STUDY ABOUT DUCKBILL CHECK VALVES IN NEUROLOGICAL APPLICATIONS

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Abstract. *Hydrocephalus (also known as "water on the brain") is a medical condition that affects both adults and children, and it can be caused by birth defects, brain abnormalities, tumors, inflammations, infections, encephalitis, intracranial hemorrhage, trauma and others. In hydrocephalus a significant increase of the intracranial pressure (ICP) occurs due to the excessive accumulation of cerebrospinal fluid (CSF) in the ventricles, or cavities, of the brain, this can result in permanent brain damage and even death. After the diagnosis of hydrocephalus, there are some surgical options for treatment. The process involves the placement of a ventricular catheter into the cerebral ventricles to bypass the flow obstruction and drain the excess fluid to somewhere else. The draining can be done by different methods. Draining the CSF into a bag outside the body is a temporary treatment, also known as external ventricular drainage (EVD). It is also possible to perform a permanent treatment, in this case, a shunt system is placed in order to promote the drainage of CSF to another body cavity and the abdominal cavity is one of the most common used for this procedure, called internal ventricular drainage (IVD). In this present research work, first experiments were performed to study the behavior of a specific kind of one-way valve, known as duckbill, when subjected to different pressure gradients, in order to apply in external devices for CSF drainage. The results obtained for hydrodynamic behavior of duckbill valves are compared with the commercial one way membrane valve, available for EVD shunt systems showing a similar behavior.*

Keywords: *Hydrocephalus, Cerebrospinal Fluid, Duckbill check valves.*

1. INTRODUCTION

The word hydrocephalus comes from the Greek "hydro" - water, and "cephalic" - head. The popular term "brain water" is currently utilized for cerebrospinal fluid (CSF), an uncolored fluid which fills interconnecting internal cavities of the brain. The CSF normally presents a very low quantity of cells and usually containing an average of 20 mg/ml of proteins. The main purpose of CSF is to protect the brain and the spinal cord from mechanical shocks, beside the fact that it plays an important role in the biological protection of the nervous system, distributing nutrients, proteins and agents of defense against infections and carries away metabolites (because the brain has no lymphatic vessels), in accord to Waxman (2010).

In accord to Camilo (2005), the CSF is continually produced by a tissue called the choroid plexus situated in the lateral cerebral ventricles. After generated, CSF is continuous drained through the foramens (very small brain orifices which intercommunicate several brain ventricles) up to the subarachnoid spaces and cisterns (the subarachnoid space is a cavity that cover the brain and spinal cord, bounded externally by a fine arachnoid membrane and internally by the surface of the brain). CSF recovers all the brain and spinal cord and is absorbed by special tissues existing in cephalic box, as can be seen in Fig. 01. Blue arrows show the CSF way from plexus choroids to the back of the brain where it is absorbed. The cerebrospinal fluid shows an uninterrupted cycle of production, circulation and absorption. A healthy adult presents about 150 ml of CSF total volume flowing throughout its body in a continuous daily production rate between 400 and 500 ml. Therefore, a state of dynamic equilibrium for the CSF must exist, since the amount produced in one part of the system is simultaneously absorbed elsewhere. Hydrocephalus occurs when there is an excessive imbalance between production and absorption of this fluid, this can happen due to a decrease in the absorption or when there is obstruction in the passage of liquid through the foramens (most common), causing a CSF accumulation inside the brain ventricles and consequently increasing internal brain pressure and also the intracranial pressure (ICP).

According to Carlotti Jr, Colli & Dias (1998), the intracranial pressure (ICP) in a healthy person ranges from 5 to 15 mmHg and this is because the relationship between the contents of the skull (brain, blood and CSF) and skull volume (considered constant). Hydrocephalus can be congenital (present at neonates), due to genetic factors, brain malformation, or even by the baby being premature, and there is also acquired hydrocephalus resulting from infections, tumors, cysts, hemorrhages, meningitis, increased protein content in CSF, among other causes. This abnormal accumulation of spinal fluid in the ventricles can occur at any age and there is no known way to prevent it. Estimations from studies based on data from health systems, in developed countries, shows that the incidence of hydrocephalus occurs in one to three each one thousand births, only to congenital or early onset.

