CHAPTER

18

Cerebrospinal Fluid Shunt Technology

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INTRODUCTION

Since the invention of the first implantable shunt valve by Nulsen and Spitz (12) almost 50 years ago, there has been a remarkable number of ingenious modifications and new designs of shunt equipment to treat pediatric hydrocephalus. These developments were in response to the immediately evident high shunt failure rate. These designs included anti-siphon devices (15), on-off devices, gravity-actuated changes in opening pressure, and even externally adjustable valves, some with electromagnetic programmers (16) (*Fig. 18.1*). Aside from the introduction of the silicone elastomer material, there has in fact been little clinical impact on the treatment with patients with shunts. Moreover, there has been a recognition of the unexpected complications-cor pulmonale (11) and shunt nephritis (19) from cardiac shunts, bowel erosion from spring-coiled catheters (1), obstruction of anti-siphon devices by capsule formation (3), and tonsilar herniation by lumboperitoneal shunts (2). In fact, each new shunt equipment design has in many cases brought along its own unique set of complications.

Interpretation of the results of new shunt hardware was often hampered by the design of the studies. They often contained small retrospective series of patients, loosely defined inclusion criteria, poor definition of outcome events, short follow-up, and inappropriate statistical analysis. These studies were often conducted by enthusiasts of the devices who had vested interests in the outcome, including financial incentives. Early enthusiastic reports were often followed by less enthusiastic ones, often about unexpected complications.

PROSPECTIVE RANDOMIZED TRIALS OF CSF SHUNT VALVE DESIGN

Pediatric Shunt Design Trial

With the recent advances in valve design, aimed at reducing shunt overdrainage in the upright position, there were again reports of improved outcome in slightly improved but nevertheless significantly

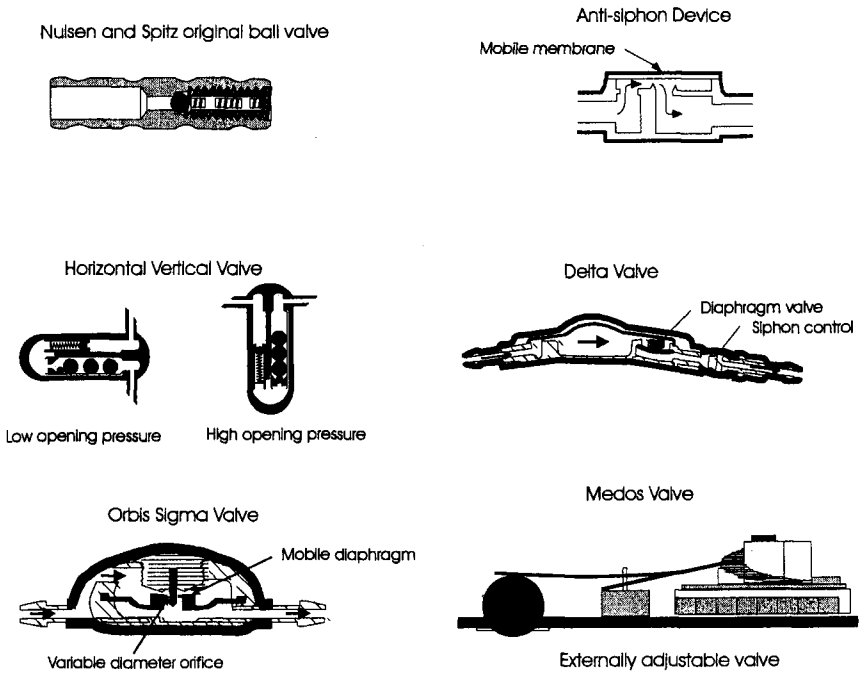

FIG. 18.1 Schematic diagrams of a number of valve designs starting with the original Nulsen and Spitz valve developed in the early 1950s (12). The designs reflect the progress valve development including antisiphon devices, gravity-actuated valves, and ultimately an externally adjustable valve. Unfortunately, the increased complexity and sophistication has not to date resulted in improved efficacy.

