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Shunt For Treatment Of Hydrocephalus

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1 The Three Components Influencing CSF Dynamics: Production, Circulation, Drainage

1.1 CSF Production

The process of CSF production is done by the active secretion from the cerebral arterial blood. It is believed that this process happens and is limited to the choroid plexus of the ventricular System. In 1910s, there was a surgical operation that targeted the removal of plexus (plexectomy) as a treatment for hydrocephalus, but the outcome of the operation was not satisfactory; due to the Extra-choroidal secretion in the remaining plexuses.

Under normal conditions, it is believed that the CSF production rate is constant. Until current time, scientists have not found a direct and easy method to measure CSF production and because of that, there is still no accurate way of measuring the dynamics of CSF production. There is some hypothesis predict that the production of CSF is affected by some of the CSF waveform components like: respiratory waveform and slow vasogenic (B) waveform.

An operation of pumping Sodium (Na) and Potassium (K) ions through the epithelial walls occurs in the presence of Adenosine Triphosphate (ATP) is essential in the CSF secretion. The Mean rate of CSF secretion is 0.35 , and it is kept proportional to brain metabolism rate.

In the meantime, the CSF formation measurement techniques are imprecise. The first one is called The Messner technique, this technique depends on withdrawing a known volume of CSF and then measuring time needed for intracranial pressure (ICP) to return to its normal value. Unfortunately, this is not an accurate technique, actually it's far from accurate, because technically, the time needed is infinite. The second one depends on the assumption that the rate of production is equal to the rate of drainage with zero absorption, it uses continuous CSF drainage at a pressure that is lower than the sagittal sinus pressure. This technique is much more accurate than the first one but may cause serious complications to the patient's health, due to the CSF over drainage effects.

The third and last technique is considered the most accurate one, it uses perfusion at constant rate for a tracer put in a liquid, this technique requires a prolonged time of measurement, then takes the average of the dynamic components in the production of CSF. It assumes that prolonged time of perfusion makes the difference in the tracer concentration at both input and output to describe the rate of CSF production. The downside of this measurement is that it has to assume that no leakage of CSF occurs to

the brain tissue.

1.2 CSF circulation

CSF produced mainly in lateral and third ventricles along adequate sylvius to the fourth ventricle. Passage through narrow aqueduct is fast and pulsatile-can be detected by MRI techniques. CSF then goes through foramen of magendie and lateral foramen of luschka into subarachnoid space.

It flows upward to superior sagittal sinus where it is most absorbed. Some flows downward to lumbar subarachnoid space which is important for fluid change and volume compensation. Then CSF enters brain and spinal cord to start picking up wastes then to arachnoid villi to sinus system and finally to jugular vein back to heart.

If downward CSF is disturbed-as in arnold chiari malformations-fluid will build up to develop syrinx. Undistributed circulation of CSF is what keeps the CNS functioning correctly. On one hand brain and spinal cord float in CSF thus reducing their relative weight according to Archimedes law, it also acts as a mechanical shock absorber. On the other hand there is no ICP gradient or risk of volume shift or herniation. Brain trauma may cause elevation of ICP from normal ranges 20-25 mmHg to higher levels that may result in herniation which is fatal.

In communication hydrocephalus ICP can reach 40-50 mmHg without sensation or negative effects which could be treated by a SHUNT. In non communicating hydrocephalus obstruction between third and fourth ventricles due to congenital stenosis or mass which could be treated by ventriculostomy (endoscopic procedure).

1.3 CSF drainage

From the anatomical view of the brain it is obvious that the only pathway for the CSF to go out to the blood stream is through arachnoid granulations (Figure 1) which acts as a pressure controlled paths that enable CSF drainage only if ICP is greater than P_{ss} (sagittal sinus pressure) and the drainage stops in case the P_{ss} is greater than ICP.

The relation between the drainage and the pressure gradient is linear ,and the resistance of the CSF outflow $R_{CSF} = \frac{1}{slope}$. its range ($6 - 10 \text{ mmhg.ml}^{-1}.\text{min}$). (Figure 1).

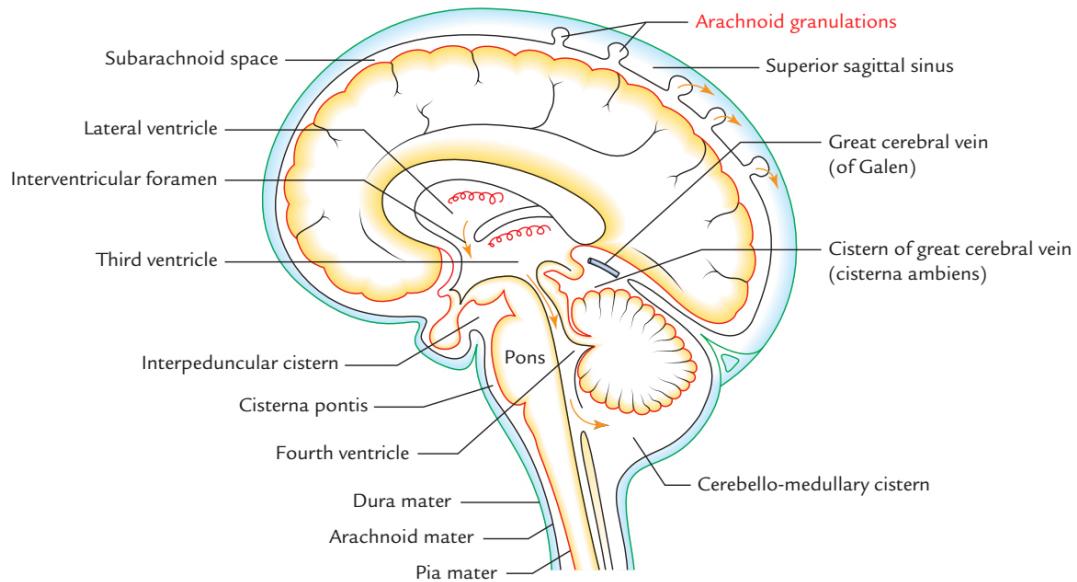


Figure 1: Anatomical view of the brain

2 model of CSF dynamics

in 1978 marmarou introduced his mathematical model of CSF (pressure volume compensation) and then modified to give more application in diagnosing.