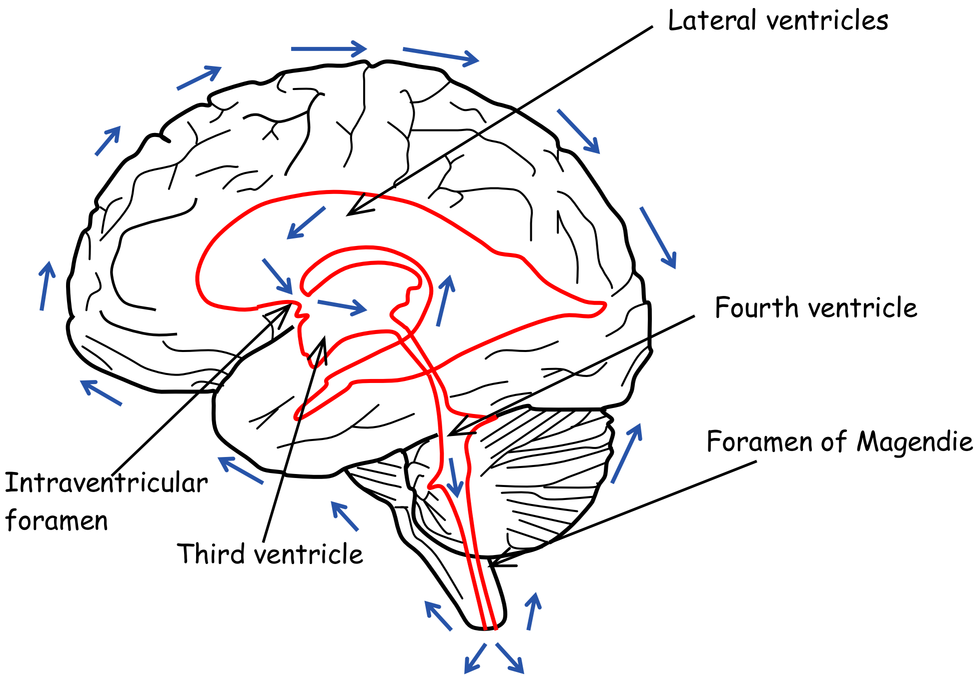


Figure 1. Sketch of the brain and CSF flow system (adapted from Bim *et al*. 2010).

Hydrocephalus can generate several consequences such as causing a weakening of intellectual functions, serious neurological damage (decreased movement, sensation and functions), critical physical disabilities and even death. Practically, about all medicine history there are reports, since the antique ages, of the practice and attempts to drain the intracranial fluid, even with no knowledge about human anatomy and the characteristics and functions of this fluid. Since prehistoric times use of trepanation practices for CSF drainage is observed by archeological discovery with a relative success. The initial development of valves to control ICP and minimize the hydrocephalus effects was done by the hydraulic technician John Holter who began his contribution to medicine when her son had this problem in the 50's. The first CSF drainage valve proposed initially by John Holter, in accord to several authors, including Aquino (2004), control the flow of by means a catheter and several control valves, initiating a new era in the treatment of hydrocephalus. Fig. 2 shows a CSF external drainage from lateral ventricles to an external bag.

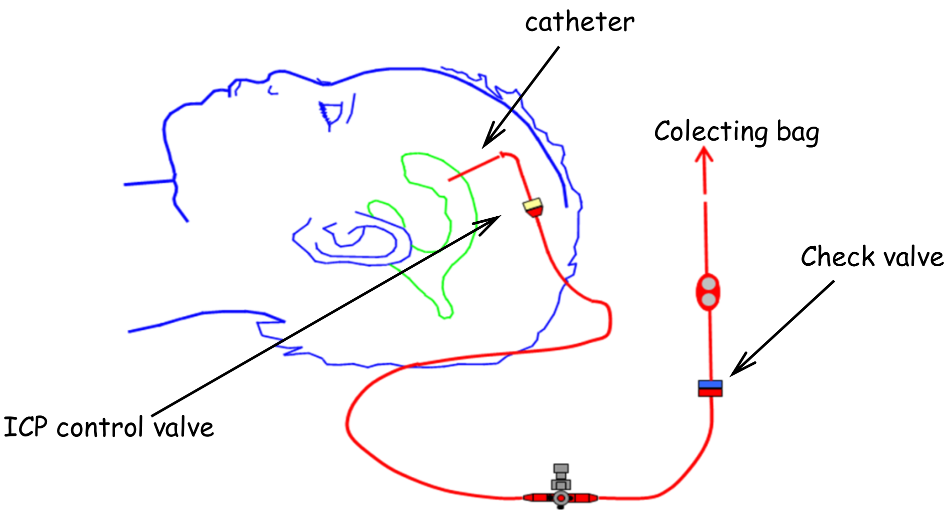


Figure 2. External drainage of CSF (adapted from Camilo *et al*. 2007).

Currently the diagnosis of this condition may be assisted easily by ultrasound, computed tomography (CT) and magnetic resonance images (MRI). Hydrocephalus treatment can occur with surgical placement of a valve attached to a flexible tube, placed into the ventricular system of the brain, in order to drain the excess of the intracranial fluid into a body cavity, usually the abdomen, this is a kind of permanent treatment also known as abdominal ventricular internal drainage (AIVD). An emergence solution is the CSF drainage to a reservoir outside the body, which is a non permanent treatment called external ventricular drainage (EVD), and with this comes the reduction and control of the intracranial pressure. These procedures can result in several complications; besides the risk of infection, there is also the problems such as when the liquid is not removed quickly enough, or when the amount of CSF drained from the ventricles is higher than its production. This can occur in the everyday situations such as, when the patient is bent over or tilting his head or even when he lies down.

