Proceedings of the 11th Brazilian Congress of Thermal Sciences and Engineering -- ENCIT 2006
Braz. Soc. of Mechanical Sciences and Engineering -- ABCM, Curitiba, Brazil,- Dec. 5-8, 2006

Paper CIT06-811

AN APPARATUS FOR TESTING EXTERNAL SHUNTS UTILIZED IN HYDROCEPHALUS SURGERY TREATMENT

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Abstract. *The watery solution continually produced inside the brain in the choroid plexus tissues is named cerebrospinal fluid (CSF). Humans are estimated to produce about 0.5 ml/kg per hour, or about 500 ml or more of CSF each day. A discrepancy in CSF production and absorption cumulates an excess of fluid in the brain. Elevated levels of CSF are associated with traumatic brain injury, meninge infections (meningitis) and a pediatric disease known as hydrocephalus. In all of these cases, an increasing fluid pressure (intracranial pressure), resulting in permanent brain injury and death, can be observed. Following the diagnosis of hydrocephalus, there are few options other than surgery for treatment. Most surgeons use various types of systems called shunts to channel the fluid from the ventricles to other sites in the body such as the abdominal cavity (internal shunts). Liquor can also be drained towards an external reservoir (external shunts). In the present work an apparatus operating as bench test has been developed for testing external shunts. Utilizing automated control and data acquisition system, in order to realize the experiments, hydrodynamics characteristics of several shunts parts can be rapidly obtained. Some first results from a first prototipe of an anti-siphon valve are included.*

Keywords*. External shunt, cerebrospinal fluid, hydrocephalus, neurosurgical devices.*

1. Introduction

The watery solution continually produced internal the brain in choroid plexus tissues is named, in medical literature, liquor or cerebrospinal fluid (CSF). The CSF flows through a series of cavities (ventricles) out of the brain and down along the spinal cord. The brain and spinal cord float in a sea of cerebrospinal fluid within the skull and spine. Additionally, brain and spinal cord are covered by a series of membranes called meninges.

Humans are estimated to produce continually about 0.5 ml/kg per hour, or approximately 500 ml or more of liquor each day. In an adult, in normal conditions, 150 ml of CSF have been estimated at any given time located in the brain ventricles. A discrepancy in CSF production and absorption cumulates an excess of fluid in the brain. Elevated levels of CSF are associated with traumatic brain injury, meninge infections (meningitis) and a pediatric disease known as hydrocephalus. In all of these cases, an increase fluid pressure (intracranial pressure – ICP) can be observed resulting in permanent brain injury and death.

If diagnosis of hydrocephalus has been obtained there are rarely options other than surgery for treatment. If a definable mass is causing the obstruction of flow it may be possible, if not essential, to remove the mass and allow for normal flow and resolution of the hydrocephalus. More often then not however, the blockage can not be removed and the fluid needs to bypass the normal circulation. Most surgeons use various types of systems called shunts to channel the fluid from the ventricles to other sites in the body such as the abdominal cavity (internal shunts). Liquor drainage can be realized also for an external reservoir (external shunts). In accord to Sesay *et al.* (2002), the external drainage of CSF has been realized only in emergency situations and frequently external drainage is a provisory condition after the surgery to implant semi permanent internal drainage device. A sketch of an external device for CSF drainage has been shown in Fig. 1. External reservoir is submitted to atmospheric pressure (Patm) and the height H should be carefully determined by surgeon. ICP should overpass the height H to produce drain effect. If height H is very small or negative over-drainage occurs after shunting. Over-drainage of cerebrospinal fluid can occur with relative high frequency and after few seconds in this adverse condition unavoidable non reversible cerebral damage occurs. Over-drainage of gravitational external shunts studies have been intensely realized by Camilo *et al.* (2005) and Maset *et al.* (2005). Over drainage of the ventricles can result in collapse of the brain away from the inner surface of the skull with a resultant risk of bleeding with compression of the brain. Long term over drainage can result in headaches of a very debilitating degree.