2.1 mathematical model

$$CSF_{production} + CSF_{external\ infusion} = CSF_{storage} + CSF_{reabsorption}$$

- $CSF_{production}$ is almost constant
- $CSF_{external\ infusion}$ is the artificial CFS added.
- $CSF_{reabsorption} = \frac{p - p_{ss}}{R}$ where p is the CSF pressure, P_{ss} is the pressure on the sagittal sinus.
- $CSF_{storage} = c \frac{dp}{dt}$ where c is the cerebrospinal compliance. ($mm/Hg ml^{-1}$)

the cerebrospinal compliance is rely on two factor.the cerebral elestance (E) and the reference pressure (P_0) $\rightarrow c = \frac{1}{E(p - p_0)}$.

this equation reflects that the compliance of the brain decreases when CSF pressure increases.

combining equation together we get

$$\frac{1}{E(p - p_0)} \cdot \frac{dp}{dt} \cdot \frac{p - p_b}{R} = I(t)$$

- $I(t) \Rightarrow$ rate of external volume addition
- $P_b \Rightarrow$ baseline pressure

it can be solved for various types of external volume addition . the most common

1. constant infusion of CSF ($i(t) = 0$ for $t < 0$ and $i(t) = I_{inf}$ for $t > 0$) we can match the real curve by this equation

$$p(t) = \frac{\left[I_{inf} + \frac{P_b - P_0}{R} \right] \cdot [P_b - P_0]}{\frac{P_b - P_0}{R} + I_{inf} \cdot e^{(-E[\frac{P_b - P_0}{R} + I_{inf}]) \cdot t}} + p_0$$

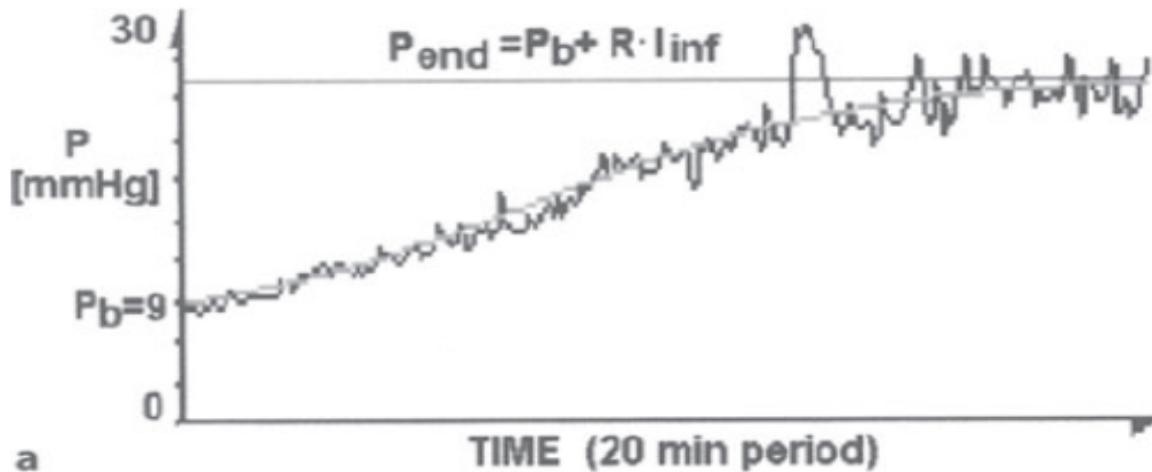


Figure 2: pressure recording during infusion test

2. abolus infection of CSF (volume δV)

- purposes
 - calculating PVI pressure volume index . it is defined as the volume added externally to produce a ten fold increase in pressure. $PVI = \frac{1}{43 \cdot E}$ and if it is less than $13ml$ indicates that pressure volume compensatory reverse isn't sufficient. and if it is greater than $26ml$ it indicates over compliant brain.
 - important in theoretical calculation of the relation between the pulse wave amplitude of ICP and mean CSF pressure.
 - describe the relation between the net effective volume increase and P_{csf} (pressure volume curve) by substituting with $t=0$ in the general equation that give

$$P = (P - P_0) \cdot e^{E\delta V} + P_0$$

2.2 Model Of CSF & blood Pathway

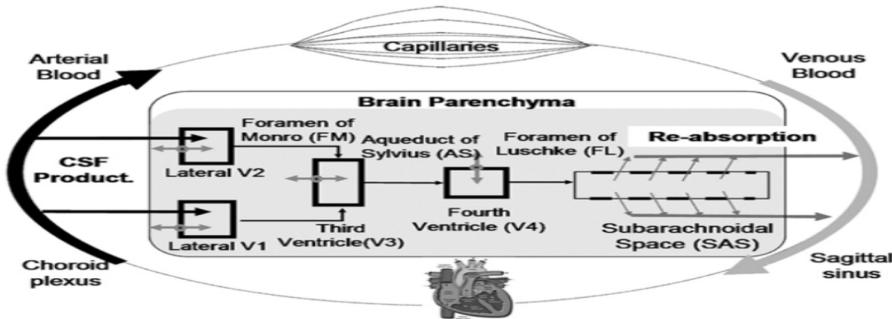
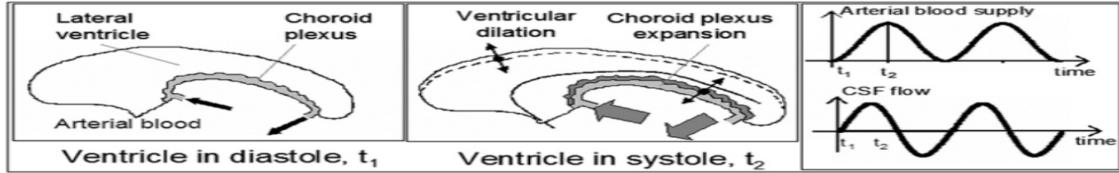


Figure 3: schematic of CSF pathway and vascular system

2.3 Cyclic Motion Of Choroid Plexus Follow Cardiac Cycle By Forcing Function

$$a(t) = \alpha \left(1.3 + \sin(\omega t - \frac{\pi}{2}) - \frac{1}{2} \cos(2\omega t - \frac{\pi}{2}) \right)$$

where:

- $a(t)$ choroid plexus displacement [m].
- α amplitude of choroid expansion [m].
- ω heart rate frequency [rad/s].