The one-way valves are important parts of drainage systems (shunts), also known as check valve, which are exactly designed to ensure that the flow will be drained from inside the brain to outside, and never the other way. The use of one-way valves minimize the infection risks. As noted by Jucá *et al*. (2002), introducing the use of unidirectional CSF drainage for other body cavities and was a great breakthrough in the treatment history of hydrocephalus. According to the author, there was a sensible decrease in mortality after the introduction of this kind of procedure. It can be found in the market many kinds of shunts, each one of them differ themselves from their principle of working, size and range of pressure. The review of Garton & Piatt, Jr. (2004) shows an extensive explanation of the hydrocephalus treatment and complications. Unfortunately, the hydrodynamics performance of several types of check valves is few explored in technical literature for EVD – Camilo (2005). In opposition, hydrodynamics studies of IVD valves show only a total loss of pressure for entire system involving catheter, check valve, pressure control valve and other apparatus - Sood *et al*. (2001).

Maset *et al*. (1996) carried out a detailed study of the CSF over drainage problem in a hydrodynamic view point. In this study, a first anti over drainage valve was proposed for EVD system. Due to several diary changes in ICP values the flow can arise to undesirable values and provoke excessive drainage. Due to precise control of the loss pressure in all shunt components a detailed hydrodynamic study is absolutely needed. In this sense, Camilo *et al*. (2007) shows detailed study of the reverse flow in EVD systems utilizing membrane valves showing the regurgitation occurrences in function of the pressure level and the time variation of pressure gradient. Bim *et al*. (2010) shows a study of micro spring and ball check valves. Ball valves utilize ruby micro spheres and operate rapidly by very small pressure gradient and provoke small regurgitation, unfortunately are very expensive devices.

The one-way valve studied in this present effort of work, known as duckbill, is designed to work outside the body. Since the hydraulic resistance direct influences to the valve performance, it is necessary to study its behavior at different pressure gradients, this way it is possible to determine the valve's coefficients of pressure loss. In this research, a first hydraulic study of the one way duckbill valve has been carried out and results are evaluated with the behavior of the conventional commercial external valve, known as membrane valve, in order to determine the possible application in external drainage systems.

Duckbill-shaped elastomer check valves are often installed in several industrial applications to prevent backflow or undesirable flow intrusion. Hydraulic characteristics of a duckbill elastomer check valve is showed by Lee *et al*. (2001) modeling the duckbill valve as a two dimensional rubber membrane relating the material properties and flow conditions to the valve deformation. The valve opening area is a direct function of the driving pressure head producing a linear head-discharge relation. Fig. 3, depicts a sketch of an elastomer duckbill one way valve utilized in this work for shunt drainage of external devices.

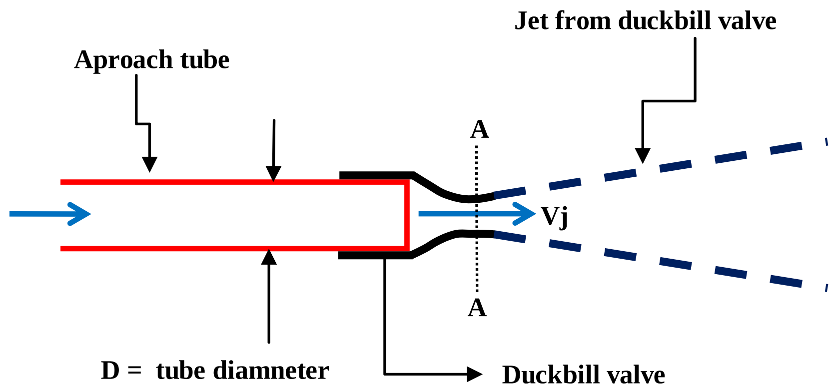


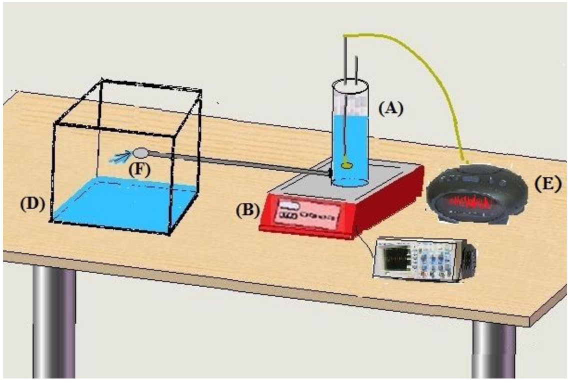
Figure 3. Sketech of a jet discharge from a duckbill valve fitted onto a round catheter (adapted from Lee *et al.* 2001)

