Ventriculoperitoneal cerebrospinal fluid (VP CSF) shunts are the standard treatment for patients with hydrocephalus. Recently, a new CSF shunt system based on older principles, placing the distal catheter in the transverse sinus instead of the abdominal cavity, was reported. The advantage of this new CSF shunt system is mainly prevention of complications related to over drainage associated with VP shunts, by avoiding the distal hydrostatic component in the upright position. The flow profile of the Sinushunt® is characterised by a linear correlation between the pressure difference between the ventricle and sinus and the resulting CSF flow. The Sinushunt is marketed in Europe and is a realistic alternative for the neurosurgeon. However, only case series have been published thus far, and there are no randomised trials comparing this new technique with the traditional VP shunt. In one shunt there was reflux, and in another two shunts there was a very small, but similar, pressure calibration between every cycle. On five cycles the shunt was set to 0 and on five cycles to 6.5 mm Hg. One of the 50 experimental apparatus without shunt and shunt tubing was measured to be Rsinus = 2.6 (0.1) mm Hg/ml/min (n = 12).

**METHODS**

**Shunts**

Sinushunts supplied by the manufacturer were tested (fig 1). The shunts were tested with their distal catheter. To confirm reproducibility five shunts were tested.

**The in vitro test**

The in vitro experimental set up has previously been described. In summary, a computerised system collects data and regulates the pressure. Flow is calculated from the pressure drop over a glass constriction with known resistance. The pressure drop over the hydrocephalus shunt are measured with differential pressure transducers (LPM8000, Druck, Leicester, UK).

The shunt was mounted on a support and submerged into 100 mm of water corresponding to a subcutaneous scalp tissue pressure of 7.4 mm Hg. A study on rats determined the tissue pressure around an implanted shunt to be 64 mm H2O. Suspecting that it can be slightly higher in humans, we chose 100 mm H2O. Outflow from the shunt is led into an overflow container with a constant water level at the zero pressure level, or at 6.5 mm Hg level when testing with a distal pressure component corresponding to a normal sinus pressure, Psinus. The experimental apparatus was built into an incubator at 37°C.

The proximal pressure, corresponding to intracranial pressure (ICP) was in cycles increased from 0 to 18.5 mm Hg (shunt 1) or from 0 to 22.1 mm Hg (shunt 2–5) and back to 0 again over a time period of 1 hour (fig 2). The test cycles were automatically repeated 10 times on each shunt with a pressure calibration between every cycle. On five cycles Psinus was set to 0 and on five cycles to 6.5 mm Hg. One of the 50 measurements was omitted owing to suspected air bubbles in the shunt system.

Calculation of resistance, Rsinus and opening pressure, Popen, is shown in fig 2. The resistance of the tubing in the experimental apparatus without shunt and shunt tubing was measured to be Rsinus = 2.6 (0.1) mm Hg/ml/min (n = 12).

**Abbreviations:** CSF, cerebrospinal fluid; ICP, intracranial pressure; VP, ventriculoperitoneal
RESULTS

$P_{\text{open}}$ was highly dependent on the sinus pressure, $P_{\text{open}} = 1.3 (0.6)$ mm Hg (mean (SD), $n = 25$) with $P_{\text{sinus}} = 0.0$ mm Hg, and $P_{\text{open}} = 7.5 (0.6)$ mm Hg (mean (SD), $n = 24$) for $P_{\text{sinus}} = 6.5$ mm Hg.

There was a small, but significant, difference in $R_{\text{shunt}}$ with respect to the two levels of sinus pressure (10.5 mm Hg/ml/min versus 10.6 mm Hg/ml/min) (one way analysis of variance: $p = 0.046$, $n = 49$). However, the difference had no clinical significance and the subsequent analysis was therefore based on all measurements together. Resistance for the five shunts with tubing was $R_{\text{shunt}} = 10.5 (0.3)$ mm Hg/ml/min (mean (SD), $n = 49$). This leads to a shunt resistance of 7.9 (0.3) mm Hg/ml/min after subtraction of the tubing resistance related to the experimental apparatus. There were significant (one way analysis of variance: $p < 0.01$, $n = 49$) differences in resistance between shunts. However, the maximum differences between $R_{\text{shunt}}$ mean values were $<0.6$ mm Hg/ml/min (fig 3).

Test with $P_{\text{sinus}} = 6.5$ mm Hg revealed a clear backflow through one of the shunts for an ICP interval of approximately 4.0–6.5 mm Hg (fig 4). This interval corresponds to a negative pressure interval of 0.0–2.5 mm Hg over the shunt.

DISCUSSION

The Sinushunts tested in this study produced very stable and reproducible results. Resistance was within specification and in the middle of the interval for normal values. $P_{\text{open}}$ was directly dependent on the distal pressure—that is, the $P_{\text{sinus}}$. Our results show a minor difference between $P_{\text{sinus}}$ and $P_{\text{open}}$. This is explained by the method of linear extrapolation that we use for defining $P_{\text{open}}$. On pressures where the flow is close to 0, there was an intermediate phase where the pressure and flow curve was not linear (fig 2). A positive flow through the shunt was typically shown as soon as ICP > $P_{\text{sinus}}$ (fig 4).