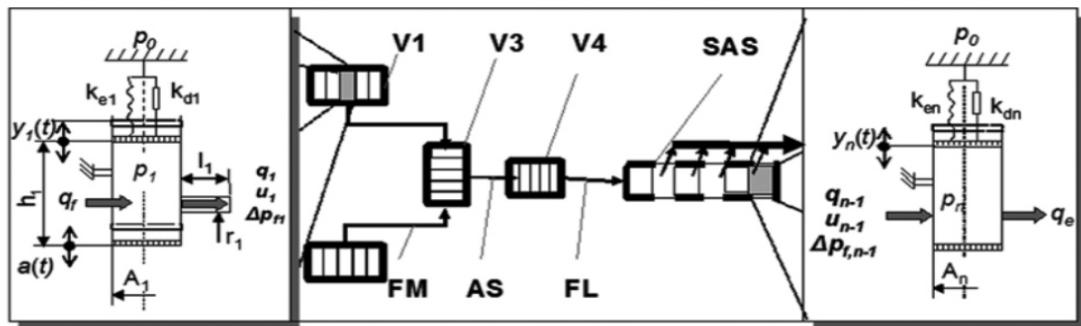


Figure 4: model of CSF flow induced by choroid plexus

2.4 Acceleration Of Elastic Tissue

$$\rho_\omega A_i \delta \frac{\partial^2 y_i(t)}{\partial t^2} + K_d \frac{\partial y_i(t)}{\partial t} + K_e y_i(t) - A_i [P_i(t) - P_o(t)] = 0, i \in LV_1 - LV_4, SAS$$

,where:

- ρ_ω tissue density [K_g/m^3].
- A_i cross section of the ventricles or subarachnoid
- δ tissue width[m].
- $y_i(t)$ tissue displacement in the section [m].
- k_d tissue compliance [N S /m].
- k_e tissue elasticity constant[N/m].
- $P_o(t)$ pressure of brain parenchyma[N/m^2].
- $P_i(t)$ CSF pressure in ventricles and subarachnoid section(ICP) [N/m^2].
- L_i length of foramen connecting ventricles[m].
- $V_i(t)$ axial CSF flow velocity[m/s].
- **SAS** sub arachnoid section.

2.5 Continuity Of CSf Flow In The Ventricles

$$\frac{\partial [A_i[h_i + a(t)] + y_i(t)]}{\partial t} = q_{f,i} - q_i, i \in LV_1 - LV_4$$

where:

- A_i cross section of the ventricles or subarachnoid
- h_i height of the ventricles or subarachnoid section[m].
- $a(t)$ choroid plexus displacement[m].
- $y_i(t)$ tissue displacement in the section [m].
- $q_{f,i}(t)$ CSF production rate in choroid plexus[m^3/s].
- $q_i(t) = A_i V_i$ CSF flow rate leaving ventricles[m^3/s].
- L_i length of foramen connecting ventricles[m].
- $V_i(t)$ axial CSF flow velocity[m/s].

2.6 Axial Momentum Along The Streamline In The flow direction

It is valid for axial CSF flow velocity.

$$\rho \left[\frac{\partial v_i}{\partial t} + v_i \frac{\partial v_i}{\partial z} \right] + \frac{\partial P_i(t)}{\partial z} = -F_i, i \in FM, AS, Fl$$

$$F_i = \frac{8\mu}{r_i^2} v_i$$

,where

- $V_i(t)$ axial CSF flow velocity[m/s].
- $P_i(t)$ CSF pressure in ventricles and subarachnoid section(ICP) [N/m²].
- F_i poiseuille friction [N/m³].
- μ fluid viscosity[Pa s].
- r_i radius of foramine [m].

2.7 Continuity of CSF Flow In SAS Without Choroid Plexus Effect

$$\frac{\partial (A_j[h_j + y_i(t)])}{\partial t} = q_{j,i} - q_{e,j}, j \in SAS$$

,where:

- A_i cross section of the ventricles or subarachnoid section[m²].
- h_i height of the ventricles or subarachnoid section[m].
- $q_{f,i}(t)$ CSf production rate in choroid plexus[m³/s].
- $q_i(t) = A_i V_i$ CSf flow rate leaving ventricles[m³/s].
- $y_i(t)$ tissue displacement in the section [m].

2.8 Diffusive Reabsorption Of CSF $q_{e,j}$ In SAS

$$q_{e,j} = \kappa[P_j(t) - P_o(t)], j \in SAS$$

,where:

- κ reabsorption constant[m³/Pas].
- $P_o(t)$ pressure of brain parenchyma[N/m²].
- $P_{i(t)}, P_{SAS}(t)$ CSF pressure in ventricles and subarachnoid section(ICP) [N/m²].