2. METHODOLOGY

2.1. Experimental Apparatus

An extensive number of publications are available in technical literature showing a large number of experimental apparatus for testing valves showing very sophisticated measurement instrumentation. The work of Camilo (2005) shows several of these tests, expensive devices designed in order to simulate the CSF flow behavior. Fortunately, use of cheap conventional measurement instruments are possible for the CSF drainage studies and, in many cases, generating good results. For example, in order to measure the flow rate, it's possible to utilize several expensive medical instruments specially designed or adapted. Basically, ultrasound or electromagnetic medical flowmeters permit precise measurements of very small rate of flow, but, generally, are very expensive measurement devices. Many researchers utilize very cheap and precise flowmeters by means the use of basic hydraulic engineering knowledge. Of course, several biological flows can be precisely measured utilizing only basic instrumentation and Camilo (2005) shows a cheap flowmeter utilizing a conventional electronic balance.

The Figure 04 (a) shows a simplified sketch of the experimental apparatus utilized in this work, which consists of: a Mariotte bottle (A) adequately placed on a sensible digital balance (B) – Marte balance model AS 2000 – with ± 0.005 g of accuracy and measurement up to 2000 g. An electronic digital chronometer made by Cronobio model SW2018 with an uncertain of ± 0.05 s directly coupled in the balance permits to determine the instantaneous mass flow rate. The liquid inside the Mariotte bottle is continuously drained to the reservoir (D) through a stainless steel rigid tube with 3.30 mm of internal diameter and 480.0 mm of length, where the valve under study (F) is located in one of its ends. Throughout the process of data acquisition the temperature of the fluid is continually measured by means of a digital thermometer (E) Minipa MT 40IA with ±0.5 ^{o}C of dial indicator uncertain with a range of -50 ^{o}C ~ 750 ^{o}C. The Mariotte bottle is an ingenious device utilized for small liquid flows able to remain a constant exit pressure, and consequently, a constant flow rate in the exit, regardless the level changes of liquid inside the bottle. All instruments utilized have been adequately evaluated in order to determine the uncertain. The balance has been evaluated using ABNT standard mass. The digital thermometer has been evaluated using a micro processed water thermostatic bath – Cold Lab – operating with 20 ^{o}C ~ 30 ^{o}C range. Stainless steel tube used in this work has been produced by pharmaceutical industry in order to make hypodermic needles showing stable dimensions. The fig. 04 (b) depict a panoramic view of the test apparatus.



(a) Schematic view

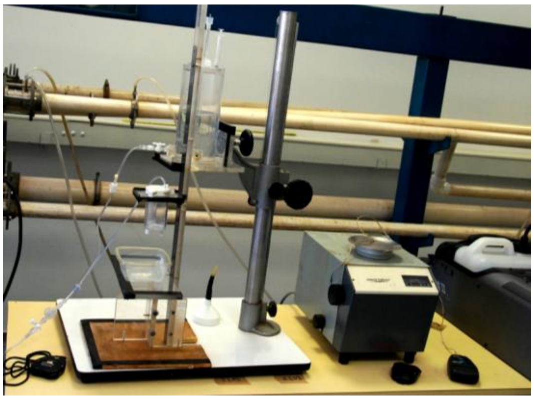

(b) Panoramic view

Figure 4. Schematic of experimental apparatus

In this experimental procedure we utilize water as the working fluid. The physical cerebrospinal fluid characteristics are very close to the double distilled water near ambient temperature. All experiments have been carried out using bi distilled water in ambient temperature. Use of water ambient temperature for EVD system test is frequently observed in several works - Camilo (2005). The mass flow is continuous recorded by means of a digital media.

2.2. Mathematical procedure

From the first thermodynamics law, we can write the general hydraulic energy equation Eq. (1) for a control volume. In according to the Fig. 05, ρ fluid density and P_1 is the statics pressure internal the Mariotte bottle. Statics pressure in the Mariotte bottle is equal to ambient pressure (P_{amb}). The statics pressure in the tube end (P_2), for the present case, an incompressible flow ($d\rho = 0$), the pressure P_2 is also equals to ambient pressure and α is the kinetic energy coefficient. The level difference can be calculated by $z_1 - z_2 = \Delta h$. The mean flow speed (V_1) inside the Mariotte bottle is zero and the mean flow speed in the end of the tube (V_2) can be calculated by the volumetric flow rate divided by the cross section area of the tube. The gravitational acceleration (g) is utilized as the conventional value of 9,807 m/s^2. Finally, α is kinetic energy coefficient and in the end of the tube values of α can be accepted very close to 1.0.

