurosurgeons advocate a ventriculo-peritoneal shunt (VP shunt) as the preferred system for implantation. In some circumstances (eg. inadequate absorption in a patient with multiple previous abdominal operations) alternative sites are required (eg. ventriculo-pleural, ventriculo-atrial). VP shunt insertion is associated with numerous potential complications. These include:

- Peri-operative intracranial bleeding
- Infection
- Shunt blockage
 - Proximal catheter
 - Valve
 - Distal
- Shunt component disconnection or migration
- CSF over-drainage
 - Low pressure headaches
 - Intracranial haematomas (usually subdural)
- CSF under-drainage

Attention to detail during the placement of a VP shunt is crucial to minimise the risks of shunt insertion. Meticulous sterility, accurate catheter placement and secure connections between shunt components are essential. Consideration needs to be applied to the choice of shunt hardware. The ventricular catheter most widely used is a straight non-flanged device with multiple apertures in proximity to the catheter tip. There is no consensus over the best anatomical site for catheter placement. The distal catheter provides a conduit to drain CSF to the peritoneal cavity. Distal slit valves are unnecessary and may increase the risk of distal obstruction provided a valve is utilised proximally. Antimicrobial impregnated ventricular and peritoneal catheters have been developed in an attempt to reduce shunt infection rates.

Valves

Valve systems with different hydrodynamic properties have been developed to try and minimise complications such as over-drainage with low-pressure postural headaches and subdural fluid collections. The properties of valves have been independently evaluated *in vivo*.¹³ Valves are designed to be (1) flow regulated or (2) differential pressure regulated (Figure 3). The Orbis Sigma Valve is the archetypal flow controlled device. CSF flows through a diaphragmatic aperture whose diameter decreases as the flow rate rises above 20ml/hr. This **increases** the resistance of the valve, regulating flow. A safety mechanism leading to a reduction of resistance at differential pressures of 25-30mmHg is incorporated to avoid acute severe elevations in intracranial pressure.

Most valves are differential pressure regulated. These devices are

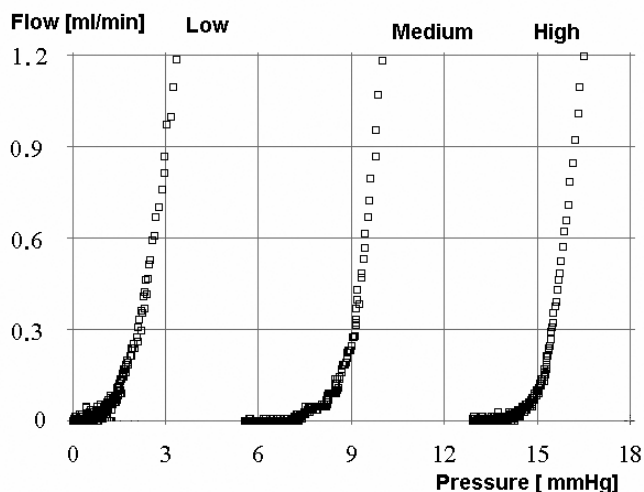


Figure 3A: Flow-pressure curves for a differential pressure-regulating valve. The pressure regulating mechanisms try to maintain the same differential pressure across the valve regardless of the flow rate. In practice most manufacturers market high, medium and low-pressure valves each with different pressure flow characteristics.

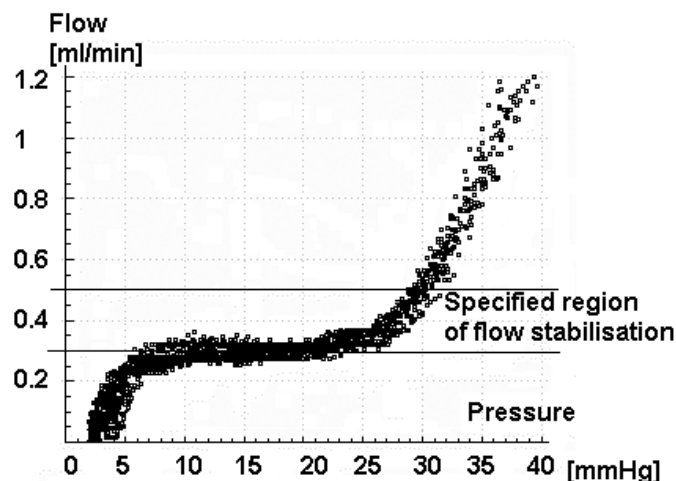


Figure 3B: Flow-pressure curve for a flow regulated valve. The flow regulator attempts to change its resistance in response to the differential pressure thereby maintaining flow at a constant level. The Orbis Sigma Valve has a variable resistance that increases in the mid-range acting as a flow control mechanism.

designed to open if the pressure differential across the valve exceeds a set value. However, as the pressure across the valve increases the resistance **decreases** allowing as much CSF to flow as is required to reduce the ICP near to the opening pressure. Postural over-drainage symptoms are common and may be averted to some extent using anti-siphon devices to minimise flow in the erect posture. Pressure-regulated valves that can be reset using transcatheter programming devices to higher or lower pressure differentials according to clinical need are now implanted as a matter of routine.¹⁴ Clinical studies, including data from the UK Shunt Registry, do not show significant differences in the shunt revision rate between different valve systems, although the management of complications such as subdural haematomas or hygromas is more readily managed using adjustable valves.