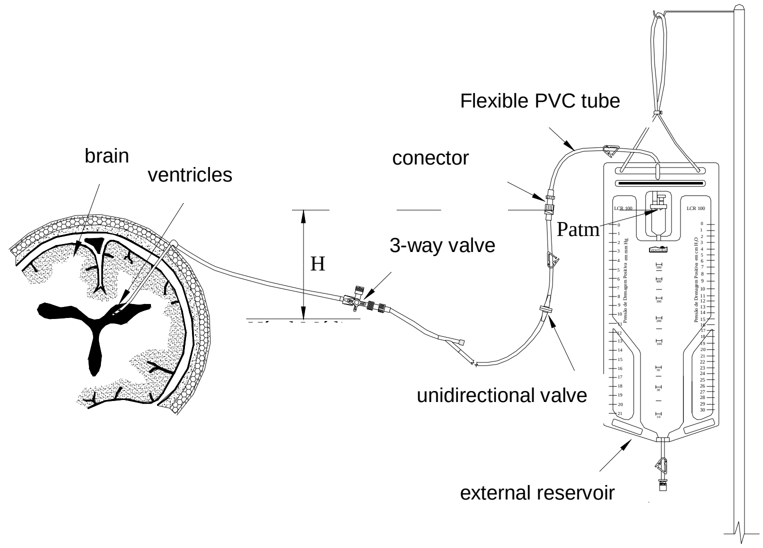

Figure 1. Neurosurgical external gravitational shunt sketch.

In 1999, Aschoff *et al*. (1999) show 127 different types of neurological valves commercially available since 1949 and more than others 70 models in different developing phases. All of these valves have been developed for application exclusively in internal shunts. Internal shunts for drainage CSF utilize a neurological valve to stabilize the ICP controlling the flow rate. Unfortunately, even at present day, the drainage characteristics of neurological valves are far from ideal. In this viewpoint, many effort of research are realized to improve of neurological valves. In addition the use of internal shunts has created problems of shunt dependence with frequent shunt revisions being the rule for most hydrocephalic children. Because of this inconvenient, internal shunt problems assume a major amount of all neurosurgeon's efforts and the more target of research. In the other side, few efforts have been realized in research in external shunts. The use of external shunts is an important provisory procedure in a first phase of hydrocephalus treatment, before the implantation of internal shunts. In this work of research an apparatus for testing external shunts utilized in hydrocephalus surgery treatment has been proposed in order to obtain hydraulic characteristics of external shunts parts. This test device permits measurements of differential pressure in function of flow rate for individual shunt parts or in testing complete external shunts. Additionally, results of a first prototype of an anti-siphon valve for external shunts have been showed.

2. Intracraneal pressure (ICP)

Hydrocephalus is caused by an increase in the production rate of CSF (very rare) or, more frequently, by disturbing in CSF absorption. Production/absorption imbalance of CSF causes a sensible increase of ICP. Second Puget (2005), congenital hydrocephalus can to occur one time in each 2 000 births. The incidence of acquired hydrocephalus is not known. The peak ages for the development of hydrocephalus are in infancy, between four and eight years, and in early adulthood. Normal pressure hydrocephalus generally occurs in patients over the age of 60.

In accord to Gusmão *et al*. (2000), in an adult laing, the intracranial pressure changes from 50 to 200 mm of water. Frequently, in several works utilize 150 mm of water column as a reference value. In this situation, the ICP is same into ventricles and around all spinal cord. In standing up position, measured in hydrocephalus patient, ICP shows small values near atmospheric pressure. In children, ICP shows a medium value around 45 mm of water in standing up position and near zero in lay down position.

Measurement, involving 80 patients, performed by Kajimoto *et al*. (2000) show ICP value in lay position of 4.6 ± 3 mm of Hg and for standing up of -14.2 ± 6.3 mm of Hg. Negative values of ICP have been observed because different measurement procedures. Utilizing an adequate referential of pressure, ICP in standing up position can be corrected utilizing an adequate referential.

Kajimoto *et al*. (2000) also studied the ICP variation in function of changes in postural position Sudden alteration in postural position provokes rapid alteration, less than 30 seconds, in ICP values.