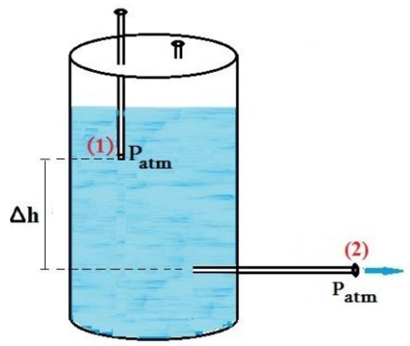


Figure 5. Schematic drawing of the Mariotte bottle used in the experiment

$$\left(\frac{P_1}{\rho}+\alpha_1\frac{V_1^2}{2}+g\ z_1\right)-\left(\frac{P_2}{\rho}+\alpha_2\frac{V_2^2}{2}+g\ z_2\right)=h_{lt} \quad (1)$$

Is important to show, in thermodynamics view point, which Eq. (1) is obtained from energy equation to viscous flow, valid to steady flow, incompressible flow, uniform pressure and internal energy in point (1) and (2) across section and in absence of thermodynamics works. Of course Eq. (1) is valid for viscous flow.

The kinetic energy coefficient (α), is defined in according Eq. (2) and (3), where $\dot{m}$ is the mass flow, *A* is cross section area.

$$\int_A \frac{V^2}{2}\rho V\ dA=\alpha\int_A \frac{\overline{V}^2}{2}\rho V\ dA=\alpha\ \dot{m}\frac{\overline{V}^2}{2} \quad (2)$$

$$\alpha=\frac{\int_A \rho V^3 dA}{\dot{m}\overline{V}^2} \quad (3)$$

Considering that $\alpha_1=\alpha_2=1$, that $V_1=0$ and that $P_1=P_2=P_{amb}$, Eq. (1) becomes Eq. (4), in which the hydraulics losses (h_{lt}) are given by Eq. (5), where h_l represents the losses in the stretch of straight horizontal pipe, with constant diameter and h_{lm} represents the losses by flow singularities.

$$g\left(z_1-z_2\right)-\frac{V_2^2}{2}=h_{lt} \quad (4)$$

$$h_{lt}=h_l+h_{lm} \quad (5)$$

where

$$h_l=f\ \frac{L}{D}\ \frac{V^2}{2} \quad (5a)$$

$$h_{lm}=k_E\ \frac{V^2}{2} \quad (5b)$$

The hydraulics loss for straight tube (h_l) is calculated for the length of the (L), for the tube diameter (D) and the Darcy friction factor (f). In other hand, the hydraulics loss of load for singularities is calculated for the tube entrance and too the valve placed in the tube extremity.

Therefore, measurements without the valve, we obtain Eq. (6) and when the valve is coupled at the end of the pipe we get the Eq. (7).

$$g\left(z_1 - z_2\right) - \frac{V_2^2}{2} = f\,\frac{L}{D}\frac{V^2}{2} + k_E\,\frac{V^2}{2} \tag{6}$$

$$g\left(z_1 - z_2\right) - \frac{V_2^2}{2} = f\,\frac{L}{D}\frac{V^2}{2} + k_E\,\frac{V^2}{2} + k_V\,\frac{V^2}{2} \tag{7}$$

The value of k (load loss coefficient) in the inlet of the tube (k_E) is in accord to Fox &McDonald (1995) is conventionally equal to 0.8; the tube length (L) is 0.480 m and the diameter (D) is 3.3 mm.

Only for laminar flow inside the tube, the friction factor (f) can be calculated in terms of the Reynolds number *(Re)* using the Stokes relation, Eq. (6).

$$\mathrm{Re} = \frac{\rho V D}{\mu} \tag{8}$$

$$f = \frac{64}{\mathrm{Re}} \tag{9}$$

3. RESULTS

Technical literature shows a wide variety of one-way valve models, and their applications can be observed in many cases. A detail study of check valve operation shows absolutely necessary in order to determine the hydraulic behavior and, in this way, provides feedback to improve valve design with high efficiency.

Initially tests were performed using several pressure gradients equivalent to (ICP) without the valve, for Reynolds numbers up to near 10^3. Thus, it was calculated the friction factor of the rigid pipe (f) using Eq. (6 and 9) and the results are depicted in Fig. 06, where the blue line represents what was obtained using the first equation and the red line represents which was obtained using the second equation.