flawed clinical series (8, 18). It was at this point that the Pediatric Hydrocephalus Treatment and Evaluation Group decided to launch a carefully controlled prospective randomized trial on the Orbis Sigma valve (NMT, Boston, MA) (18), a flow-limiting device, and the Delta valve (Medtronic PS Medical, Goletta, CA) (8), a siphon control device, compared to standard differential pressure valves. The trial was well organized and multicentered, the blinded data were collected centrally, and the primary outcome event was clearly defined and blindly adjudicated (4). An adequate number of patients was recruited and followed. There was no difference in shunt failure rates between the three types of valve design at an average follow-up of 2 years (5) (*Fig. 18.2*). The patients were subsequently followed for an additional 3 years, and no obvious changes from the initial analysis were noted (9).

In this trial, shunt failure occurred at an exponential rate for the first year and then leveled off. Overall, the one-year failure rate was 40%,

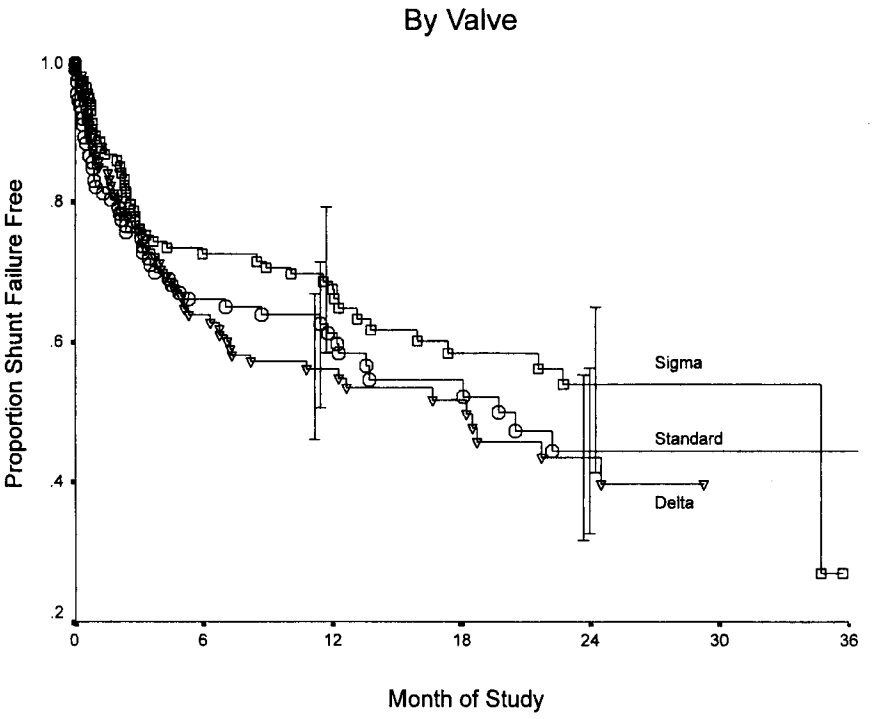

FIG. 18.2 Results of the prospective randomized trial of valve design comparing the Delta valve, the Orbis Sigma valve, and "standard" valves. There is no difference in complication free shunt survival between the three groups. From Ref. 5 with permission.

and the two-year failure rate was 50%, remarkably similar to what had been reported before, and upon which the trial estimates for sample size had been based. The commonest cause of shunt failure was obstruction (31.4%) followed by infection (8.1%), overdrainage (3.5%), and loculated ventricles (0.6%).

SECONDARY OUTCOMES

A number of other extremely interesting findings emerged from the data collected, which, though not part of the primary outcome, nevertheless shed some light on the state of treatment of pediatric hydrocephalus at the time. The secondary outcome measures of type of shunt failure and site of shunt obstruction indicated that the Delta valve, which was designed to prevent subdural collections, actually had the highest number (5). The Orbis-Sigma valve had very few obstructions of the ventricular catheter (the commonest site of shunt obstruction)

but a higher number of valve failures, as though the site of obstruction had been moved downstream.