ICP monitoring studies are now being used more frequently in younger patients and older patients with possible low grade hydrocephalus – Pople (2002). ICP monitoring may reveal "B waves" either at night time alone or throughout the day and night. An ICP above 15 mm Hg at frequent intervals during the night or day while asleep or resting is abnormal, and patients with functioning shunts should normally have an ICP below or near to zero while 45° head up in bed. CSF infusion tests measure CSF outflow resistance, which in simple terms represents the overall compliance of the intracranial and spinal CSF compartment. During this test saline or artificial CSF is constantly infused via a lumbar puncture needle or catheter, and the subsequent gradient of rise in the ICP with time is recorded. A low outflow resistance corresponds to high cerebral compliance and vice versa. Normal values are 5–10 mm Hg/ml/minute and a value > 18 mm Hg/ml/minute appears to be the approximate cut off point for diagnosing active hydrocephalus in the elderly. Other compliance monitors have recently been developed that are placed as bolts through small twist drill holes in the skull. These tests can be used to guide treatment of patients with newly diagnosed ventricular enlargement they can also be useful in patients with possible blockage of their shunts or delayed occlusion of their third ventriculostomy site.

3. External shunts

Figure 1 shows a typical external system of cerebrospinal fluid drainage. This apparatus consists of a proximal (ventricular) end that is inserted through the skull (via a small hole), through the brain substance, and into the cerebral ventricles. This catheter is connected to a small diameter flexible tube. A typical flexible tube made in PVC is depicted in the Fig. 2. The three-way taps were utilized in external CSF drainage in order to connect devices for monitoring ICP, to provide a rapid means of drugs infusion (antibiotics for CSF infection or chemotherapy medication for tumors) and to gather samples of CSF to be examined for bacteria, cancer cells, blood or protein, depending on the cause of hydrocephalus. In post-subarachnoid and post-meningitic hydrocephalus, CSF samples are useful for cell counts, protein concentration, and to exclude residual infection. A protein concentration greater than 4 g/l will clog up most ventriculo-peritoneal internal shunt valves. Recently, optimized design of three-way taps for external shunts attracted attention of researchers – Camilo *et al.* (2006).

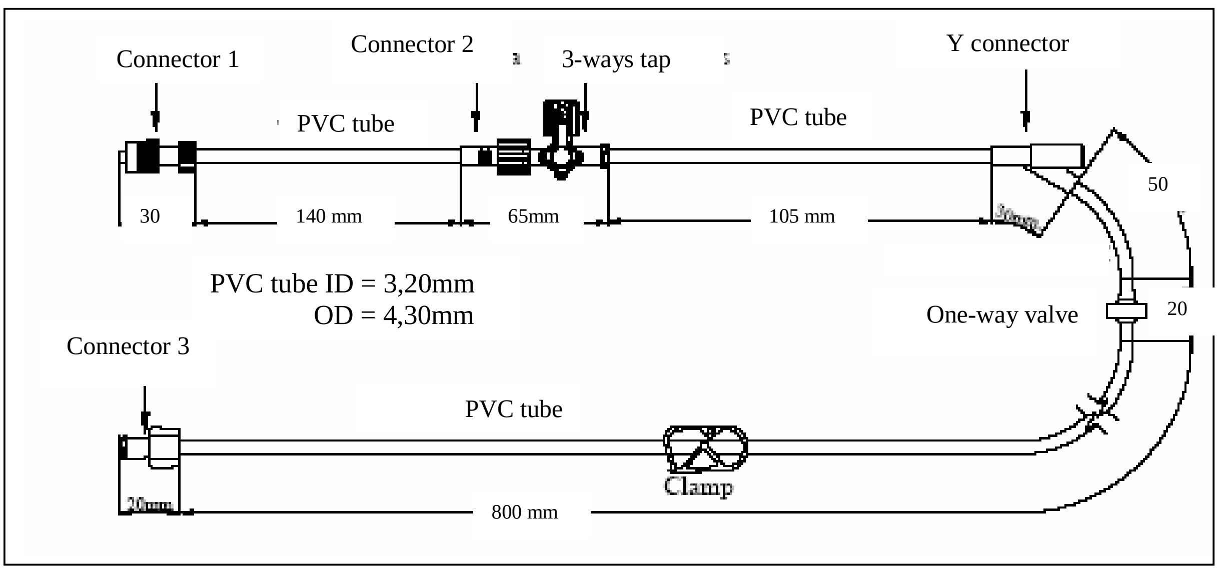

Figure 2. Ventura Biomédica mod. LCR - 500 neurosurgical external tube sketch.

