DEVELOPMENT OF A VALVE-LESS SHUNT SYSTEM

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The use of shunting for hydrocephalus has a long history of improvements made through basic science, as well as clinical innovations and biomedical products. Treatment of hydrocephalus through shunting has dramatically changed the outlook for patients. With most of them having normal intelligence as well as normal life expectancies. However the use of shunts has created many unique problems, revisions as well as dependence are frequent among children with hydrocephalus. In addition the cost of such procedures has been on the rise especially for the not so advanced countries. This has posed many new questions as to the development of a less costly yet effective shunt system.

Hydrocephalus is a common condition in children, which involves an excessive accumulation of cerebrospinal fluid (CSF) within the cavities of the brain known as ventricles. In Hydrocephalus the build of up of fluid causes abnormal enlargement of the ventricles which in turn increase the pressure on the brain potentially leading to brain damage (Albright, et.al 1999). Many treatments are available however the implantation of a shunt is the most common (Fried, 1993-2004). The research involves the production of a mathematical model of a shunt system without the use of a valve. Flow will be regulated using turns, kinks, knots etc….

Also known as "water on the brain," hydrocephalus is one of the most frequently seen problems in a busy pediatric neurosurgical practice (Fried, 1993-2004). However "water on the brain" is purely a misnomer. Everyone produces a certain amount of cerebrospinal fluid (about one pint per day) and absorbs this exact amount per day as well. The fluid will circulate throughout the head and spinal cord where it will be absorbed over the surface of the brain. This means of production and absorption provides a safe environment for the brain and spinal cord (Fried, 1993-2004).

CSF is a clear colorless fluid, which has minimal content of protein (Albright, et.al 1999). The CSF is in hydrostatic equilibrium with the interstitial tissue of the brain and can permeate across the brain tissue in both directions (Drake, 1995). It is expected that the brain tissue and the CSF would have the same hydrostatic pressure in any part of the brain. As much as the brain tissue is covered protected by blood brain barrier from changes outside the central nervous system, the CSF has the same protection and does not change its biochemical state as a result of changes in the systemic circulation (Albright, et.al 1999).

The cerebrospinal fluid fills the cavity of the ventricles and the subarachnoid spaces. The subarachnoid spaces are wide in certain areas and these are called cisterns (Fried, 1993-2004). At the cerebellomedullary area the cistern is called cisterna magna. We also have the pre-pontine cistern surrounding the basilar artery and the interpeduncular cistern surrounding the circle of Willis. The subarachnoid space extends caudally around the spinal cord and ends in lumbar -sacral dural sac where it surrounds the cauda equina (Albright, et.al 1999).

The choroid plexus produces the majority of CSF; there are assumptions that some CSF is formed outside the choroid plexuses, from the brain substance. This is estimated to be about 10 to 15% of the whole volume of CSF (Albright, et.al 1999).

It is believed that CSF is formed at a rate of 0.5 ml per minute (Drake, 1995). It is also believed that there is a persistent and steady production of CSF irrespective of systemic changes. It is independent of the mean arterial blood pressure until this is reduced below 60 mms/mercury (Drake, 1995). However it is believed that the perfusion pressure influenced the production of CSF i.e. CSF production is reduced at a higher threshold of systemic blood pressure when the CSF pressure is raised. Reduction of perfusion pressure might act by diminishing choroid plexus blood flow and the supply of necessary material for CSF secretion (Albright, et.al 1999).

CSF begins from the lateral ventricle passes through the foramen of Munro to the 3rd ventricle (figure 1). From there it passes through the aqueduct of the Sylvius to the 4th ventricle (Fried, 1993-2004). With the CSF formed by the choroid plexus in the 4th ventricle it exits through the roof of the 4th ventricle. From there it passes along the outer surface of the cerebellum and through the basal cisterns. It passes through the hiatus of the tent to the Sylvian fissures and from there to the para-sagittal area (Albright, et.al 1999). It is excreted by the arachnoid villi into the venous sinus, mainly the sagittal sinus. It is believed that

CSF takes one to two hours to reach the basal cisterns, 3 to 4 hours to reach the sylvian fissure and 10 to 12 hours to spread over the cerebral subarachnoid space. By 24 hours it started to be cleared into the superior sagittal sinus. The mechanism by which the CSF is secreted through the arachnoid villi is still not clear. (National Institute Neurological Disorders).

