HYDRODYNAMIC STUDY OF DEVICES TO PREVENT REVERSE FLOW OF CSF IN EXTERNAL SHUNTS

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Abstract. *Hydrocephalus is a pathophisiology of adults and children caused by congenital malformations, brain anomalies, tumors, inflammations, infections, encephalitis, intracranial hemorrhages, traumatisms and other. Hydrocephalus can be followed by significant rise of intracranial pressure (ICP) due to the excess of production of cerebrospinal fluid (CSF) over the absorption, resulting in permanent brain injury and death. Following the diagnosis of hydrocephalus, there are few options other than surgery for treatment. A procedure to channel the CSF from the cerebral ventricles to a bag outside of the body is a provisory treatment known as external ventricular drainage (EVD). Several precautions should be employed in the external shunt in order to minimize the infection risk. In this sense, an anti-reverse flow valve is utilized to prevent accidental return of the drained CSF to the brain. In the present work several one-way valves utilized in CSF EVD systems have been tested in order to verify the occurrence of reverse flow (or regurgitation) while submitted to a wide range of adverse pressure gradients levels. Experiments have been carried out in an apparatus for testing complete shunt systems or part of shunts revealing several regurgitation levels.*

Keywords*: Cerebrospinal fluid, CSF, EVD systems, External shunt, Liquor, Hydrocephalus*

1. INTRODUCTION

Hydrocephalus cases were regularly described by Hippocrates, Galen, and early and medieval Arabian physicians, who believed that this disease was caused by an extracerebral accumulation of water. Operative procedures used in ancient times are neither proven by skull findings today nor clearly reported in the literature. Evacuation of superficial intracranial fluid in hydrocephalic children was first described in detail in the tenth century by Abulkassim Al Zahrawi, in accord to Aschoff *et al*, (1999).

The first modern detailed register of a repeated extracranial drainage, in accord to Kompanje & Delwel, (2003), is attributed to a Claude-Nicolas le Cat in 1744. This French surgeon introduced a specially invented canula into the lateral ventricle of a newborn boy with hydrocephalus. The canula was used as a tap and was left in place for 5 days, until the death of the child. This procedure should be considered as the first documented description of a device for repeated ventricular taps in the treatment of hydrocephalus.

Effective therapy of hydrocephalus required aseptic surgery as well as pathophysiological knowledge - both unavailable before the late nineteenth century. Only in 1881, Wernicke inaugurated sterile ventricular puncture and external CSF (cerebral spinal fluid) drainage. Around 1960, the combined invention of artificial valves and silicone led to a worldwide therapeutic breakthrough. After the first generation of simple differential pressure valves, which are unable to drain physiologically in all body positions, a second generation of adjustable, autoregulating, antisiphon, and gravitational valves has been developed, but their use is limited due to economical restrictions and still unsolved technical problems. Today more than one hundred of different valves to control the drainage of CSF have been commercially available – Camilo (2005).

Humans are estimated to produce continually, inside the brain by choroids plexus tissues, around 0.5 ml/kg per day or, for a normal adult, about 500 ml per day of CSF. In accord to Pople (2002) in a healthy adult, the CSF system has only a maximum volume between 120 to 150 ml. In normal circumstances, CSF is recycled over three times each day. If CSF production exceeds absorption causes an anomaly known as hydrocephalus. Untreated hydrocephalus can produce frequently death and the survivors show severe physical and mental disabilities, in accord to Sood *et al*. (2001).

Internally a human brain there are four ventricles, which comprise the ventricular system, sketched in the Fig. 1. Two lateral ventricles, situated deep within the subcortical tissue one on each side of the midline. Each lateral ventricle communicates with the third ventricle through the intraventricular foramina (foramen of Monro). The third ventricle communicates with the fourth ventricle, located in the medulla, through the aqueduct of Sylvius (foramina of Magendie) located in the roof of the forth ventricle which communicate with the subarachniod space beneath the arachnoid membrane. The floor of the fourth ventricle is continuous with the central spinal canal. CSF is produced continuously by the choroids plexus of the two lateral ventricles at a rate approximately 20-25 ml per hour or about 500 ml per day. Once produced internally the lateral ventricles CSF flows continually through the foramen of Monro into the third ventricle and then through the aqueduct of Silvius into the fourth ventricle. Once in the fourth ventricle CSF flows through the foramen of Luschka around the brain and through the foramen of Magendie directly into the spinal cord.

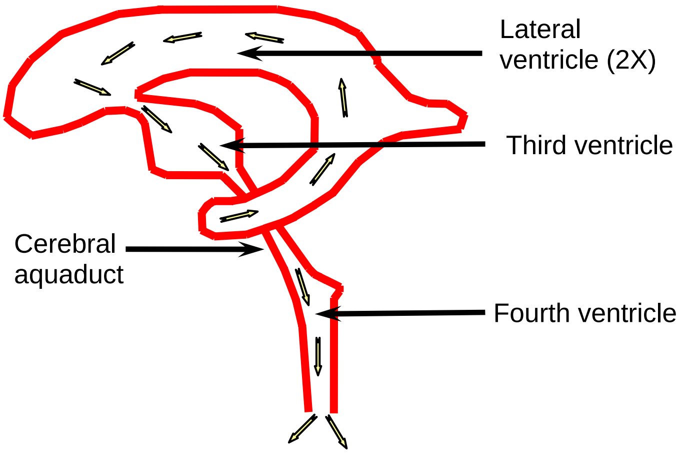


Figure 1. Ventricular system and CSF circulation.