Outcome

The primary pathological process (eg. subarachnoid haemorrhage, head injury) is an important determinant of outcome for patients with secondary hydrocephalus. In patients with idiopathic NPH, comparisons between studies are confounded by the range of symptoms exhibited in this elderly group of patients with significant co-morbidity. Certainly a widely used validated outcome assessment tool would help compare outcomes between studies. In addition, the diagnostic difficulties and variable treatment thresholds between centres influence outcome. The duration of follow-up is also important, with a reported decrease in clinical improvement at five years compared with one year. Improvements in gait decreased from 76% to 47%, improvements in memory disturbances decreased from 48% to 38%, and improvements in urinary symptoms reduced from 58% to 29%.¹⁵

Summary

Simple hydrodynamic physics can be used to help the clinician understand CSF physiology and valve mechanics. Despite advances in neurodiagnostic techniques the diagnosis and management of patients with probable INPH requires sound clinical judgement. In clinical practice we use clinical, radiological, ICP and CSF infusion tests to help select patients for shunt insertion. A standardised easily applied mini-battery assessment tool would be useful to provide an objective measure of treatment effect.

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Box 1

Diagnostic testing

The data of Boon et al¹² are used to demonstrate the concepts around the efficacy of a diagnostic test. For any test a simple table can be constructed.

Rcsf >18mmHg/ml/min	Shunt responsive (SR) hydrocephalus	Non-shunt responsive hydrocephalus	Totals		
Test Positive	33	a	3	b	36
Test Negative	39	c	20	d	59
Totals	72	23			95

From this data several parameters can be calculated:

$$\text{Sensitivity} = a/(a+c) = 33/72 = 46\%$$

$$\text{Specificity} = d/(b+d) = 20/23 = 87\%$$

$$\text{Likelihood ratio for positive result} = \text{sensitivity}/(1-\text{specificity}) = 46/(1-0.87) = 3.5$$

$$\text{Positive predictive value} = a/(a+b) = 33/36 = 92\%$$

$$\text{Negative predictive value} = d/(c+d) = 20/59 = 34\%$$

$$\text{Prevalence of SR hydrocephalus} = (a+c)/(a+b+c+d) = 72/95 = 76\%$$

$$\text{Pre-test odds of having SR hydrocephalus} = \text{Prevalence}/(1-\text{prevalence}) = 0.76/(1-0.76) = 3.2$$

$$\text{Post test odds of having SR hydrocephalus} = \text{Pre-test odds} \times$$

$$\text{Likelihood ratio} = 3.2 \times 3.5 = 11.2$$

$$\text{Post-test probability of having SR hydrocephalus} = \text{Post test odds}/(\text{Post test odds} + 1) = 11.2/12.2 = 92\%$$

If the Rcsf test had a very high sensitivity a negative result effectively rules out the diagnosis of shunt responsive (SR) hydrocephalus. This is not the case. The Rcsf test does have a high specificity. A positive result therefore makes the diagnosis of SR hydrocephalus very likely. Tests that produce big changes from the pre-test to post-test probabilities are likely to be clinically useful. The likelihood ratio of 3.5 is in the mid-range, but given that most patients investigated turned out to have SR hydrocephalus (high prevalence) the probability of having the target disorder was high if the Rcsf exceeded 18mmHg/ml/min. If a second independent test is performed with a different likelihood ratio, eg. B wave analysis of ICP recordings at 1mmHg threshold⁹ (Likelihood ratio = Sens/(1-Spec) = 0.78/(1 - 0.6) = 1.95), this can be used to adjust the post-test probability of having SR hydrocephalus:

$$\text{Post test odds of having SR hydrocephalus} = 3.2 \times 3.5 \times 1.95 = 21.8$$

$$\text{Post test probability of having SR hydrocephalus} = 21.8/22.8 = 96\%$$

Therefore a combination of investigations can prove useful at helping to determine whether or not shunt insertion likely to be beneficial. Using Boon's data at the 12mmHg/ml/min threshold, the likelihood ratio reduced to 1.4 and the post-test probability to 82%. Whilst this seems quite high it is only just better than clinical acumen alone (76% of patients with clinical features had SR hydrocephalus in this series).