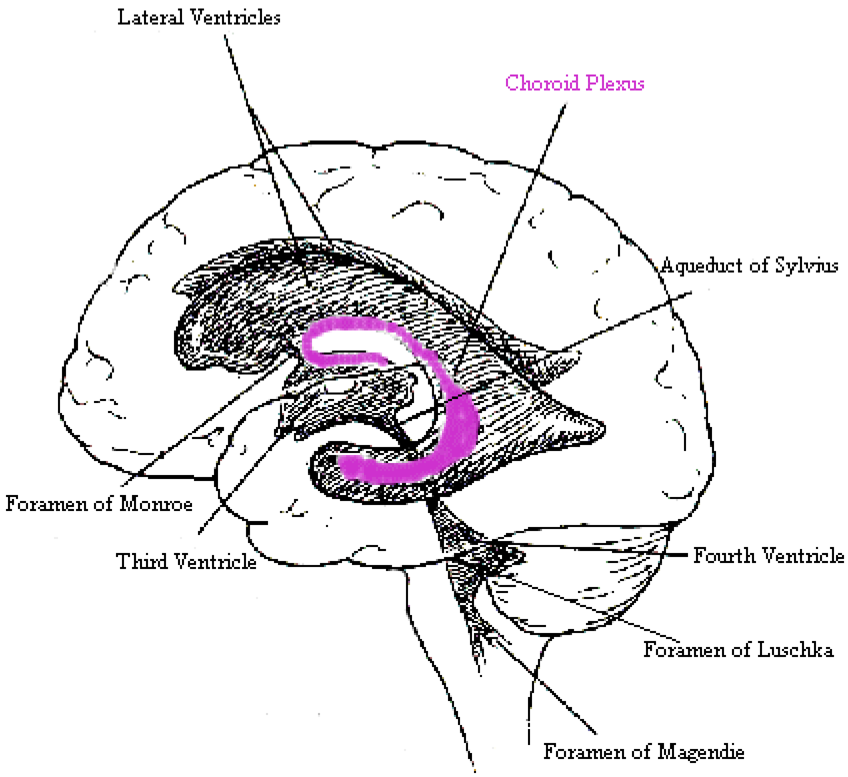

Figure 1.

In children and babies CSF pressure is low. In infants it is estimated to be 40 to 50 mms of water and in children from 40 - 100 mms of water (Albright, et.al 1999). In older age group it remains constant of about 150 mms of water or 15 mm of Mercury. Pressures above 200 mms of water or 20 mms of Mercury are considered abnormal (Drake, 1995).

The cerebral spinal fluid pressure is dependent on intracranial venous pressure; it is usually about 40 to 50 mms of water above the intracranial venous pressure. The difference in pressure is related to the continuous production of CSF and resistance to its secretion (Drake, 1995).

There are fluctuations in the CSF pressure; these are influenced by ventilation and cardiac contraction. CSF pressure falls with inspiration and rises during expiration, a variation of about 40 mms of water. (Drake, 1995)

With cardiac contraction there is a variation of about 20 mms of water with ventricular systole. (Albright, et.al 1999).

Classification

Observations by Key and Retzius in 1875 demonstrated the CSF pathways and ventricles, providing the groundwork for future physiological advances. Dandy and Blackfan demonstrated the CSF production within the ventricles by the choroid plexus and divided hydrocephalus into communicating and non-communicating types. Where non-communicating is the lack of communication between the ventricular system and the subarachnoid space. The most common cause is aqueduct blockage (GP Notebook, 2004). Communicating is where there is a communication between the ventricular system and the subarachnoid space. The most common cause of this group is post infective and post hemorrhagic hydrocephalus (Albright, et.al 1999).