CSF has a lot of functions; it provides buoyancy and support to the brain and spinal cord as well as maintaining a constant extracellular fluid composition for central nervous system metabolic activity. CSF also provides a medium for unnecessary substances and metabolites to be drained away from the neurons. Unfortunately, any type of obstruction at any point of the flow of CSF will result in dilation of the cerebral ventricles and a condition known as obstructive hydrocephalus – Jones & Caynard (1982).

According to Pople, (2002) and Jucá *et al.* (2002), hydrocephalus occurs in neonates, children and aged mans, caused by several congenital malformations (like intracranial cysts, aneurisms and others brain anomalies), extreme premature, tumors, inflammations, infections (meningitis, encephalitis, toxoplasmosis, etc), intracranial hemorrhages, brain aneurism, cranial traumatisms (before and after birth) and other non determined causes.

Hydrocephalus diagnostic is easily confirmed utilizing computer tomography or nuclear magnetic resonance scan. Small abnormalities that may not be detected using tomography, such as cysts and abscesses, are often seen with magnetic resonance images. Following the hydrocephalus diagnostic, there are few options other than surgery for treatment. Nowadays, the treatment of hydrocephalus constitutes an important part of the neurosurgical practice. Despite significant advances in our understanding of the hydrocephalus pathophysiology, the gold standard for treatment remains CSF diversion shunts. Other treatments like third ventriculostomy, for management of obstructive hydrocephalus, choroid plexectomy inducing a reduction of CSF production and the use of several pharmacotherapy with similar intentions have had limited success and many questions remains about its utilization.

External ventricular drainage (EVD) systems are a form of CSF diversion shunt constituted by a close sterile system that allows CSF to drain freely from the lateral ventricles into an external chamber or collection bag. Nowadays, there are a wide variety of EVD systems commercially available. Unfortunately, several complications are associated to inadequate use of EVD systems. Excessive drainage of CFS may also occur if the system is placed too far below the level of the foramen of Monro. This hyper drainage (or siphon effect) may cause the ventricles collapse and pull the brain tissue away from the dura, causing tearing of the blood vessels and resulting in a severe hemorrhage, in accord to Bracke *et al.* (1978). An anti –siphon effect valve possible to be employed in EVD systems and able to prevent over drainage has been extensively developed by Camilo *et al.* (2006 and 2007).

Nowadays, hospital-acquired infections (HAI) affect more than 20 % of patients in intensive care units and have a high associated mortality rate of more than 30 %. Patients receiving neurosurgical intensive care are exposed to several risk factors for the acquisition of HAI. One of the major complications of having an EVD system is infection. Of course, the technical literature shows numerous studies available reporting infection rates relating to shunt diversion, despite sterile techniques during insertion and the use of prophylactic antibiotics. In accord to Orsi *et al.* (2006), 7,6 % of the EVD users patients acquire infections. Pople (2002) relates an incidence of shunt infection in most neurosurgical units of about 5 – 8 %. External ventricular devices utilized in acute neuroscience patients are associated with infections due to prolonged insertion times, deficient insertion or inadequate manipulation technique. Historically, the infection is determined based on positive CSF analysis. In the work of Travis *et al.* (2006) the infection rate for EVD users was 12.7 infections per 1000 days of use.

Once the CSF is channeled out of the brain, in order to avoid infection risk, an anti-return valve, adequately positioned in EVD system, prevent a blockage of return flow. Meantime, typical anti-return valves utilized in commercially available EVD systems produce regurgitation. High level of regurgitation increases the risk of infection. In this effort of work, several anti-return valves are experimental tested in order to study the behavior of the flow under several pressure gradients in order to determine the regurgitation levels.

2. ICP behavior

A simple model to describe the ICP behavior of the brain and internal ventricles in function of volumetric quantities of CSF is proposed by Drake & Sainte-Rose (1994) and a sketch is depicted in Fig. 2. The ventricles are represented by a recipient partially filled of liquid. The recipient has a connection of fluid entrance and a second connection destined to fluid escape. The flow rate entrance is constant and represents the CSF production and in the output connection (CSF absorption) the flow resistance is constant. Three distinct phases can be clearly observed in relation of the volumetric capacity of CSF. First of all, the phase 1, for low level of CSF, is characterized by a noticiable rise of internal pressure with a small value CSF volume increase. For intermediary levels (phase 2), a low rise of ICP is observed for high rise of CSF level. Finally, the phase 3 behavior is identical to phase 1, i.e., small rise of CSF levels provoke a sensible rise in ICP.

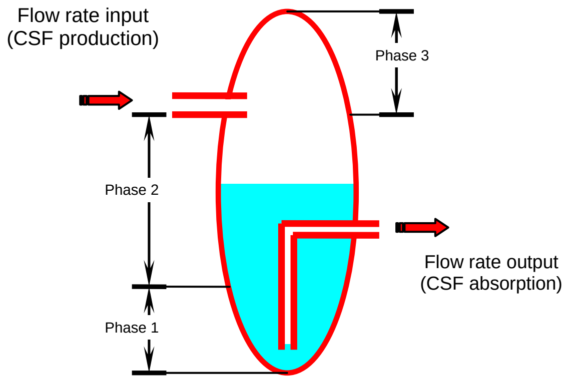


Figure 2. Model of brain and ventricles showing the ICP behavior in function of CSF volumetric level, after Drake & Saint-Rose (1994).