The trial received considerable attention, as well as some criticism. Some claimed that the valves were never designed for small children, that the wrong "level" of Delta valve was used, and that the results would have been different in older children. In fact, these valves were being implanted in enormous numbers of children at the time of the study; the number of overdrainage complications was similar in children over age 2; and inspection of the shunt survival curves for different standard valve opening pressures, or different Delta valve "levels," indicated that it likely had little effect. Since three very different valve designs had no apparent effect, the trial authors felt it was unlikely that small differences in valve design would have had much effect.

POST HOC ANALYSIS

There was a great deal of data collected during the trial that could be examined, particularly to explore whether previously held suppositions were possibly correct or could more appropriately be put to a subsequent clinical trial. There was no apparent difference in outcome according to whether the burr hole was frontal or occipital, whether the ventricular catheter was placed with assistance (ultrasound, endoscopy, or x-ray), the training level of the surgeon, or whether the hair was clipped, shaved, or left alone.

Perhaps the most interesting follow-up information was on the analysis of the considerable imaging data that had been collected. Each patient had up to six follow-up radiologic images. Excluding the images taken at the time of shunt failure, each image was analyzed for the size of the ventricles, the position of the tip of the ventricular catheter within the ventricle (frontal, occipital, or body), and the catheter tip environment (surrounded by CSF, touching ventricular wall, surrounded by slit ventricle). Ventricular size was measured using a modified Evan's ratio, which was an average of the frontal and occipital horn width divided by the maximum biparietal diameter. This ratio had been shown to be an accurate and reliable estimate of ventricular volume in pediatric patients (10, 13).

The ventricular size declined at an exponential rate reaching a minimum plateau at 1 year. Remarkably, there was no difference in ventricular size among the three valves (22) (*Fig. 18.3*). This was extremely interesting because the valves behave quite differently on bench testing. It had also been previously reported in a retrospective review with historical controls that the Orbis-Sigma valve in particular kept the ventricles enlarged (17). The newer valves had been designed with cer-

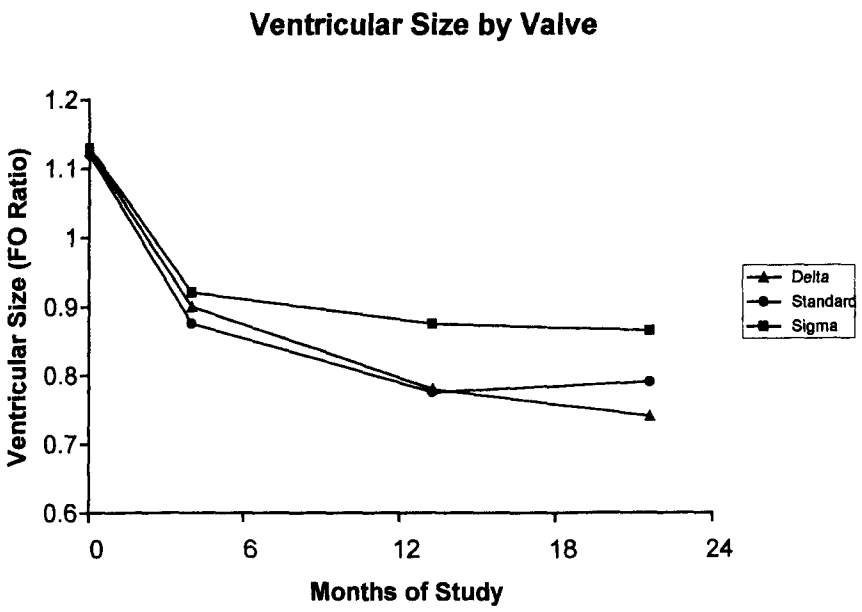

FIG. 18.3 Ventricular size as a function of time post shunt implantation from image data from the shunt design trial. There is no difference in ventricular size among the three valves, which have very different pressure/flow characteristics. From Ref. 22 with permission.

tain assumptions made about the brain's mechanical properties and the response to shunt implantation. These models are based on the limited knowledge of CSF production and pressure changes seen over very brief time periods (7). These ventricle size measurements from this study suggest that the current biomechanical models are woefully inadequate and must address much larger time scales-on the order of a year. A follow-up baseline study for a newly shunted patient, to determine ventricular size when the patient is well, should also be carried out at approximately 1 year after implantation.