Causes

There are three main groups of causes related to hydrocephalus. One being, excessive secretion of CSF by the choroid plexus, such cases are called "choroid plexus papilloma or carcinoma. This is however a rare cause (GP Notebook, 2004). Second, we have blockage to the circulation of CSF. This can occur at any level of the CSF circulation. Such as to the level of the foramen of Monro where we have either unilateral or bilateral coverage of the foramen of Monro giving dilation of one or both lateral ventricles. The most common cause of obstructive hydrocephalus is congenital aqueduct stenosis (Albright, et.al 1999). There is a narrowing or complete blockage of the aqueduct. Other obstructive causes include Posterior fossa tumors, where blockage of the 4th ventricle will take place. However the most common cause of obstructive hydrocephalus is Dandy Walker Syndrome (Fried, 1993-2004), where there is a blockage of the foramina of the 4th ventricle. This is a congenital condition associated with agenesis of the cerebellar vermis. Lastly, poor secretion of CSF into the venous sinuses, which allow absorption, this is caused by scarring of the arachnoid villi. This is quite common after meningitis and/or hemorrhage (Albright, et.al 1999).

Clinical Features

It is very important that Hydrocephalus be diagnosed early to minimize morbidity and mortality. The common clinical presentation in a child is increasing head size, irritability, failure to feed and vomiting. Motor and general developmental delay, failure to make appropriate visual and social contact is among the most common neurological problems found in children with hydrocephalus (Albright, et.al 1999). The most important sign is the excessive rate of head growth, which occurs in about 40% of cases. In addition, delayed motor development can occur, due to the raise in intracranial pressure.

Treatment

Treatment is broken down into two categories, non-surgical and surgical. Non-surgical involves head wrapping and drug treatment. The theory behind head wrapping is to raise the intracranial pressure, which will increase Tran ependymal absorption of CSF, or the reopening of compromised CSF pathways. However this method was relegated to oblivion. Drug treatment was successful in many instances, in that the use of a shunt was avoided. Production of CSF was reduced, which in turn reduced ICP. The modern treatment of hydrocephalus started with the development of a shunt system regulated by a valve by Halter and the application by Nelsen and Spitz (fig 2).

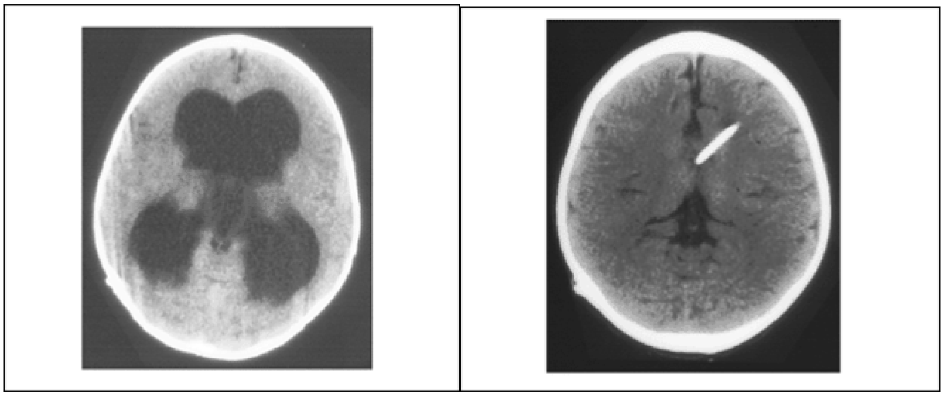

Figure 2. Before and after MRI images of patient with hydrocephalus treated with a shunt.

Surgical treatment involved intraventricular and extraventricular shunts. Intraventricular shunts were done in cases of obstructive hydrocephalus where the subarachnoid spaces are still patent. These procedures include, Third Ventriculostomy and Ventriculocisternostomy (Albright, et.al 1999). Ventriculocisternostomy is no longer used due to its high morbidity and mortality rate.