Several researchers, in accord to Camilo (2005), show a lot of evidences of an elastic behavior of the brain ventricles characterized by three distinct phases. In the phase 1, for low volumetric levels of CSF, the ventricles show an inelastic behavior impling in an abrupt rise of pressure for a small increase of CSF volume. In the phase 2, for intermediate CSF volumes, the ventricles show a high elasticity changing considerably their volumetric capacity without sensible pressure increase. Finally, for the phase 3, for elevated volume of CSF, the ventricle return to inelastic behavior showing a relative incompressibility implicating in elevated rise of ICP for small rise of CSF volume.

Figure 3, shows the ICP behavior in function of the CSF volume. The brain presents inelastic characteristics like that one produced by an incompressible cistern, showed in the Fig. 2 by a dashed line, where a small increase in the volume generating an elevated rise in the ICP. The ventricular system, showed by the continuous line, presents the three phase behavior. An EVD system should provides only release the excess of CSF present internally the cerebral ventricles permitting the ICP to achieve normal values.

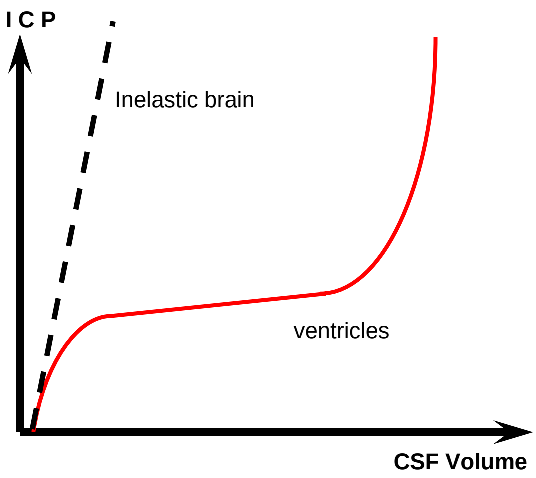


Figure 3. ICP behavior in function of the CSF volume.

3. EVD SYSTEMS

External Ventricular Drainage systems are temporary apparatus which allow drainage of CSF from the brain ventricles to an external bag (collection bag). EVDs are commonly utilized within the neurosciences unit for the management of patients requiring urgent control of the raised intracranial pressure. A sketch of an external device for CSF drainage has been shown in Fig. 4. An external reservoir (adjustable chamber) 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 high frequency and after few seconds in this adverse condition unavoidable non-reversible cerebral damage occurs. Long term over drainage can result in headaches of a very debilitating degree. Over-drainage of gravitational external shunts have been intensely studied by Camilo *et al.* (2005) and Maset *et al.* (2005).