TABLE I
TISSUE AND FLUID PROPERTIES

Property	Value	Source
Young Modulus for ventricles	2,100 N/m ²	[27]
Young Modulus for SAS	3,500 N/m ²	Derived from [28]
Fluid density, ρ_f	1,004 - 1,007 kg/m ³	[29]
Fluid viscosity, μ	10^{-3} Pa s	i.e. water
Spring elasticity, k_e	8 N/m (normal)	Extracted
Brain Dampening, k_d	0.35×10^{-3} (N s)/m	Assumed - low dampening effect
Ependyma density, ρ_w	1,000 kg/m ³	i.e. water
Reabsorption constant, κ	1.067×10^{-11} m ³ /(Pa s)	Estimated

Figure 5: tissue and fluid properties

2.9 Measuring the Resistance to CSF Outflow

There is a diverse number of methods to measure the , It is useful to diagnose patients with hydrocephalus and to access patients with malfunctioning shunts, whom already were diagnosed with hydrocephalus.

We will have a look at 4 techniques of measurement

- The least invasive and also the least accurate, but the quickest one is the Bolus injection of fluid to the cerebrospinal fluid space.
- Katzman's constant rate infusion. It is more accurate, but has limited applications, which is the communicating hydrocephalus.
- Constant pressure servo-controlled perfusion is equally accurate to the multiple rate infusion studies, but more time consuming.
- The most invasive and most accurate one is the Lumbo-ventricular perfusion.

2.10 Computerized Infusion Test

Using computer algorithms for calculating the mean pressure and pulse amplitude is much more accurate than human analysis. That is because sometimes a strong vasogenic waves above 40 mmHg disrupted the of pressure plateau, so in the case of computer, the algorithm uses series analysis in a sophisticated way to get the results even if the infusion was terminated prematurely. (Figure 6).

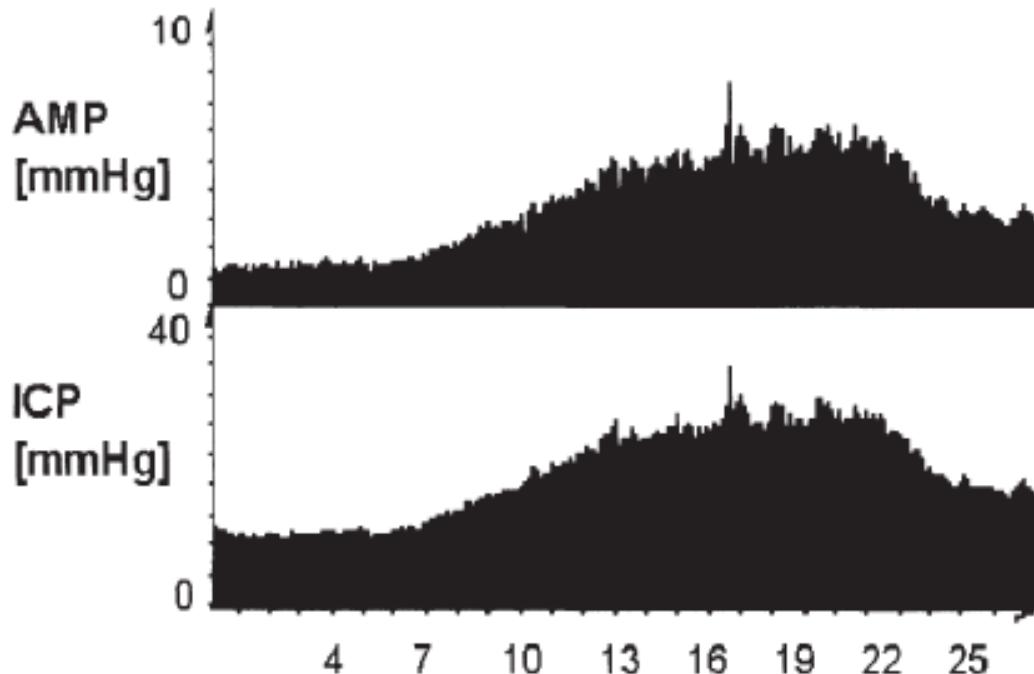


Figure 6: Mean pulse amplitude of CSF pressure (AMP) and mean pressure (ICP) recorded during infusion test (x axis: time in minutes from the beginning of recording). The infusion of 1.5 ml/min starts in the 5th min and finishes around the 22nd min. Figure reproduced from [20], with permission

3 Testing Of CSF Dynamics In Shunted Patients

Testing a shunt before and after surgery is important to ensure its function, so high resting pressure, increase resistance to CSF outflow or decrease PVI should return to its nominal value.

The magnitude of plateau which is higher than opening pressure by 1 – 5 mmHg should not exceed shunt operating pressure + R_{shunt} + infusion rate + 5 mmHg, where R_{shunt} is hydro dynamic resistance and 5 mmHg is a safety margin.

There are three main ways to test CSF space in shunted patients. Infusion study through CSF reservoir, lumbar puncture, and through valves that have reservoir proximal to the valve.