Extraventricular shunts are by far the most common treatment today (Drake, 1995). This procedure involves the diverting of CSF from the lateral ventricle into another body cavity. The most common site is the peritoneal cavity (Albright, et.al 1999). Other sites such as the atrium and pleural cavities are occasionally used (National Institute Neurological Disorder). The goal of the procedure is to normalize the intracranial pressure by draining the appropriate amount of cerebrospinal fluid. This is achieved by creating appropriate CSF flow through a specially designed shunt valve with the appropriate rate of flow and pressure. Modern shunts are made of medical grade silicon, which is well tolerated by the body. It causes minimal or no tissue reaction or intravascular thrombosis. The shunt system is either made of one unit or several parts. An essential component of the shunt system is the shunt chamber which houses the valve, which opens at a certain pressure to regulate the CSF flow in a unidirectional way. The shunt chamber is proximally attached to ventricular catheter, which passes to the lateral ventricle Distally it is attached to a catheter, which leads the CSF into a body cavity. The flow of CSF across the valve depends on the differential pressure between the inlet and the outlet. (Drake, 1995)

Figure 3. Delta Valve by Medtronic.

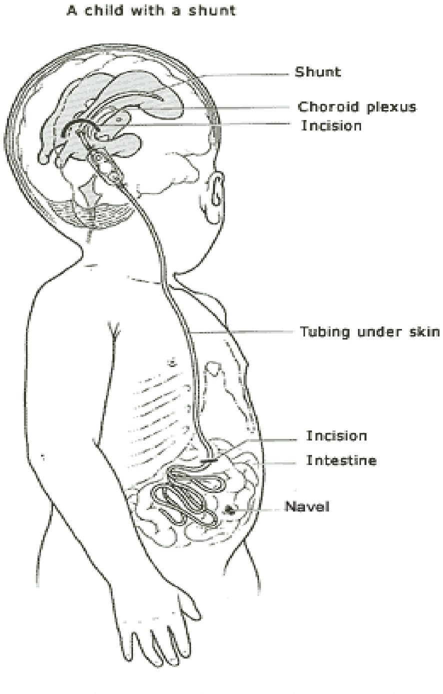

Figure 4. Diagram of a ventriculo peritoneal shunt.

Currently ventriculo- atrial, ventriculo -peritoneal and lumbar -peritoneal shunts are the most common used (Albright, et.al 1999). The majority of surgeons prefer using the ventriculo peritoneal shunt (National institute of Neurological Disorder). The problem with the ventricular atrial shunt is that it would need repeated revision, which becomes difficult as the child grows older and venous access becomes more difficult. It also has a higher rate of complications. While with the peritoneal cavity,plenty of tubing is left inside the peritoneum to accommodate for the child's growth. In ventriculo-peritoneal shunts about 30cms is left in the peritoneal cavity (fig 4). (Albright, et.al 1999).

Method

The research involves the development of a practical yet effective shunt system with the use of only turns, kinks, knots, etc… Valves are a very costly part of the shunt system typically incurring 90% of the total cost. Often this is not a big call for concern in advanced countries, however in developing countries the cost is often doubled and at times tripled. This is due to the increase in the number of "middle men" as well as lack of resources. Substituting the valve with a less costly method can result in the improvement of many children and adult lives.

Problem

Average person typically produces 1cc of CSF per three minutes (Albright, et.al 1999). Therefore the shunt needs have a flow rate of approximately 1cc per three minutes. Flow must be consistent regardless of the position of child and/or adult. No use of any mechanical device desired. Shunt system must be only comprised of a smooth silicone catheter. Flow through the catheter must be laminar at all times. It shall flow under the laws of gravity and siphoning only. Operation of the shunt system shall hold no relationship with any outside external forces.

In using Bernoulli's equation, determining the velocity at the distal end of the catheter (neglecting all friction and resistance) was now possible. In obtaining the velocity, calculations for the flow rate are now accessible. Upon completion of the previous step a foundation is set to work off of. (Crowe, 2000).

$$\frac{-\partial}{\partial s}(P+\gamma Z)=\rho a_t$$

$$a_t = v\frac{\partial V}{ds}+\frac{\partial V}{\partial t}$$

$$-\frac{d}{ds}(p+\gamma z)=\rho V\frac{dV}{ds}=\rho V\frac{d}{ds}(\frac{V^2}{2})$$

$$\frac{d}{ds}(p+\gamma z+\rho\frac{V^2}{2})=0$$

$$\frac{p}{\gamma}+z+\frac{V^2}{2g}=h+\frac{V^2}{2g}=C$$

$$p_1+\gamma z_1+\rho\frac{V_2{}^2}{2}=p_2+\gamma z_2+\rho\frac{V_2}{2}$$

Figure 5. Derivation of Bernoulli equation using Euler's equation.