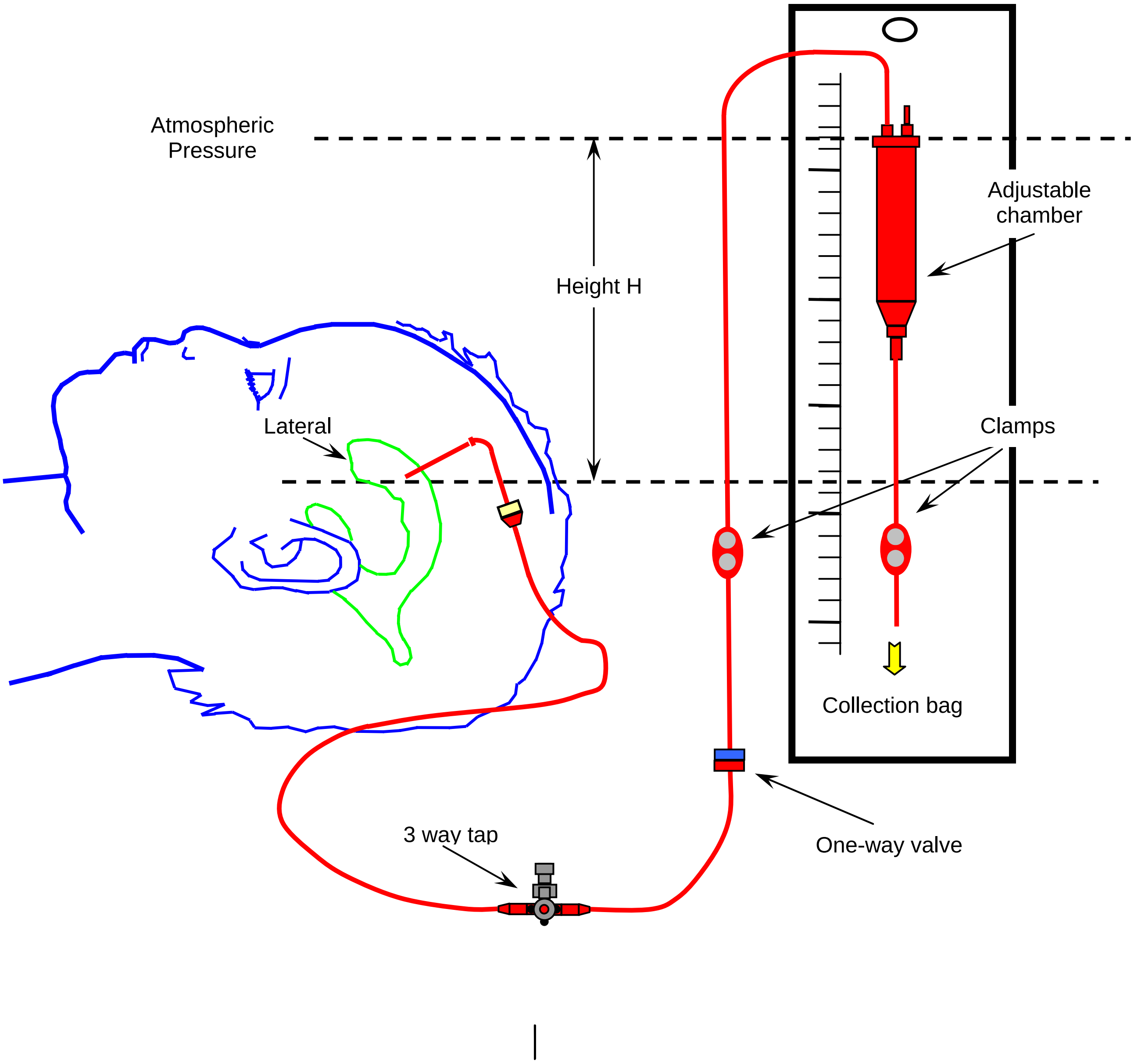


Figure 4. EVD system.

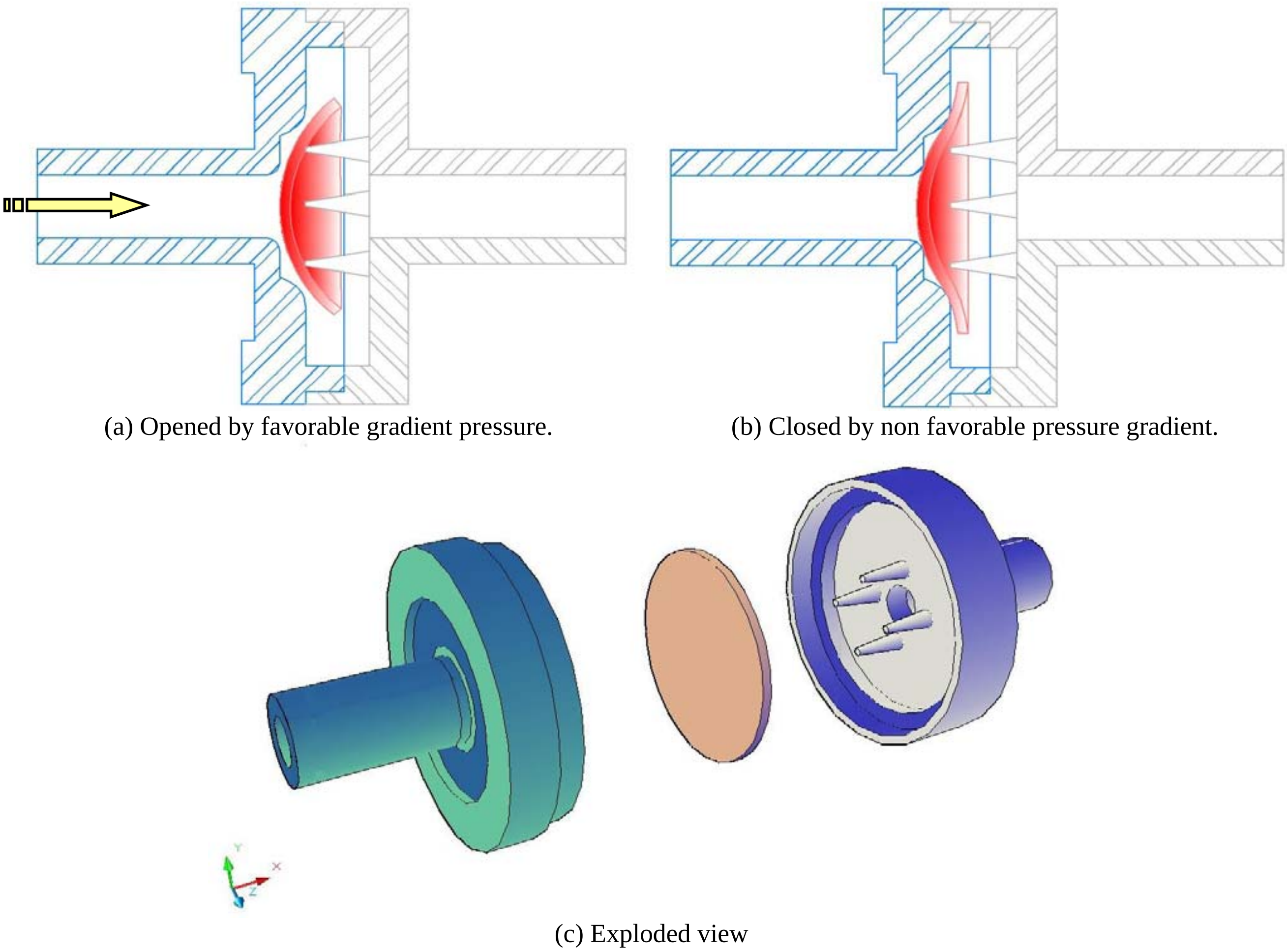
Figure 4 shows a typical commercial external system of cerebrospinal fluid drainage. This apparatus consists of a proximal (ventricular) end that is inserted through the skull (via a small hole), through the brain substance, and into the lateral ventricles. This catheter is connected to a small diameter flexible tube. The three-way tap has been utilized in external CSF drainage in order to connect devices for monitoring ICP, to provide a rapid means of drugs infusion and to gather samples of CSF to be examined. One-way valve is a smart device to prevent CSF reverse flow. Finally, a simple plastic clamp permits a complete flow blockage, if necessary. After the adjustable chamber, a bag operating as an external reservoir receives the CSF flow drained.