The position of the ventricular catheter and the amount of CSF surrounding it also appeared to have an effect on shunt failure (22) (*Table 18.1*). By multivariate analysis, having a catheter in the occipital horn had a hazard ratio of .45 compared to catheters in the body of the ventricle. Ventricular catheters surrounded by CSF had a hazard ratio of .21 compared to those in a slit ventricle. The position and environment of the ventricular catheter tip accounted for fully three-quarters of the variability of the multivariate model, indicating that they are likely very significant risk factors. Maintaining a catheter tip surrounded by

TABLE 18.1
Independent Predictors of Cerebrospinal Fluid Shunt Malfunction

Predictors		Hazard Ratio	95% CI	*P* Value	R^2
Etiology	Myelomeningocele	1.78	1.18–2.67	0.006	0.037
	Head Injury	4.56	1.07–19.39	0.04	0.018
Ventricular size		2.33[1]	1.08–5.00	0.03	0.025
Ventricular catheter location	Occipital	0.45	0.28–0.74	0.001	0.052
	Frontal	0.60	0.39–0.91	0.02	0.033
Ventricular catheter environment	CSF	0.21	0.094–0.45	0.0001	0.13
	Touching Brain	0.33	0.21–0.51	0.0001	0.16

[1]HR of 2.33 refers to an increase in the risk of shunt malfunction for every unit increase in the ventricular size (as per the modified Evans' ratio).

CSF in an expanded occipital horn might significantly reduce shunt failure. Whereas this might seem like common sense, this is really the first time this has been demonstrated using prospectively collected data analyzed by multivariate methods. It should be added that there are many "common sense" solutions to shunt failure, such as using "more physiologic valves," which have not proved to have treatment value.

Other factors that might affect shunt failure were included in image data analysis. Etiology, namely myelomeningocele, also increased the risk of shunt failure. Although this is not a modifiable risk factor, identification of high risk groups is important to target those who might benefit the most from treatment changes.

The Medos Programmable Valve Randomized Trial

A subsequent prospective randomized trial comparing the Medos valve (Johnson & Johnson, Randalph MA), a programmable differential pressure valve, to all other valves also found no difference in reoperation rate for shunt failure (14). The trial was somewhat different in that it included pediatric and adult patients undergoing a first shunt insertion or valve revision. Nevertheless, the 2-year shunt survival rates for the patients for the first shunt insertion were 52% in the Medos group and 50% in the control group, remarkably similar to the previous randomized valve design study. Although the valve was frequently reprogrammed (66% of the patients) and this was felt to avert an operation in 61 patients, the overall reoperation rate was the same in the control group. Only four valves required explantation because of an inability to reprogram.

REPEATED SHUNT FAILURE

In the Medos trial referred to above, patients having a subsequent shunt operation including a valve revision fared slightly worse than the first implantation group, with 2-year survival rates of 43% in both groups. The issue of repeated shunt failure, particularly in the same patient, is a complex one. We enrolled a cohort of patients over 10 years into a hydrocephalus data base. Each patient was then followed for up to 10 years for any episodes of shunt failure to determine what if any were risk factors (21). The data were then analyzed by multivariable time to event analysis.

There were 1183 shunt failures in 839 patients. Failure time from the first shunt procedure was an important predictor for second and third failures so that if an individual patient failed early, they were likely to fail early again-and this was not a particular effect of infection. Age of less than 40 weeks' gestation at time of first shunt implantation had a hazard ratio of 2.49 (95% CI, 1.68–3.68) for the first failure and remained high for subsequent failures. Age of 40 weeks to 1 year (at the time of the initial surgery) also proved to be an important predictor of first malfunctions (HR = 1.77, 95% CI = 1.29–2.44). The etiology of hydrocephalus was significantly associated with the risk of initial failure and, to a lesser extent, later failures. Concurrent other surgical procedures were associated with an increased risk of failure (*Table 18.2*).