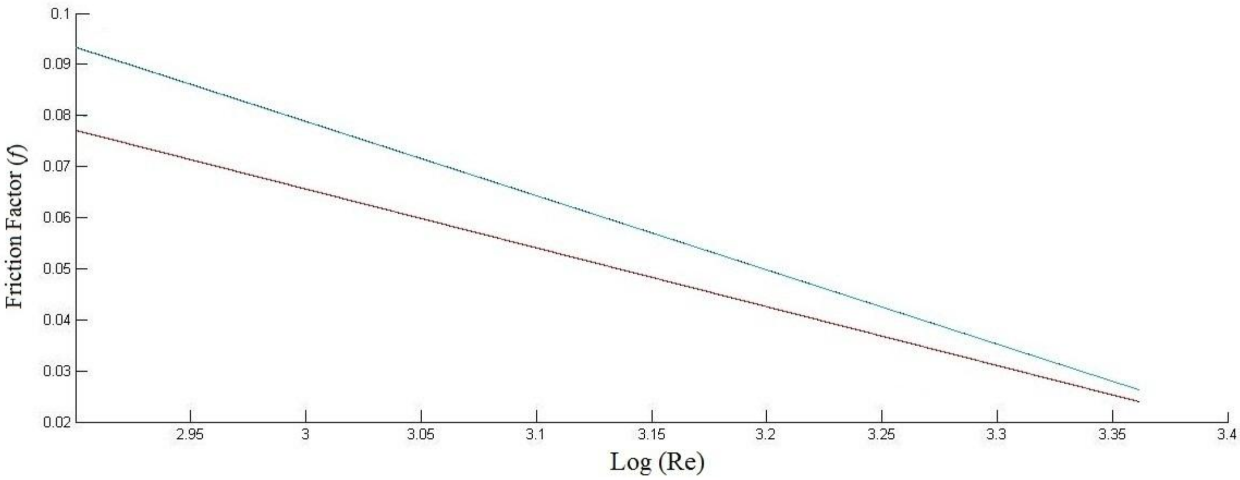


Figure 6. Friction factor (f) versus Log (Re)

The Figure (6) shows that there is a significant difference between the experimental values of friction factor (f) obtained through Eq. (6) and those calculated theoretically by Hagen & Poiseuille (red curve), obtained from Eq.(9). It is important to keep in mind that the equation of Hagen & Poiseuille is only valid for steady laminar flow inlet tubes (Reynolds numbers less than 2100) of Newtonian fluids having a fully developed velocity profile (Fox &McDonald, 1995), which is not always observed in the experiments. Thus, it was chosen to work with the experimental friction factor obtained from the tests. Several medical simulation applied Hagen &Poiseuille formulation without checking its validation.

Knowing the friction factor (f) of the pipe, it was possible to obtain the coefficient of pressure loss (k_V), using Eq. (7), both to the duckbill valve and the membrane valve, when subjected to different pressure gradients. The results are shown in Fig. 7 and 8 for the duckbill valve and the membrane valve, respectively.

ICP for healthy persons depend of physiologic conditions. In an adult, a maximum value acceptable of ICP for test is around 105 mm of water – Camilo (2005).

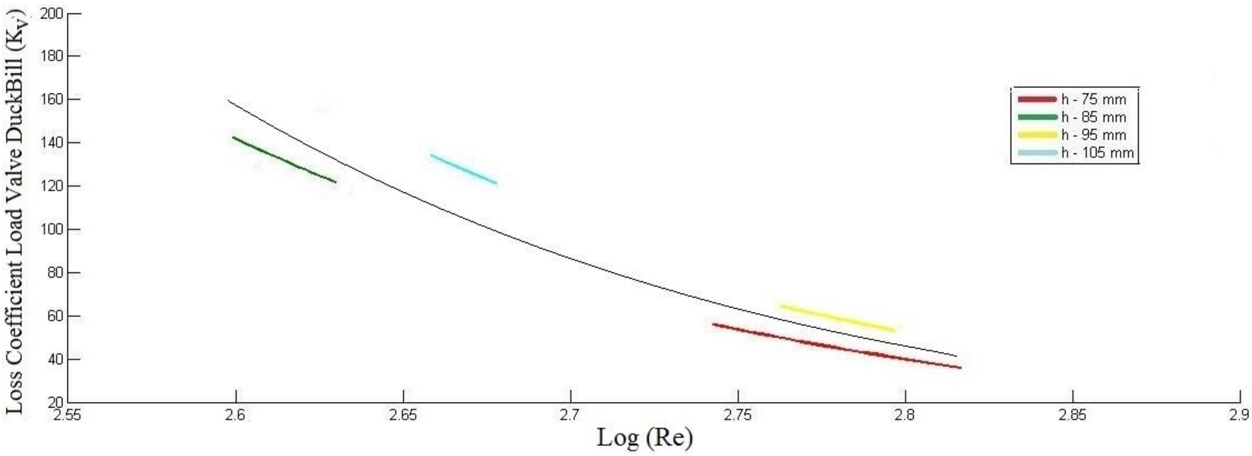


Figure 7. Loss coefficient load duckbill valve versus Log (Re)