If pressure gradient between proximal catheter and external reservoir assume non-favorable values, reverse flow can to occur. The pressure gradient depends only of the ICP and height H (like depicted in Fig. 4). Unfortunately, if height H assumes relative high values, can provokes undesirable reverse flow. Reverse flow can to cause dilation of the ventricles, and subsequent herniation of the cerebral tissues, and, principally, to submit the patient to infection risk. The one-way valve should supplies adequate protection against reverse flow caused by adverse pressure gradient.

In this research work an apparatus for testing external shunts - detailed in Camilo (2005) and Camilo *et al*. (2006) - has been utilized in order to cause several level of pressure gradient in several anti-reverse flow valves permitting to analyze the occurrence of regurgitation effects or reverse flow.

4. ANTI-REVERSE FLOW VALVES

Several models of one-way valves (also know as unidirectional or check valve) have been available in the technical literature utilized in many types of mechanical devices in order to avoid reverse flow (reflux). A check valve is a mechanical device that allows the flow only in one direction. This device, generally, are composed of two-port valves, one to fluid entrance and other to fluid leaves to output. One-way valves have been many applications, since they work automatically and are not controlled by external control. Heart valves are essentially inlet and outlet check valves, since the heart ventricles act as a pump. Several design conceptions are available for one-way valves for fluid applications; the best known being the ball valves which operates with the help of a spring and a spherical ball. Check valves utilized in CSF external drainage systems are generally a lift-membrane disc valve. An elastic membrane in disc format can be lifted up off its seat by higher pressure of upstream (favorable gradient) to allow flow to inlet to outlet port. If higher pressure acts from downstream (non favorable gradient), the membrane is compressed against their seat shutting the valve. In the Fig. 5 is depicted a typical elastic membrane disc unidirectional valve utilized in EVD system.



(a) Opened by favorable gradient pressure.

(b) Closed by non favorable pressure gradient.

(c) Exploded view

Figure 5. Typical one-way valve utilized in EVD systems operated by lift of an elastic membrane disc. (a) Opened operation – the flow across the aperture in membrane seat; (b) Closed operation and (c) exploded view.

5. EXPERIMENTAL APPARATTUS

A CSF drainage system works by hydrostatic equilibrium principle and essentially is composed of a ventricular catheter, flexible tube and bag reservoir. The height H is determined in order of providence adequate CSF drainage by regulating the slide adjustable chamber above the head of the patient. The experimental apparatus for shunt testing utilized in this present work is able to operate under positive, near null as well as 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*. (2001) 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.

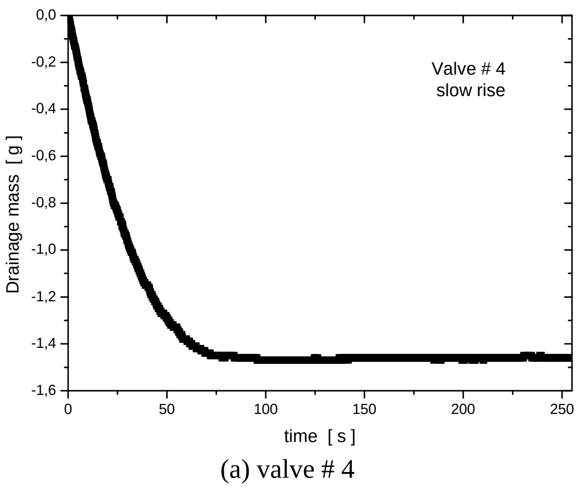
The physical characteristics of CSF, especially the density, are close to ultra centrifuged plasma. Several researchers utilize bi-distilled water in ambient temperature in test of neurological valves of internal shunts, Horton & Pollay (1990), Kremeer *et al*. (1994) and Sood *et al*. (2001). In the present work is also employed bi-distilled water (I).

The present device permits to obtain reliable measurements of the mass flow internal to the shunt as a function of the differential pressure and data acquisition is automatically realized. This automated test produces rapid and precise results. Details of the experimental apparatus are available in the work of Camilo (2005) and Camilo *et al*. (2006).