However the neglecting of all friction and resistance needs to come into account, otherwise the calculated flow rate will not correspond to the actual, and there would be an excessive amount of flow. In using Bernoulli we had to apply energy to the equation to account for all the added resistance. At this time, the aim is to calculate the amount of resistance needed using the energy equation. In (fig. 6) "K" is the symbol for the induced friction. Upon solving for "K" we can get a close enough approximate of how much resistance is required to acquire a flow rate of 1cc per three minutes. (Crowe, 2000)

$$_1+\gamma z_1+\rho\frac{V_1{}^2}{2}=p_2+\gamma z_2+\rho\frac{V_2{}^2}{2}+\rho K\frac{V_e{}^2}{2}$$

Figure 6. The energy equation

Upon solving the above equation for K, it was determined that "K" would need to be approximately 400,000 to acquire the flow rate desired. A smooth 90-degree turn has losses that are near 0.35, depending on the radius and diameter ratio. This would result in a system that would require a ridiculous number of turns. In acquiring this news, a new model was developed which involved a typical 2-turn knot. The flow rate from one knot was measured so that its "K" could be calculated. It was determined that one knot gave losses of approximately 2500. This is obviously considerable to that of one turn. However this calculated "K" was only the induced resistance. The resistance of the walls of the catheter needed to be calculated. Unfortunately, the above equation does not implement the losses due to the internal resistance. A modification was done to the energy equation to implement the added resistance that was being neglected. The new equation was formed from that of the energy equation (fig.5), which gave us (fig. 7). (Crowe, 2000)

$$H = (nK + 1 + f\frac{nL}{d})\frac{V_e^2}{2g}$$

$$\frac{P_0}{\gamma} + z_0 = (nK + 1 + f\frac{nL}{d})\frac{V_e^2}{2g}$$

K = Resistance of one knot.
f = Friction due to the catheter.
n = Number of knots.
L = Length of one knot.

Figure 7.

This final equation can now be solved for either "K" or "n" depending on what one would like to solve for. The calculation for one knot gave us a "K" of 2500. In plugging in for "K", "n" is the only unknown, which will determine how many of those particular knots would be required to acquire the flow rate desired. The beauty of this equation is that it can be solved for either "K" or "n" (fig. 8 & 9) depending on the preference of the researcher (Crowe, 2000). The research conducted involved constructing a mathematical model of a practical valve-less shunt system that performed as a modern shunt system. In accordance to our data, the knot with a calculated "K" of 2500 resulted in an "n" of approximately 120 knots.

$$n = \left[\frac{2g\left(\frac{p_0}{\gamma} + z_0\right)}{V_e^2\left(K + \frac{fL}{D}\right)} \right] - 1$$

Figure 8.

$$K = \left[\frac{2g(\frac{p_0}{\gamma} + z_0)}{nV_e^2} - \frac{1}{n} - f\frac{L}{d} \right]$$

Figure 9.

Conclusion

In conducting this research, its complexity increased with time. Alongside the complications of the initial design came the complications of achieving the new design. More and more steps were required to take into consideration in achieving the main goal. Our current results are nothing but preliminary, the implementing of 120 knots to a catheter is still not of practicality. However current testing is being conducted for flow rates in the horizontal position. As of right now test models are being constructed to record data for 8-10 knots, 10-20 knots, and 20-40 knots, so that we can test the accuracy of these equations. In saying that, it has been a great ride getting to where we have and accomplishing all that we have. I personally find it fascinating to know that the most complex of devices, can be reproduced using the simplest of materials.

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