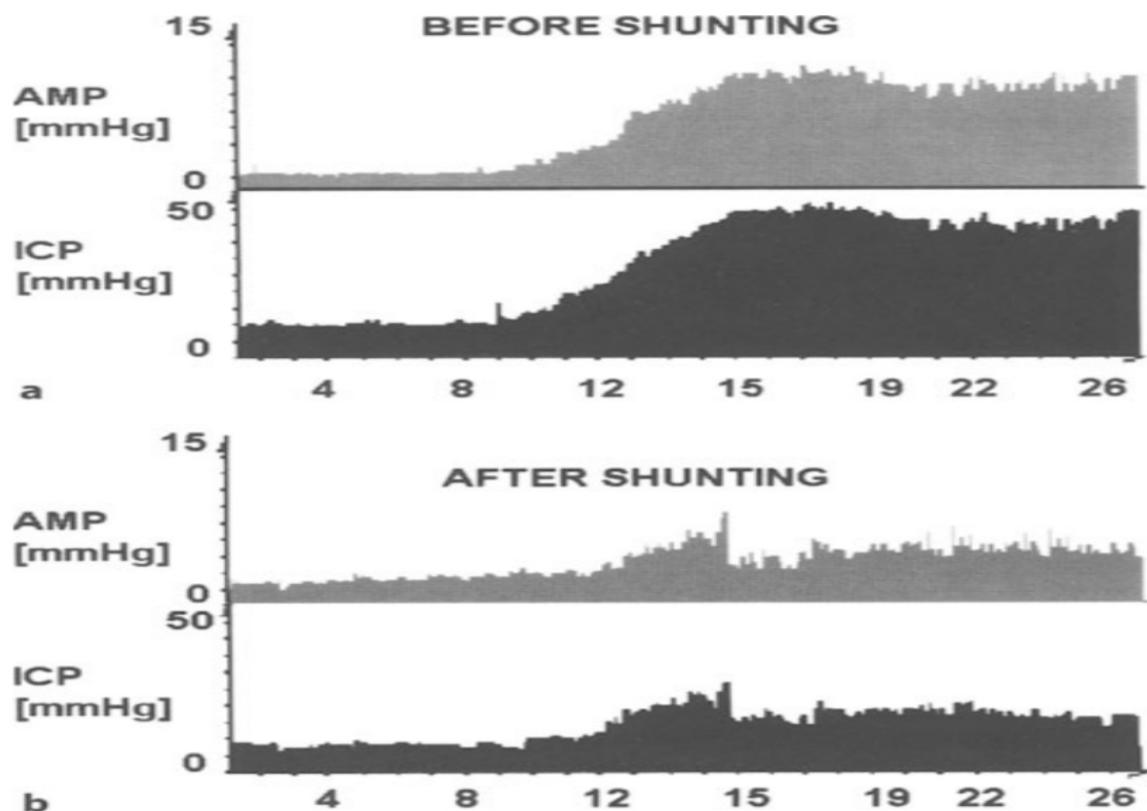


Figure 7: resistance to CSF flow decreased from 20 to 6 mmHg.min/ml

Over drainage is when the pressure and pulse amplitude is in horizontal position are lower than baseline. Change in posture like sitting or tilting may cause over drainage.

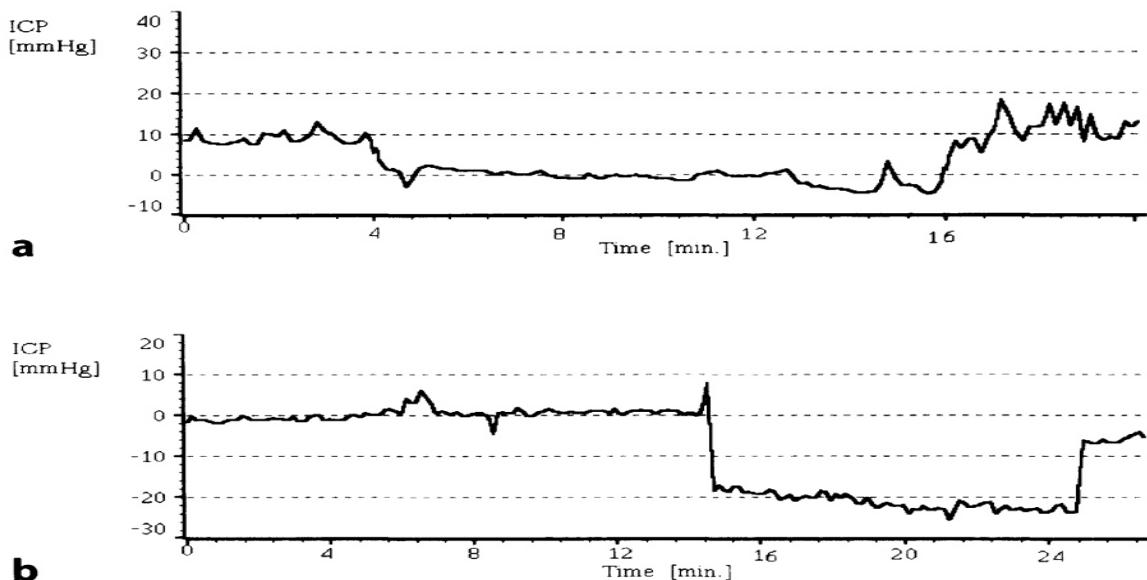


Figure 8: (a) patient with delta shunt (b) a shunt with siphon

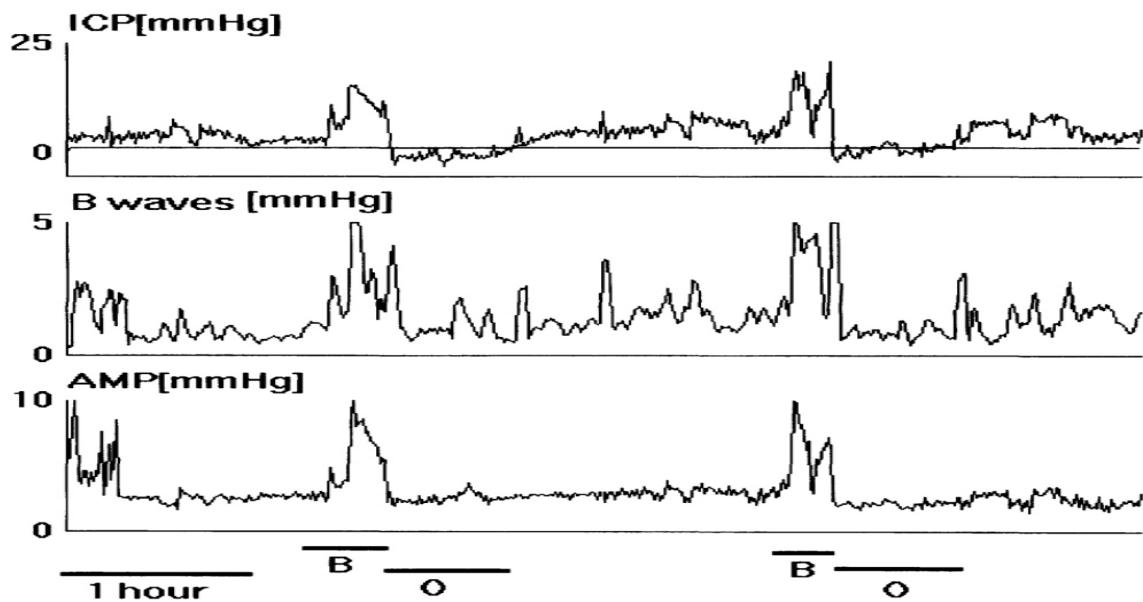


Figure 9: overdrainage related to nocturnal vasomotor waves (B waves), ICP, and AMP amplitude

4 CSF Dynamic Testing Versus Overnight ICP monitoring

Increasing the number of patients increase the accuracy and reliability of the correlation between B waves increase with peaks of ICP. This could be done by a randomized trial.