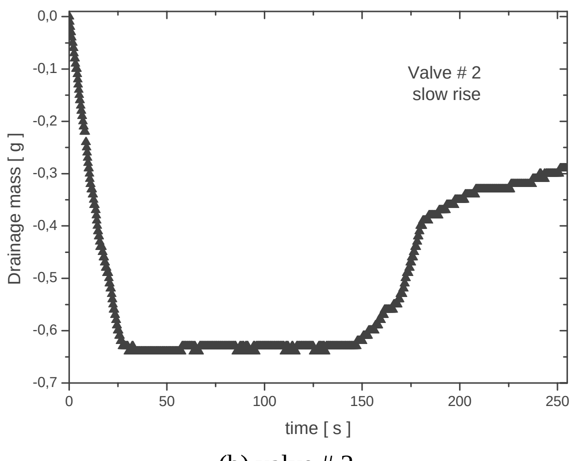
6. EXPERIMENTAL RESULTS

In consequence of their mechanical construction, in the closing process of a one-way valve necessarily regurgitation or reflux occurs. When ICP values are less than the values of the water column pressure generated by height H between the lateral ventricle of the patient and the adjustable chamber, reflux can to occur. Five different commercial models of unidirectional valves have been submitted to several levels of pressure gradient (measured with 1.0 % of uncertainty) and the flow rate measured with 0.12 % of uncertainty. In this present work the valves have been denoted by #1 to #5.

The preliminary tests have been carried out utilizing a starting pressure gradient of -15 mm of water column (favorable gradient) and finishing with +33 mm of water column (non favorable gradient) in a time interval of 250 seconds, representing a slowly rise of height H. Fig. 6 shows the behavior of the drained mass (from ventricle) in function of the time for this slow rise of eight H for valve#4 (Fig. 6a) and valve#2 (Fig. 6b). A drained mass decrease represents CSF out of ventricles and increase of drained mass values represents a reverse flow (mass inlet ventricles).



(a) valve # 4



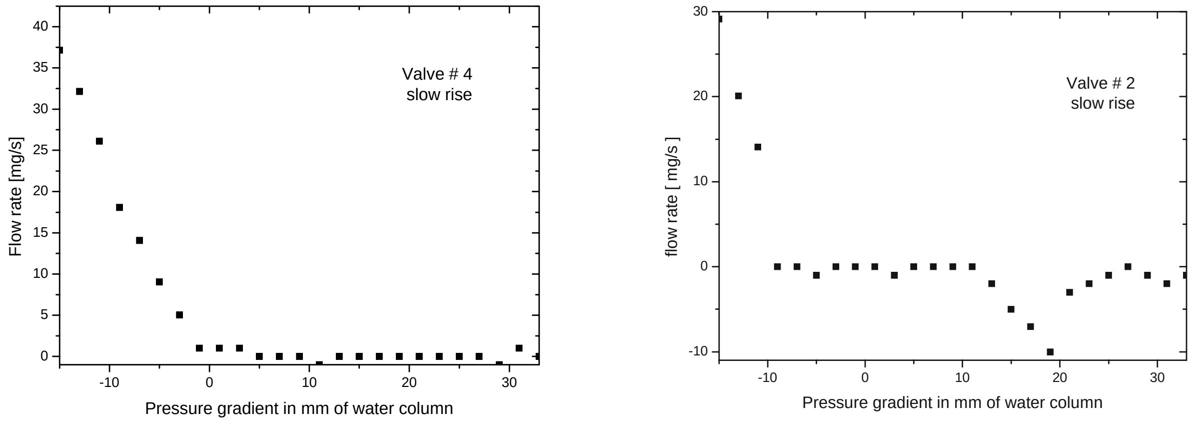
(b) valve # 2

Figure 6. Mass drained in function of time for a slowly rise of height H.

In the figure 6(a) is possible to verify a blockage flow of the valve#4 near 95 s (pressure gradient of 3 mm of water). In opposition, valve#2 behavior, showed in Fig. 6(b) shows a blockage flow around 30.5 s (near -9 mm) but, for more elevated values of pressure gradient (13 mm positive, around 150 s), reverse flow clearly occurs. Is evident the inadequate operation of valve#2 under a small velocity rise of pressure gradient.

The values of drainage mass of Fig. 6 can be converted into mass flow rate. In this case mass flow rate with negative values denotes a CSF drainage from ventricles, mass flow rate null means a complete blockage flow and, finally, negative values of mass flow rate implicates reverse flow. Fig. 7 depicts the mass flow rate behavior in function of the pressure gradient of the valves # 4 (Fig. 7a) and #2 (Fig. 7b) for a temporal slowly rise of pressure gradients.