It was also interesting to note what did not appear to carry any risk for first or subsequent failures: valve design (standard/flow regulated), distal catheter design (slit/open ended), antibiotic prophylaxis, emergency/ASA class, burr hole site (frontal/occipital), burr hole side (left/right), duration of surgery, or preadmission stay. Although it was disappointing that easily modifiable factors were not important, nevertheless it identified patients at high risk. It also suggests that there is a process initiated by shunt failure, perhaps an inflammatory response, that leads to further shunt failure.

CONCLUSION

What should be our treatment goals over the next decade as we enter the next millennium? It seems eminently reasonable that neurosurgeons could achieve a 1-year failure rate of 5% including an infection rate of 1%. How can this be achieved? It seems clear that this will require a cooperative multifaceted approach. There is much about the complex interactions between the hydrocephalic patient and the shunt, which are not well understood. Better mathematical models would allow simulations of the response of the hydrocephalic patient to be carried out more accurately and over a much longer time scale. These mod-

TABLE 18.2
Hazard Ratios, 95% Confidence Interval, and P Values for the First Three Failure Groups

	Failure Groups								
	1st			2nd			3rd		
Risk Factors	Hazard Ratio	95% C.I.	*P* Value	Hazard Ratio	95% C.I.	*P* Value	Hazard Ratio	95% C.I.	*P* Value
Gap time of previous failure				1.72	1.28–2.30	<0.001	1.50	1.05–2.16	0.027
Age*									
Less than 40 weeks	2.49	1.68–3.68	<0.001	1.59	0.93–2.74	0.096	1.71	1.05–2.79	0.032
40 weeks to 1 year	1.77	1.29–2.44	<0.001	1.33	0.84–2.11	0.22	0.90	0.57–1.42	0.65
Etiology**								Not significant	
Aqueductal stenosis	1.83	1.13–2.96	0.01	0.77	0.36–1.64	0.50			
IVH	1.78	1.18–2.68	0.006	1.85	1.03–3.33	0.039			
Postmeninigitic	2.08	1.26–3.44	0.004	2.32	1.19–4.54	0.014			
Myelomeningocele	1.95	1.34–2.85	0.001	1.10	0.63–1.92	0.74			
Posttraumatic	2.80	1.39–5.64	<0.004	1.86	0.67–5.18	0.23			
Tumor	2.33	1.48–3.68	<0.001	2.34	1.22–4.48	0.01			
Other	1.56	1.03–2.35	0.03	1.31	0.72–2.39	0.38			
Ventriculoperitoneal vs. other shunt types	0.69	0.50–0.95	0.92		Not significant			Not significant	
Concurrent surgery	1.44	1.06–1.94	0.02		Not significant		1.89	1.01–3.53	0.047

*Corrected for gestation; age greater than 1 year is chosen as the reference category.
**Congenital is the reference category.

els are not easy to develop, as there is little known about even the normal mechanical parameters of the brain. Animal models of shunt failure would also allow the mechanisms of particularly proximal catheter occlusion to be dissected, including possible reactive mechanisms induced by repetitive trauma. Ongoing clinical trials are also extremely important; hypotheses such as placing a ventricular catheter in an expanded occipital horn need to be tested by prospective studies, as is currently being done with endoscopic placement of ventricular catheters.

The search for new shunt designs and new materials should continue. No one should conclude that shunt valve designs are not important. Whereas the shunt design trials have been negative to date, valves have important effects that just have not as yet been translated into improved outcome. The search for alternative treatment strategies should also continue, i.e., endoscopic third ventriculostomy, but should be subjected to the same scrutiny as the clinical trials in CSF shunts (20).