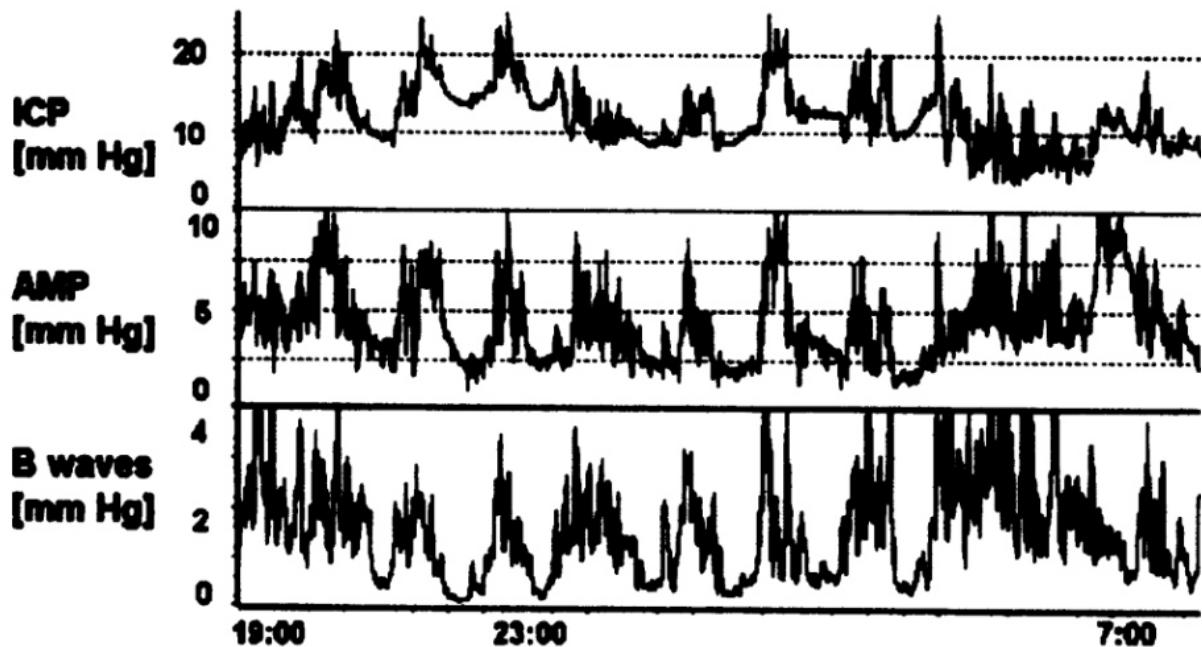


Figure 10: overnight monitoring of ICP with NPH patient showing the correlation 70% of the time

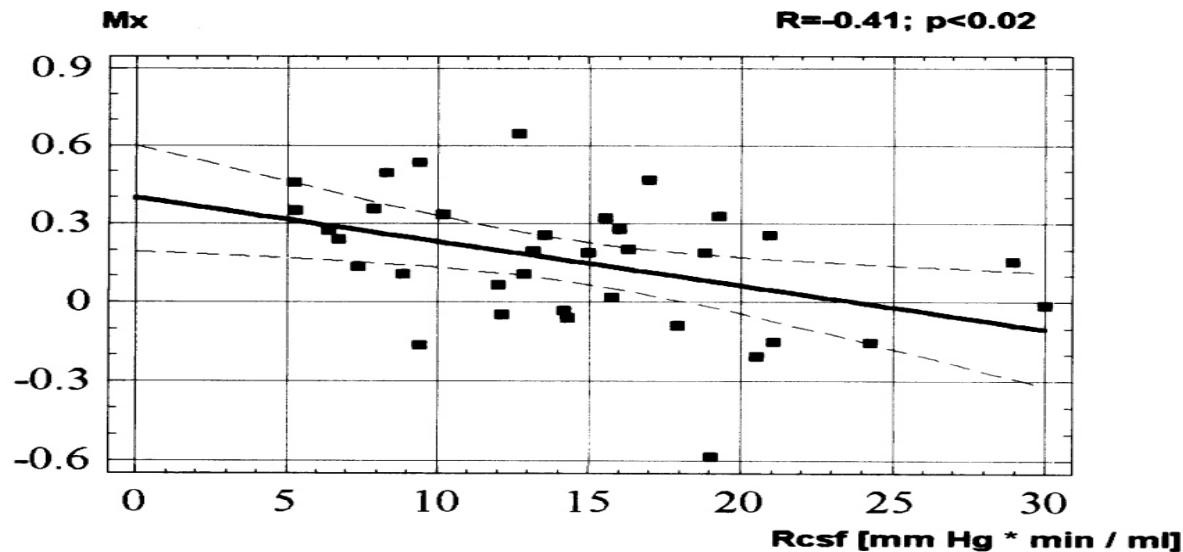


Figure 11: (a)28 patient study with no correlation (b) 73 patient study with positive correlation

5 Vascular Components Of CSF Compensation

In infusion study ICP increase affect blood flow and volume which cause ICP to vary even more ,placing a shunt and describing acetazolamide(vasodilator drug) has positive effects, but the CSF circulation model should be reconsidered.