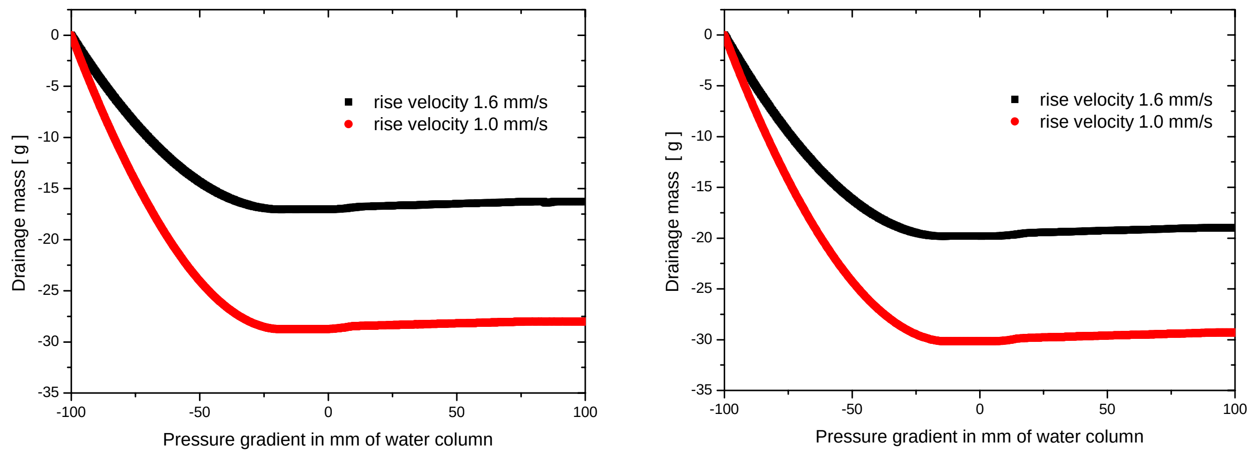
Valves # 1, 3 and 5 behavior has been observed to be very close the valve # 4, i.e., for a rise of pressure gradient near nulls values the flow is blocked. Valve type # 2 shows an anomalous behavior because the flux is null after zero pressure gradient and the flow turns reverse around a pressure gradient around 13 mm of water. These tests have been carried out in slow rise of pressure gradient (from -13 to +33 mm of water column in 250 seconds of time). Again, in this situation, the measured dynamic flow rate is very close to static measurement in permanent regime, like demonstrated by Camilo *et al*., (2006).



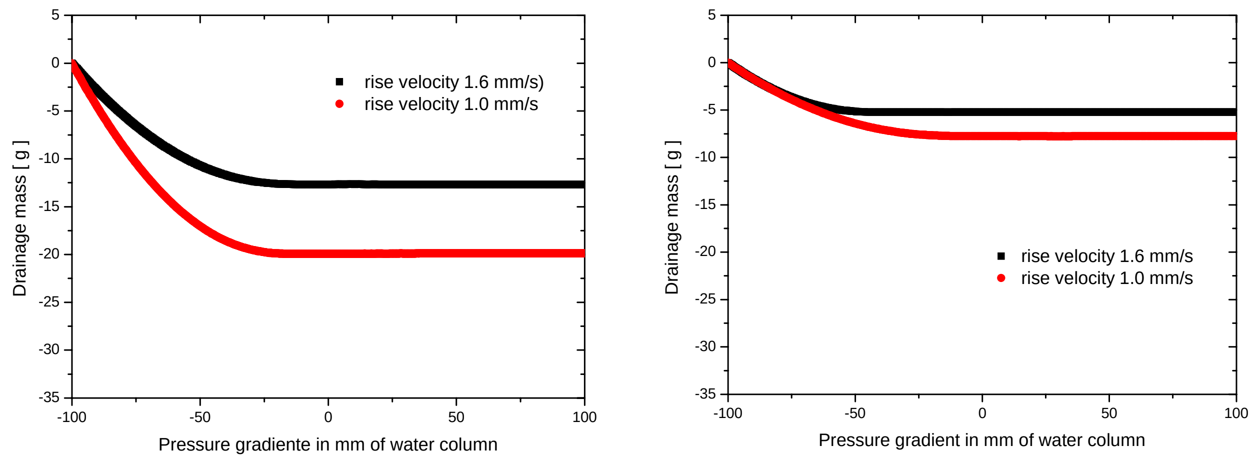
(a) valve # 4 (b) valve # 2

Figure 7. Mass flow rate function of pressure gradient for a slowly rise of height H.

Results showed in Fig. 6 and 7 are related to tests under very small variations of pressure gradient and are very close to static measurements. Others tests have been carried out in more higher rate of increase of pressure gradients, more precisely, the pressure gradient change from -100 to +100 mm of water column in a rate of 1,0 mm/s and 1.6 mm/s and are called by dynamic tests, like depicted in Fig. 8.



(a) valve # 1 (b) valve # 2



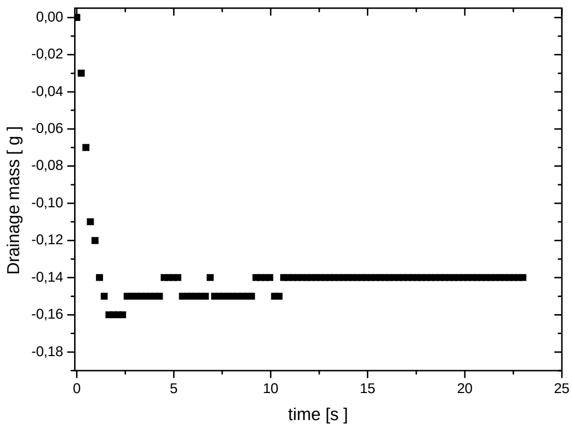
(c) valve # 3 (d) valve # 5

Figure 8. Dynamic testes of drainage mass from ventricle in function of pressure gradient.