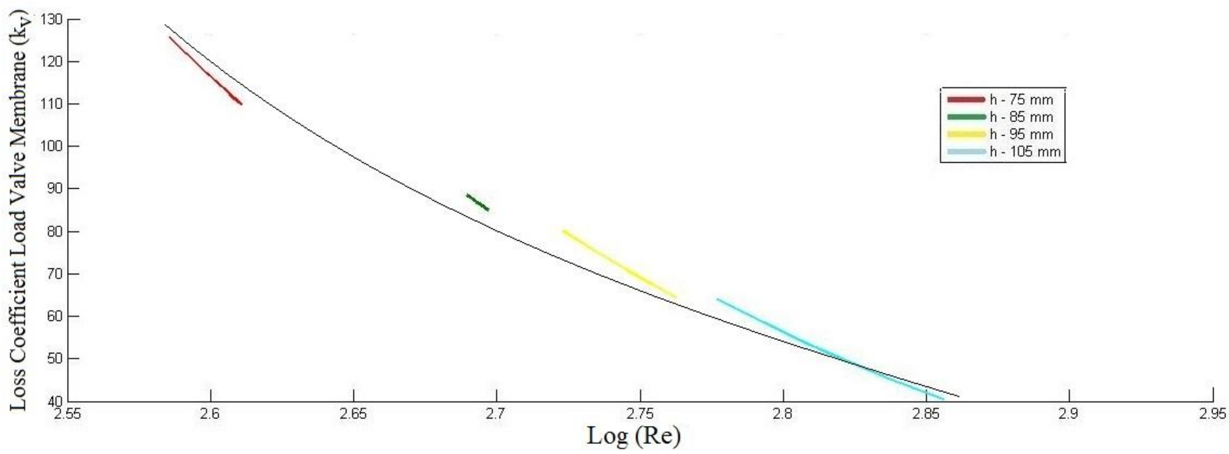


Figure 8. Loss coefficient load membrane valve versus Log (Re)

3.1. Uncertainties

Using Equation (9), the friction factor (f) is obtained to a fully developed Newtonian laminar steady flow. This condition for a rigid circular pipe in an axisymmetric flow is named to Hagen & Poiseuille equation. Hagen & Poiseuille equation is applicable to viscous flow. Unfortunately, other loss of pressure to take place in an EVD system. Of course, several factors affect the pressure changes. The loss of pressure will be divided into major losses caused by Hagen & Poiseuille affects (h_l) and minor losses (h_{lm}) resulting from other nonconstant area portions of the system.

In this work, the uncertainties is obtained by a difference between the loss of pressure due to frictional effects in a fully developed flow in constant circular area tube and the loss of pressure resulting from entrances area changes and singularities. In other works a difference between a system considering only major losses and a system considering the major and minor losses separately. Uncertain has been calculated for the friction factor rigid pipe (results are shown in Fig. 6). The percentage uncertain is shown in the Fig. 9.

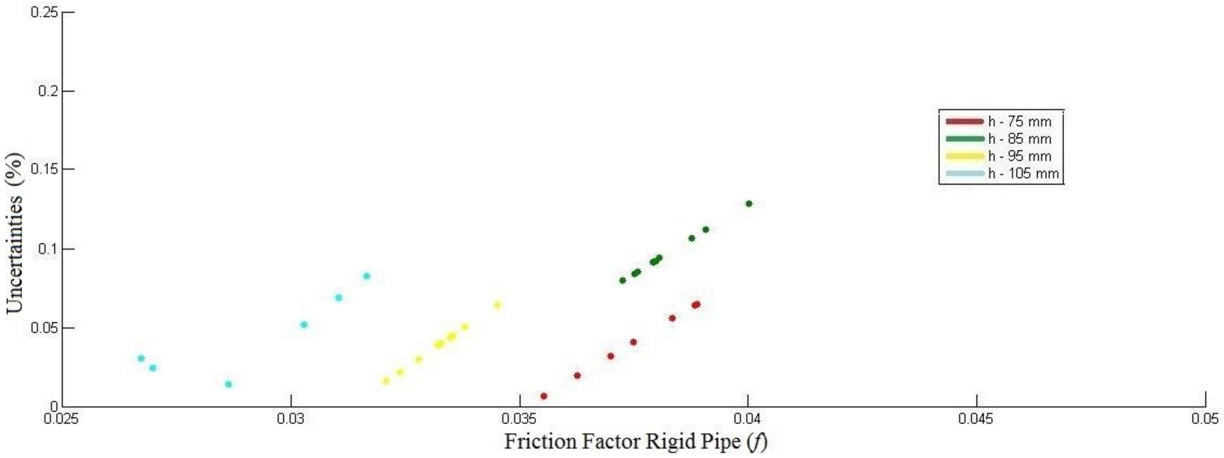


Figure 9. Friction factor rigid pipe (*f*) versus uncertainties (%)

The Fig.10 and 11 shows the uncertainties in percentage which belongs to the results of the loss coefficients load (*k*) for duckBill's and membrane's valves, respectively.