Influence on CSF dynamics

In contrast to traditional VP shunts, the Sinushunt uses no valve mechanism to regulate the opening pressure for control of the ICP. Flow through the shunt started when the differential pressure over the shunt was positive—that is, when the ICP exceeded the sinus pressure. The resistance of the Sinushunt was of the same magnitude as the resistance of normal pathways of a human. The resistance of the sinus shunt was approximately three times higher than that of a Delta shunt. The Sinushunt works in parallel with arachnoid villi and reduces the ICP by reducing total resistance. It is described by the Dawson equation:

$$ICP = P_{\text{sinus}} + R_{\text{out}} q_f$$

Where $q_f$ is the CSF formation rate. For a shunted patient, the post-operative $R_{\text{out}} = R_{\text{postop}}$ and can be estimated from shunt
resistance, $R_{\text{postop}}$, and normal pathways resistance, described by the pre-operative resistance, $R_{\text{preop}}$, as:

$$\frac{1}{R_{\text{postop}}} = \frac{1}{R_{\text{preop}}} + \frac{1}{R_{\text{shunt}}}$$

Thus, as shown in fig 5, the expected post-operative resistance will depend on both the pre-operative resistance and the resistance of the Sinushunt. Expected post-operative ICP can be estimated according to that post-operative resistance and the Dawson equation.

In contrast to a regular differential pressure VP shunt, the function of the Sinushunt is thus to reduce ICP by a moderate reduction of the total resistance to outflow. Pre- and post-operative measurement of resistance with an infusion technique is regularly performed in hydrocephalus patients and with this technique it would be possible to confirm the in vitro results presented in this study.

The main advantages of the Sinushunt compared with more conventional shunts are that the siphoning problem caused by the distal hydrostatic component in the upright position is avoided by shunting into the sinuses, and that the more physiological sinus pressure, rather than the abdominal pressure, is used as distal reference.

**Pathophysiology**

If the pathophysiology of hydrocephalus is solely due to an increased resistance to outflow and a subsequent increased ICP, the Sinushunt has the potential to work well. In this case, the shunt would normalise the hydrodynamics of the patient. For high pressure hydrocephalic patients with a high $R_{\text{preop}}$ this definition fits reasonable well and they may be good candidates for the Sinushunt. We therefore suggest that an infusion test where both $R_{\text{preop}}$ and pre-operative ICP are determined should be performed before choosing the Sinushunt. Janny et al. have shown that high ICP can be a consequence of high $P_{\text{sinus}}$; for those patients, shunting with a Sinushunt would not be effective for reducing ICP. Preferably, the pre-operative $P_{\text{sinus}}$ should also be measured, but as this is not a simple procedure it is not likely to be used as a standard pre-operative investigation.

For normal pressure hydrocephalus patients, the hydrodynamic pathophysiology is not as clear. Even if studies indicate that an elevated outflow resistance is a predictor for positive outcome of shunt surgery, it has also been shown that patients with a normal outflow resistance and normal or slightly raised ICP will benefit from shunting. Furthermore, it has been shown that in cases of unchanged ICP after shunting, patients have clinical improvement. Most of the current shunts have a resistance to outflow that is lower than normal physiological values (fig 5), which may indicate that the function of the standard shunts today is not to normalise the hydrodynamics. As the optimal post-operative range of resistance in hydrocephalus patients is unknown, it is impossible to postulate if one should aim at low (traditional differential pressure VP shunt) or normal (Sinushunt) post-operative resistance. For instance, a patient operated on with a Sinushunt may improve post-operatively, but we do still not know if the patient would show even more improvement with a VP shunt system (or vice versa). In a previous study with another ventricle to sinus shunt, only one patient of four (with low or normal pressure hydrocephalus) improved and it was concluded that its use in normal and low pressure hydrocephalus must still be evaluated. Randomised studies are urgently needed to clarify this intricate topic.

**Reflux**

In one of the five shunts, there was reflux, a flow of fluid toward the inflow catheter, within a physiological range of differential pressures between the ventricle and the sinus (fig 4). In another two shunts, there was a similar tendency to reflux, however probably without clinical significance. In the worst case scenario, reflux could cause blood to flow from the venous sinus through the shunt and into the CSF of the ventricles. A more likely scenario is that refluxed blood clogs the titanium tube in the shunt and obstructs the CSF outflow. Our sample of five shunts was too small to make any statement about the likelihood of occurrence of reflux in other samples of the Sinushunt.

When testing the shunts with high negative pressures over the shunt—that is, $P_{\text{sinus}} > P_{\text{ICP}}$, all valves closed and there was no backflow. The problem with a high pressure test is that the unidirectional valves use the negative pressure as a driving force to close. The valves therefore get more effective the higher the negative pressure. We found this dysfunction by continuous variation of ICP during a constant small distal pressure. The ISO 7197 standard for shunts prescribes a reflux test with static distal pressures of 10, 50, and 500 mm H$_2$O (0.8, 3.8, and 38 mm Hg) and a maximum allowed reflux of 0.02 ml/min. The first pressure level should have detected an non-permitted reflux in the dysfunctioning valve, while the other four shunts would have passed the ISO reflux test. However, for improved testing we suggest that the manufacturers use continuous pressure variation test, similar to the one used in this study.

**CONCLUSIONS**

This study confirms that shunt resistance was comparable to the physiological values previously given by Ekstedt. There was minimal variability in the resistance. A weakness of the anti-reflux system of the Sinushunt must be suspected and further investigations are needed. As VP shunts are still the golden standard, and as the pathophysiology of hydrocephalus is not unequivocal, and the optimal post-operative resistance for different hydrocephalus types is unknown, clinical trials comparing traditional shunt systems with the Sinushunt are needed.

**ACKNOWLEDGEMENTS**

The authors wish to thank M Lundmark for her skilful technical assistance.

**Authors’ affiliations**

A Eklund, Department of Biomedical Engineering and Informatics, Umeå University Hospital, Umeå, Sweden
L-O D Koskinen, J Malm, Department of Clinical Neuroscience, Umeå University, Umeå, Sweden

Competing interests: CSF Dynamics A/S contributed the valves. The company did not claim any service in return. The authors do not have any financial interest in the company.
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