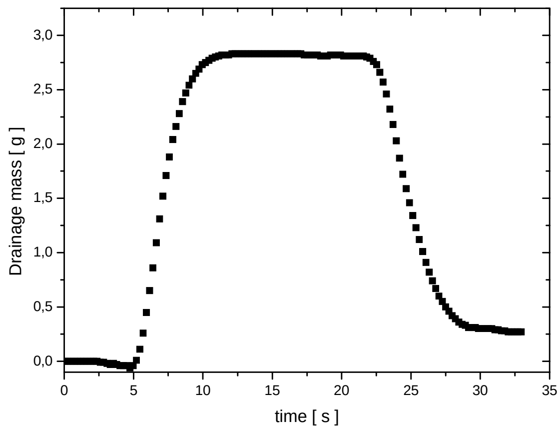
Figure 8 reveals slight reverse flow in all tests carried out independently of the rise velocity of the pressure gradient. A primary observation of the Fig. 8 shows an apparent normal operation of the valve # 2, when compared with other valve operation in dynamic test. In the quasi-static tests, depicted in Fig. 6 and 7, they have been carried out in conditions very close to the steady because pressure gradient variations are very small. In static conditions the system operating in regime permanent in laminar flow producing very small perturbation.

Finalizing, all valves have been submitted to an abrupt rise of pressure gradient and the results have been plotted in the Fig. 9. An abrupt rise in the pressure gradient can be caused by a sudden rise of external reservoir, for example, generates a hydrostatic pressure forcing the reverse flow.

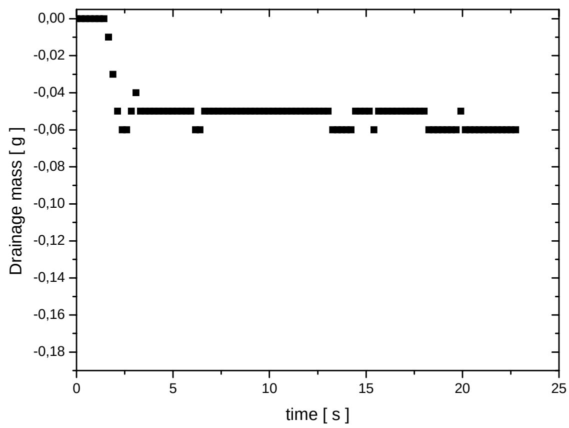
Sudden rise of pressure gradient test have been carried out starting with a pressure gradient from -15 mm of water column and finishing in +200 mm of water column in a time interval of only 2.5 seconds. Flow drainage has been measured in a more extended time interval up to be observed a stable blockage flow.



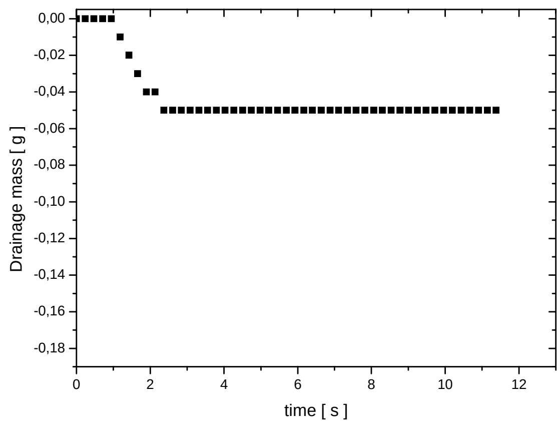
(a) valve # 1



(b) Valve # 2



(c) valve # 3



(d) valve # 5

Figure 8. Abrupt rise of pressure gradient.

Valves # 2 (Fig. 9a), in the abrupt rise of pressure gradient test, reveals an anomalous closing operation. After few seconds the valve # 2 exhibits a high level of reverse flow. Therefore, we cannot recommend the application of valve # 2 in EVD systems because elevated levels of regurgitation and anomalous operating. A more detailed observation of Fig. 9 shows different level of regurgitations in all other valves tested. Valve # 5 (Fig. 9d) shows lower levels of regurgitation, associated with an undesirable high pressure loss and lower flow rates values. In future work it should be necessary to determine the maximum level of regurgitation admissible for a safe operation in EVD systems.

7. CONCLUSION

Temporary external ventricle drainage remains as a routine procedure for the temporary relief of elevated intracranial pressure. Unfortunately, several unsolved troubles for this treatment have been associated with an effective control of height H between the auricular channel of the patient and the external reservoir. Height H is carefully determined by surgeon and should be periodically checked by the nurses. If height H is very small or negative, undesirable siphoning effects can occurs. On the other side, if height H causes water column pressure to overpass the

ICP and reflux can occurs. Reverse CSF flow is undesirable because submits the patient to infections and increases considerably the ICP.

One-way valves operated only by means of the flow field are a cheap and intensely utilized mechanical device conventionally utilized in EVD systems in order to avoid reverse flow. As all types of check valves, the lift operation of deformable elastic membrane disc is also characterized by regurgitation. In the valve closing process some flow leaks generating a back flow or reverse flow. Reflux provoked by five different models of one-way valves has been evaluated as a function of the pressure gradient in this present effort of work. Several levels of reflux have been identified in the valves analyzed. The main goal of a next effort of work will be to determine that level of regurgitation which represents a dangerous operation of an EVD system.

8. ACKNOWLEDGEMENTS

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