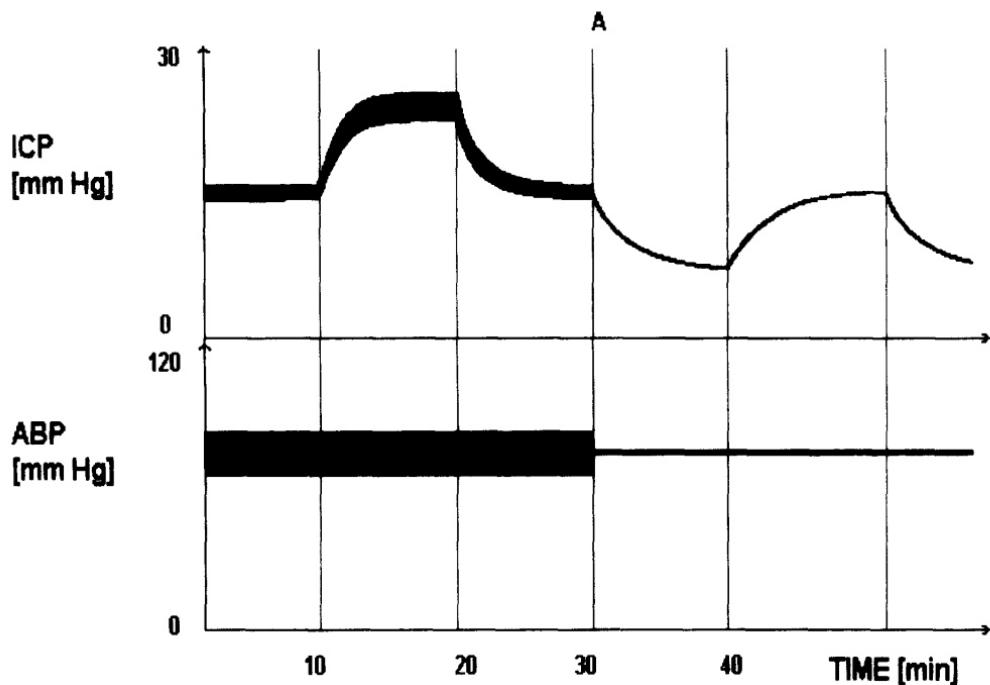


Figure 12: (a)hydrodynamic pressure-flow model (b)equivalent circuit

The balance of cerebrospinal fluid pressure and volume is maintained by volumetric change, CSF volume, and cerebral blood volume any change affect the whole CSF circulation.

Pressure-flow modeling relation between ICP, cerebral blood flow , and arterial blood pressure described by a hydrodynamic model and its equivalent circuit.

- Two external parameters: ABP(arterial blood pressure), Pss(venous pressure in sagittal sinus)
- Internal parameters: ICP in brain and small arteries, cerebral blood flow in large arteries resistance vessels. These parameters are time dependant wave form and could be presented as mean, systolic and diastolic components, or pulse amplitude values.Two major pathways for the model blood and CSF:
 - **Cerebral blood flow** pathway start with atrial inflow by R_a (intracranial vessel), C_a (atrial blood compliance), **CVR**(resistive vessel flow), C_v (capillary and venous blood as compliance), enda with R_b (venous blood outflow to sagittal sinus through bridging vein).
 - **CSF** pathway starts with **IF**(fluid formation), C_i (distensible fluid structures), R_{csf} (reabsorption to venous blood).

number of nonlinear differential equations solved numerically represent hemodynamic response to different cerebral pressure rates.

5.1 Modulation Of CSF Dynamics by vascular factors.

Cerebral vasodilation cause the whole compliance to decrease. Some effects occur due to oedema or expanding mass lesions, but there is no critical change in elasticity coefficient due to hypotension. On the other hand hypercapnia increase elasticity coefficient and brain stiffness. Rcsf increase with hypercapnia and decrease with hypotension.

6 introduction to shunt hardware design

The shunts are devices used to reroute the CSF from the central nervous system to alternate body cavity where it is absorbed. In Current time, a lot of vendors offer a diverse number of shunt devices and configurations. It is not right to describe one shunt better than the others. In this paper we will try to cover some of the shunt configurations and components.

Shunts is basically composed of three components: proximal and distal catheters and a valve. There are some peripheral components that can help the surgeons in the operation of shunt insertion to the drainage system. In the market, shunts are found in two shapes.

It is either sold as one unit or as separate pieces which are assembled by the surgeon. The most important factor when selecting the type of valve is the opening pressure. This is because sometimes the pressure is needed to be adjusted after the operation especially in growing child, so it is hard to choose a specific pressure before the operation.

The Important thing when choosing a shunt, is to know its hydrodynamic properties, also if it is adjustable valve, it is very important to set the initial settings of it. The cause for the hydrocephalus has been known as an imbalance between the CSF absorption and formation, or a block in the CSF pathway. Hakim (1971) tried a more mechanical model approach. He described parenchyma as "an open cell sponge made of viscoelastic material". This model hypothesizes that there is a resistance by CSF venous system and a parenchymal structure to the force expanding the ventricles. Recently, a lot of models that provide a theoretical basis for diagnosing the hydrocephalus have been proposed.