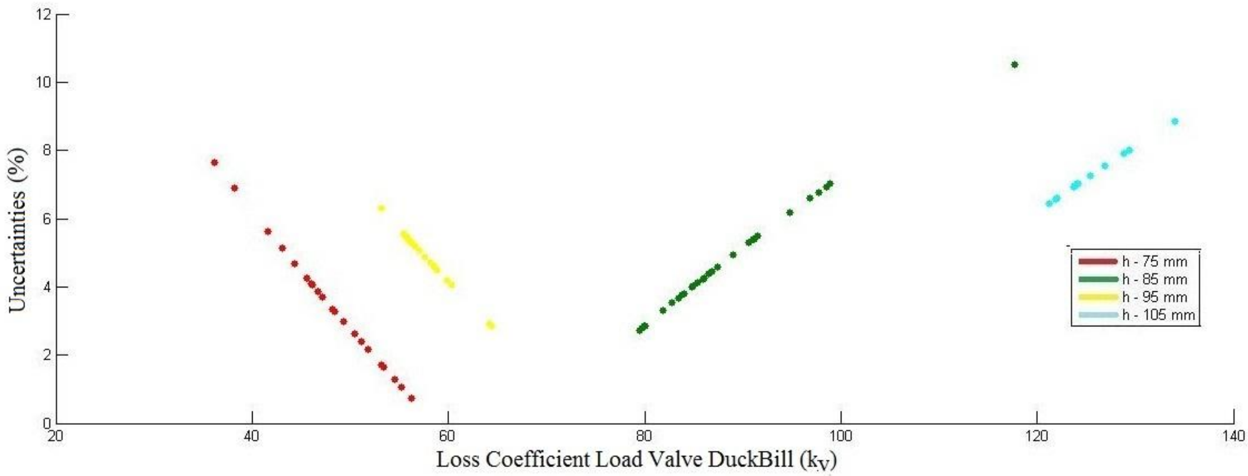


Figure 10. Loss coefficient load duckBill valve (*k*) versus uncertainties (%)

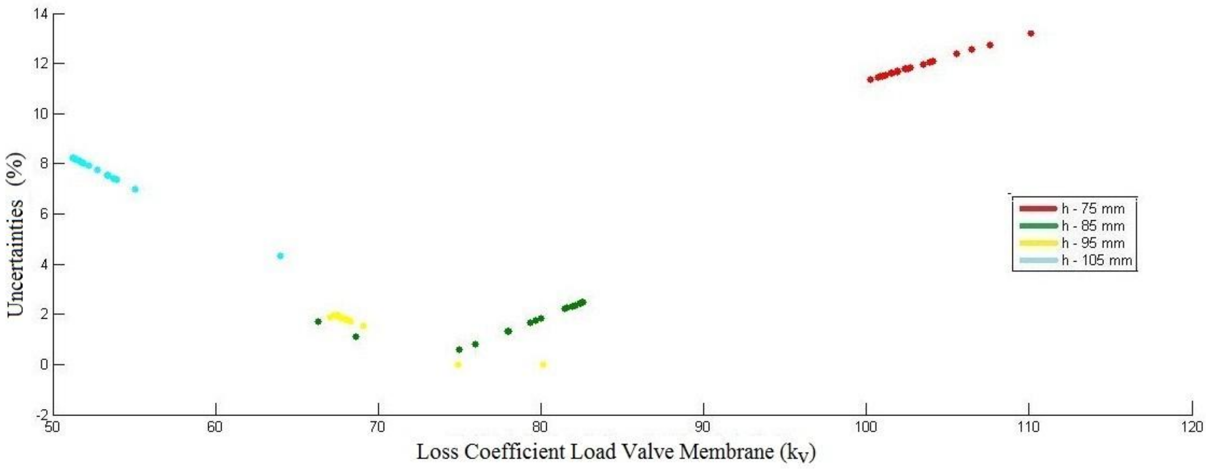


Figure 11. Loss coefficient load membrane valve (*k*) versus uncertainties (%)

4. CONCLUSION

In the present work, a hydrodynamic duckbill check valve study is proposed. Of course, the flow inside the shunt is all laminar, but several simplified assumptions are currently utilized without a detail validity study. For example, use of Hagen & Poiseuille equation is only valid to fully developed velocity profile region. Direct application of Hagen & Poiseuille laminar fully developed equation in entrance length introduces considerable non quantified error. In this present work, a first study in order to analyze the possible use of duckbill valve in external shunt devices is proposed utilizing the loss of pressure formulation based in the equation energy for viscous flow.

Technical advances have made possible to develop shunt devices that are very sophisticated compared with those initially produced giving to the brain optimal operation conditions. However, there is still a risk of shunt malfunction due, principally, to infection and valves and catheters obstruction – Arnell *et al.* (2006). Obstruction, principally due to adherence of proteins in the internal mechanism of the valves walls remains a high risk of valve failure. Because the obstruction valve risk and valve regurgitation a precise knowledge of loss of pressure in EVD systems is absolutely necessary.

5. ACKNOWLEDGEMENTS

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