The main function of Y connector is to remove the CSF sample for analysis. One-way valve is a smart device to prevent CSF reverse flow if differential pressure to assume negative or near zero values. Finally, a simple plastic clamp permits a complete flow blockage, if necessary. After the flexible tube, a bag operating as an external reservoir receives the CSF flow drained. All of these shunts components represent a pressure loss. In an external shunt can to occur over-drainage of CSF due to the siphoning effect if differential pressure assume high values. The hydrostatic pressure (25–75 cm of water), caused by the weight of the column of CSF, leads to fluid being sucked out of the ventricles in the upright position. Siphoning effect may lead to excessive CSF drainage from the ventricles with irreversible consequences for unlucky patients. Recently, Ventura Biomédica developing an ingenious anti-siphoning device to prevent with success the over-drainage of CSF in external shunt in relative high pressure gradient.

4. Experimental procedure

All efforts in this present work have been geared to design and construct a test apparatus for external CSF shunts. A CSF drainage system works by communicating vase principle and essentially is constituted of a ventricular catheter, flexible tube and bag reservoir. Two opposite conditions can be observed in relation the height H. The first one is related in Fig. 1 showing positive values for height H, i.e., the reservoir bag is positioned above the head of the patient. In opposition, if the reservoir bag is positioned below the head of the patient, height H assumes negative relative values facilitating over-drainage. The present apparatus for shunt testing is able to operate under positive, near null and negative values of H.

Apparatus for testing of anti-siphoning valves of internal shunts can be found in technical literature. Drake & Sainte-Rose (1994) show several conceptions of devices to performing test in valves shunts involving cheap and others more sophisticated apparatus utilizing infusion pumps and electronic measurements of pressure and volumetric flow. In many other works, the construction details of test devices of valves for CSF drainage are not available, such example, Horton & Pollay (1990), Sood *et al*. (1998) and Kremer *et al*. (1994).

In the present work, a device for testing complete external shunts or parts of shunts has been designed and constructed in order to measure the behavior of the flow rate as function of loss of pressure. Inlet the reservoir bag the pressure is exactly the value of the local atmospheric pressure. ICP should be sufficient to win the hydrostatic barrier of the height H (regarding H positive). For different height H a value of flow rate is observed for each individual shunt tested. Fig. 3 depicts a sketch of the test device proposed.

A –Elevator mechanism
B –Pass motor
C –Microcomputer
D –Discharge reservoir
E –Drain
F –Electronic balance
G –Mariotte bottle
H –Height
I –Bi-distillated water
J –Hole for catheter
K –Air tube
L –Shunt
M –Flexible PVC tube
N –Rigid supports

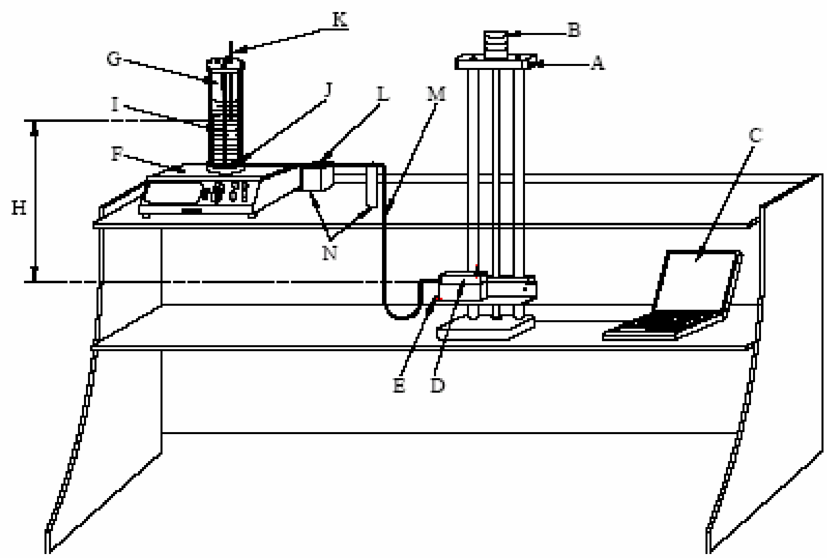

Figure 3 Device of hydrodynamic simulation of external CSF shunts.