REFERENCES

1. Adeloye A: Protrusion of ventriculo peritoneal shunt through the anus: Report of two cases. **East Afr Med J** 74:337–339, 1997.
2. Chumas PD, Armstrong DC, Drake JM, Kulkarni AV, Hoffman HJ, Humphreys RP, Rutka JT, Hendrick EB: Tonsillar herniation: The rule rather than the exception after lumboperitoneal shunting in the pediatric population. **J Neurosurg** 78:568–573, 1993.
3. Drake JM, da Silva MC, Rutka JT: Functional obstruction of an antisiphon device by raised tissue capsule pressure. **Neurosurgery** 32:137–139, 1993.
4. Drake JM, Kestle J: Rationale and methodology of the multicenter pediatric cerebrospinal fluid shunt design trial. **Childs Nerv Syst** 12:434–447, 1996.
5. Drake JM, Kestle J, Milner R, Cinalli G, Boop F, Piatt J, Jr., Haines S, Schiff SJ, Cochrane DD, Steinbok P, MacNeil N: Randomized trial of cerebropsinal fluid shunt valve design in pediatric hydrocephalus. **Neurosurgery** 43:294–305, 1998.
6. Drake JM, Sainte-Rose C: *The Shunt Book.* New York, Blackwell Scientific, 1995, p 1.
7. Drake JM, Tenti G, Sivaloganathan S: Computer modeling of siphoning for CSF shunt design evaluation. **Pediatr Neurosurg** 21:6–15, 1994.
8. Horton D, Pollay M: Fluid flow performance of a new siphon-control device for ventricular shunts. **J Neurosurg** 72:926–932, 1990.
9. Kestle JRW, Drake JM, Group PHTE: Long-term follow-up from the shunt design trial. **Childs Nerv Syst** 15:426, 1999 (abstr.).
10. Kulkarni A, Drake J, Armstrong DC, Dirks P: Measurement of ventricular size: Reliability of the frontal and occiptial horn ratio compared to subjective assessment. **Pediatr Neurosurg** 31:65–70, 1999.
11. Ladouceur D, Giroux M: Echocardiographic detection of intracardiac thrombi complicating ventriculo-atrial shunt: Report of two cases. **Pediatr Neurosurg** 20:68–72, 1994.
12. Nulsen FE, Spitz EB: Treatment of hydrocephalus by direct shunt form ventricle to jugular vein. **Surg Forum** 399–403, 1952.
13. O'Hayon BB, Drake JM, Ossip MG, Tuli S, Clarke M: Frontal and occipital horn ra-

tio: A linear estimate of ventricular size for multiple imaging modalities in pediatric hydrocephalus. **Pediatr Neurosurg** 29:245–249, 1998.
14. Pollack IF, Albright AL, Adelson PD: A randomized, controlled study of a programmable shunt valve versus a conventional valve for patients with hydrocephalus. Hakim-Medos Investigator Group. **Neurosurgery** 45:1399–1408, 1999.
15. Portnoy HD, Schulte RR, Fox JL, Croissant PD, Tripp L: Anti-siphon and reversible occlusion valves for shunting in hydrocephalus and preventing post-shunt subdural hematomas. **J Neurosurg** 38:729–738, 1973.
16. Reinprecht A, Dietrich W, Bertalanffy A, Czech T: The Medos Hakim programmable valve in the treatment of pediatric hydrocephalus. **Childs Nerv Syst** 13:588–593, 1997; Discussion 593–594.
17. Sainte-Rose C: Shunt obstruction: A preventable complication? **Pediatr Neurosurg** 19:156–164, 1993.
18. Sainte-Rose C, Hooven MD, Hirsch JF: A new approach to the treatment of hydrocephalus. **J Neurosurg** 66:213–226, 1987.
19. Searle M, Lee HA: Ventriculo-atrial shunt nephritis. **Postgrad Med J** 58:566–569, 1982.
20. Tuli S, Alshail E, Drake J: Third ventriculostomy versus cerebrospinal fluid shunt as a first procedure in pediatric hydrocephalus. **Pediatr Neurosurg** 30:11–15, 1999.
21. Tuli S, Drake JM, Lawless J, Wigg M, Lamberti-Pasculli M: Risk factors for repeated cerebrospinal shunt failures in pediatric hydrocephalus. **Neurosurgery** (in press).
22. Tuli S, O'Hayon B, Drake JM, Kestle JRW: Change in ventricular size and effect of ventricular catheter placement in pediatric shunted hydrocephalus. **Neurosurgery** (in press).