The test device, Fig. 3, is composed by an elevating mechanism (A), to apply vertical movement to a platform with controlled velocity by means a pass motor (B) interlinked to a micro computer (C). The flow is drained to a reservoir of discharge (D) localized in the platform. A drain (E) permits to evacuate the reservoir previously to begin of the test. A digital balance (F) - Mars Balanças model AS 2000 - with ±0,005 g of measured accuracy equipped with a RS232C interface permits a continuum record the mass drained with the time of the reservoir (G). The reservoir (G) is a well know Mariotte bottle, an ingenious device able to keep the pressure output constant independent of the liquid level inside the bottle. The Mariotte bottle supplies the liquid flow dependent only of the loss of pressure determined by the height H and by hydraulic resistance of the shunt tested. Constructive details about Mariotte bottle can be found on the work of Camilo (2005).

The physical characteristics of CSF, especially the density, are near to ultra centrifuged plasma. Several researchers utilize bi-distilled water in ambient temperature in test of neurological valves of internal shunts, Horton & Pollay (1990), Kremeer *et al*. (19940 and Sood *et al*. (1998). In the present work is also employed bi-distilled water (I). In the bottom of the Mariotte bottle has a small hole (J) for introducing the catheter of drainage. The height H is determined by vertical distance between the low end of the air tube (K) and the entrance of the reservoir (D) installed on the platform of vertical displacement. The shunt (L) is installed following the catheter and the flexible PVC tube (M) finishes the connection with the discharge reservoir (D). Because the vertical movement of the platform executed by means of the elevating mechanism (A), the flexible tube movement can produce interference in the weigh measured in the balance. In order to prevent interference in the weigh measured, two rigid supports (N) fix the shunt tube.

The test device has been designed to operate according to some steps. First of all, the Mariotte bottle is filled partially with bi-distilled water. The shunt or part of the shunt to be tested is connected to Mariotte bottle and to the discharge reservoir. The platform is positioned at the the top of the elevating mechanism. The pass motor is adequately adjusted by means of a digital control and the platform moves in a descends in a controlled constant velocity. The vertical position of the platform and the water mass in the Mariote bottle are continually registered in a digital data acquisition system. These data can be processed and the mass temporal difference can be converted in mass flow and the vertical position of the platform converted in equivalent differential pressure. If the vertical velocity of the platform is sufficiently small the data obtained can be considered equal to data obtained in a static test.

The present device permits to obtain reliable measurements of the mass flow internal to the shunt in function of the differential pressure and data acquisition is automatically realized. This automated test permits to obtain rapid and precise results.

4.1. Test device characterization

The flow inlet a shunt can be considered one-dimensional without significant loss of precision. The Reynolds number maximum (based in the internal diameter of the tube) is less than 600. In this situation, without shadows of doubts, the flow field can be considered laminar. Small effects of superficial stress can be observed in the test without meaningful interference in the results.

A small perturbation in the internal pressure of the Mariotte bottle has been produced introducing 2 ml of bi-distilled water by means of an infusion pump. This introduction of small water mass produces a light rise in the flow mass. Extensive measurements of the time needed to stabilize the flow after small perturbations have been made and presented very small. In all of cases tested the test apparatus shows a quick time necessary to stabilize small perturbations.

In literature consulted, all of testes realized in all devices proposed, were static, i.e., a differential pressure was created and the flow is generated and the measurements are obtained only after the assurance the flow stabilization. In this procedure, few points of measurements can be obtained only after a large time period. In the other side, the present proposed device of shunts test permits to obtain a quasi-continuous curve in an automated process in a relative small time of work.

A comparative test utilizing several descendent velocities for the platform is showed in Fig. 4. This test permits to visualize the adequate velocity of the platform. Static measurements, i.e., for the platform velocity equal to zero, is considered the reference value (vref). Three other velocity values are showed. Under very small velocity (v1), values of flow lower than the reference value are showed, probably due to surface stress effects. For a platform velocity (v2) equal to 1.07 m/h the volumetric flow measured is close to reference values. For velocity (v3) the flow values shows a large discrepancy. In this present work all of tests have been realized utilizing a platform velocity (v2).

In this present quasi-continuous process of measurements an important question should be attacked, related to the flow measurement. The balance utilized in the test have a RS 232C interface with a sample frequency of 4.21 Hz. In other words, 253 measurement points can be recorded per minute. This frequency is adequate for the present application. The mass flow can be obtained utilizing Eq. (1).

$$Q_{aver} = \frac{m_1 - m_2}{t_2 - t_1} \tag{1}$$

were, (Q_{aver}) is a average mass flow measured in a time interval determined by ($t_2 - t_1$) and ($m_1 - m_2$) is the mass difference registered in the same time interval.

In this present work, a time interval of 4.439 s (equivalent to 57 points of weight measurements) has been adequate to flow measurements. A platform velocity of (v2) equal to 1.07 m/h represents only 4.0 mm of platform displacement.

Finalizing, Table 1 shows an estimate values of uncertainty for several variables utilized in this work. The uncertainty of the volumetric flow and height H, in accord to Moffat (1998), can be calculated equal to 0.1 and 1% respectively.

4.2. Test of a anti-siphon valve.

The external shunt is implanted only in emergency situations, if the height H shows values very close to zero or negative, the flow rise and in a small time interval serious injuries can happen to the patients. This situation can be observed if the patient suddenly stands up or in case of the external reservoir fall of their pedestal. Camilo (2005) describes several prototypes of anti-siphon valves to be utilized in external shunts. Fig. 5 shows typical results of the flow in function of the height H for a first prototype of anti-siphon valve in several velocities of the platform.

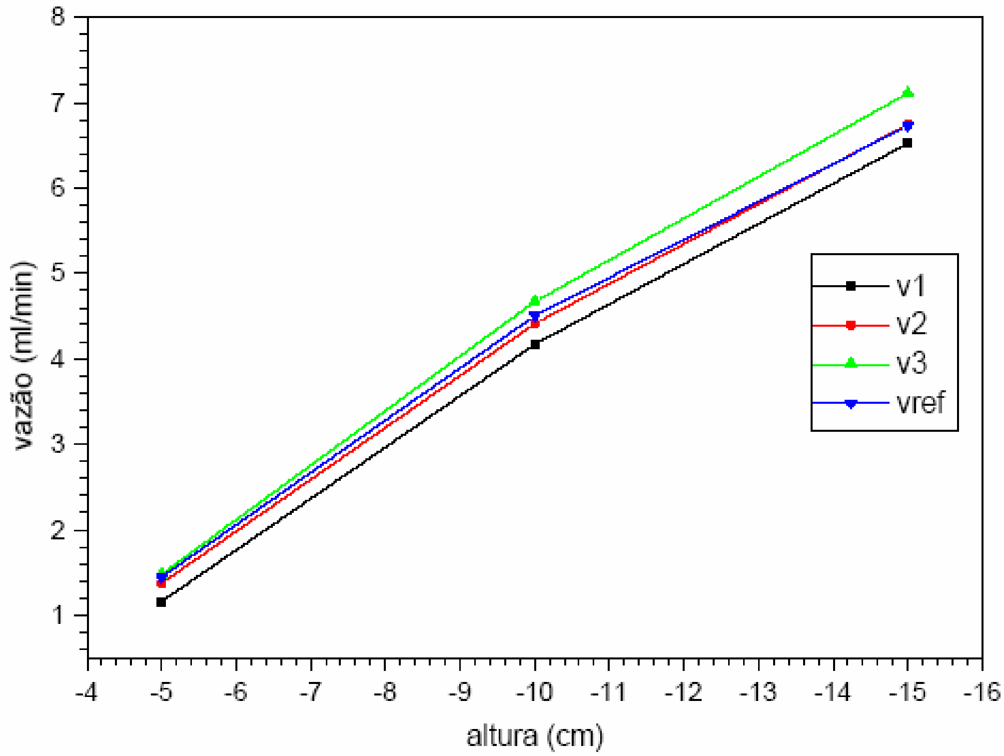

Figure 4 Experimental values of the flow [ml/min] for different values of platform velocities.

Table 1 – Uncertainty associated to shunt test apparatus

Variable measured	Sistematic error	Statistical error	Total error
Weight	<0.123%	$<10^{-3}$ %	<0.12 %
Sample frequency	$<10^{-4}$	$<10^{-4}$	$<10^{-4}$
Plataform displacment	$<10^{-2}$ mm	<0.04 mm	<0.05 mm
Time interval	$<10^{-3}$	-	$<10^{-3}$

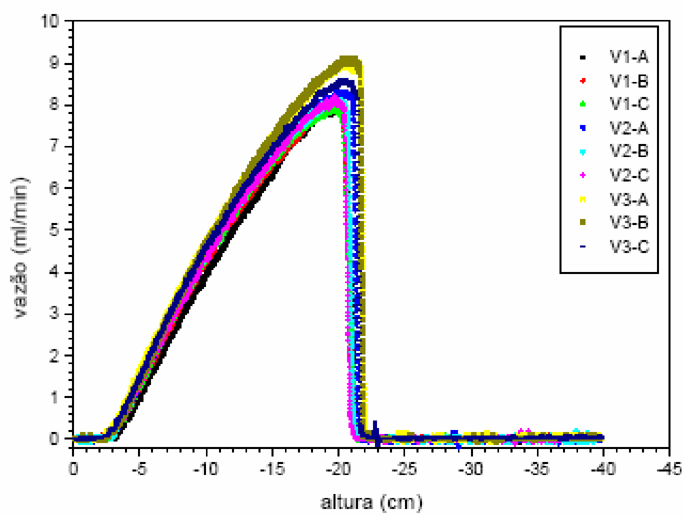

Figure 5 Volumetric flow in function of the height H for a anti-siphon prototype valve.

5. Conclusions

The use of shunting for hydrocephalus has a long history of improvements made through basic science, as well as clinical innovations and biomedical products. Shunting has dramatically changed the outlook of children with hydrocephalus, with many of them having normal life expectancies and attaining normal intelligence.

Modern trends in surgical treatment of hydrocephalus are moving towards the greater use of minimally invasive endoscopic procedures and away from routine shunting wherever feasible. Patients with isolated hydrocephalus should have a normal life expectancy, as long as prompt detection and treatment of complications is provided through maintaining appropriate arrangements for long term follow up.

The cerebrospinal fluid shunt is one of the most common surgical procedures in encephalic neurosurgery. Nevertheless, an important rate of failure (mechanical, infectious or functional) can occur in this procedure. In the engineering viewpoint, mechanical failures should be availed in details. Several engineering criterion of design should be found in order to obtain an optimized shunt operation.

Internal shunts, more precisely, peritoneal shunts have been intensively studied after the sixties and numerous internal shunt valves have been developed to provide an effective flow control. In other side, external shunt remains a procedure necessary to several neurosurgical activities and, apparently, few efforts of research have been devoted to establish optimized external shunting.

In the present work, an apparatus for testing of shunting has been proposed and extensively tested in order to study the flow behavior as function of differential pressure of shunts. Flow mass measurements have been performed utilizing an electronic balance with a digital interface and an adequate data processing. This innovating approach permits a cheap and reliable flow measurement when compared to much related expensive digital precise flow measurement devices. Other important point is relative to the use of a Mariotte bottle, permitting a continuous pressure independently of the internal level of fluid.

Utilizing a pass motor, digitally controlled, platform velocity is maintained precisely constant. In this situation, the testes have been developed in a quasi-continuous mode permitting to obtain consistent data in a short time period.

The present shunt test device is adequate for engineering of shunts investigation and permits rapid developing of parts of shunts. Additionally, preliminary results of a first prototype of a valve developed to use in external shunts impeding siphoning have been showed. Independently of statistics, siphoning is a constant source of mechanical failure in external shunt implants. Prevention of siphon effects in external shunt is a notable advance in neurosurgical procedures.

6. Acknowledgement

VENTURA BIOMÉDICA supplied all materials to manufacturing the test apparatus for external shunts and provides funding for this work. Thanks to Prof. Emanuel Rocha Woiski for proofreading the manuscripts.

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