There are a lot of physical factors regarding the CSF drainage, one of them is the patient's position, other one is the pressure difference between the catheter tips, other one is the length and diameter of the tube, or the viscosity of the fluid. The hydrodynamics of CSF must be taken into consideration. In hydrocephalus patients, the hydrodynamic resistance to the CSF outflow gets increased, for that reason, the concepts of the flow laws are essential for this system.

where Q represents the flow, ΔP represents the pressure difference, and R represents the resistance. R_v is the resistance from the valve components, and R_t is the resistance of the shunt tubing. Using Poiseuille law, we can study the results on $Q = \frac{\Delta P}{R}$, so: $Q = \frac{4\pi P R^4}{8\mu L}$ is the radius, L is the length of the shunt tube, μ is the dynamic viscosity and η is a function of temperature. μ is usually taken at $37^\circ C$, we consider as a constant and independent from the flow rate, given a certain geometry. η is not constant. The Intraventricular pressure (IVP) is highly influenced by the total resistance to flow, and effects the opening of the valve, and is found with the eq: $IVP = OPV + DCP$ Where IVP represents the intraventricular pressure, P_v represents the hydrostatic pressure, OPV represents the opening valve pressure, DCP is equivalent to the venous pressure.

The choice of the shunt material is of a top priority, because they are kept in contact with the brain for a very long period of time. The widely used material is the silicone rubber as its biocompatibility has been tested for long-term implants.

There have been limited improvements in the shunt designs, despite of a lot of years of research and redesigning, and that is because of the mechanical complications.

6.1 Ventricular Catheters

silicone polymer tubing with straight shape or angel shape and then because of obstruction is the invasion of choroid plexus via catheter which causes nearly 30% of shunts failures hakim introduced his model as j-shaped catheter with holes inside the curve but the result

of this model was disappointing.

after that Portnoy proposed a flanged catheter with a kind of soft silicone rubber “umbrella” flanges positioned between the catheter holes to preserve holes from choroid plexus invasion. but there was a higher risk during removal as it can cause the hemorrhage. also the main big problem is the adhesion of the tissue and cells to the material of the catheter causing infection and that what made Medtronic propose its design to prevent antimicrobial-impregnated catheter. The catheters feature impregnation of two antibiotics, Rifampicin and Clindamycin into the silicon matrix and positive diffusion gradient exists which causes the drugs to slowly diffuse out of the silicone drugs' concentration can highly contribute in inhibiting colonization of the catheter.

6.2 distal catheter

They are shunt tubing that vary with length due to patient height and age. They also vary by diameter, material type, and tip design.



Figure 13: distal catheter (a)open tip (b)opentip with distal slit ©closed tip

Closed tip in peritoneal cavity or right atrium, but open tip is placed only in peritoneal cavity. It could be used as a safety valve if the tip is obstructed. The catheter tips are coated with graphite to avoid silicon edges sticking.

6.3 Connectors

Short stainless steel or plastic tubes to connect catheters with tubing and valves or accessories. They are grooved to hold sutures that hold the catheter together. A 90 degree turn connector is useful to get the catheter out, rigid ones require more ties with risk of disconnecting, plastic type allow dura and tissue to maintain the shape. External right angled avoid connections, but cause skin erosions in kids. as shown in figure (14)

6.4 Tunneling Instruments And Introdors

A tunneling device is a metal tube with central trochar that bends to aid with subcutaneous passage of the shunt. If a fixed handle is used then low incision is made. Introders can be peeled for the best positioning of ventricular catheters. When peritoneum is opened a suture is made loosely to prevent free movement in the abdomen. This process was done without visual control using peritoneal portnoy trochar [Raimondi and Matsumoto 1967] laparoscopy first presented in 1993 [Armbruster et al. 1993].

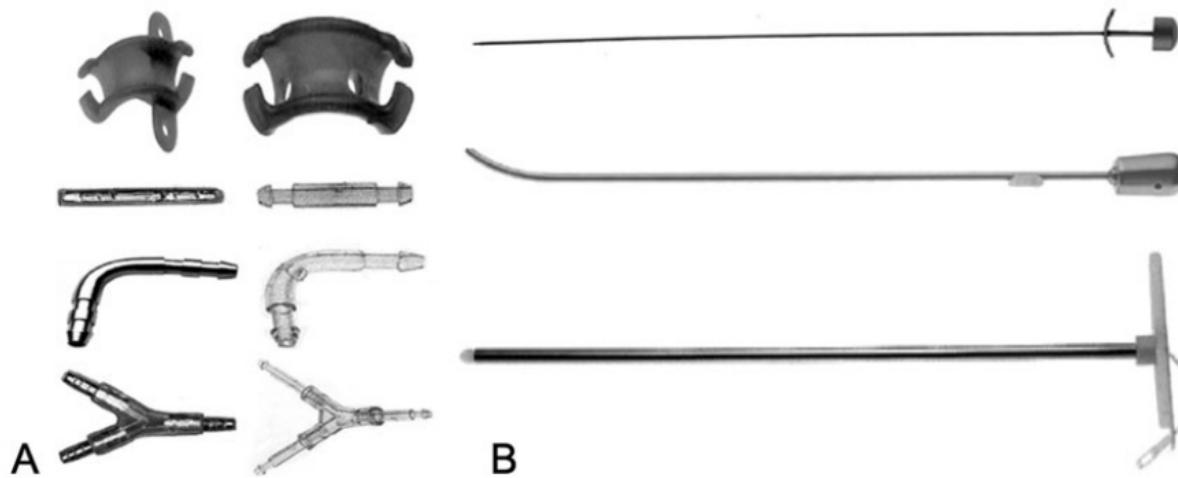


Figure 14: tunneling instrument

6.5 Antechambers And Reservoirs

It is a sampling chamber between ventricular catheter and the valve. It is used to sample CSF, inject drugs, and measure pressure. It can be pumped manually if does not spring back, then there is proximal catheter obstruction, if stiff then there is distal catheter obstruction. It has many different designs, such as burr hole, flat bottom, and rickham with cylindrical valve.

6.6 Neuronavigation Aids To Shunt Insertion

Ultrasonography, frameless guidance, neuroendoscopy, and image guidance are used to reduce the risk of hematoma, injury, and failure, especially in case of narrow ventricles.

7 Aesculap Miethke Thomale Guide

Surgical instrument used for navigation and placement of ventricular catheters . In sagittal plane an angle tangent to the surface always reach the ventricles. In coronal plane specific angle is calculated for insertion by imaging.

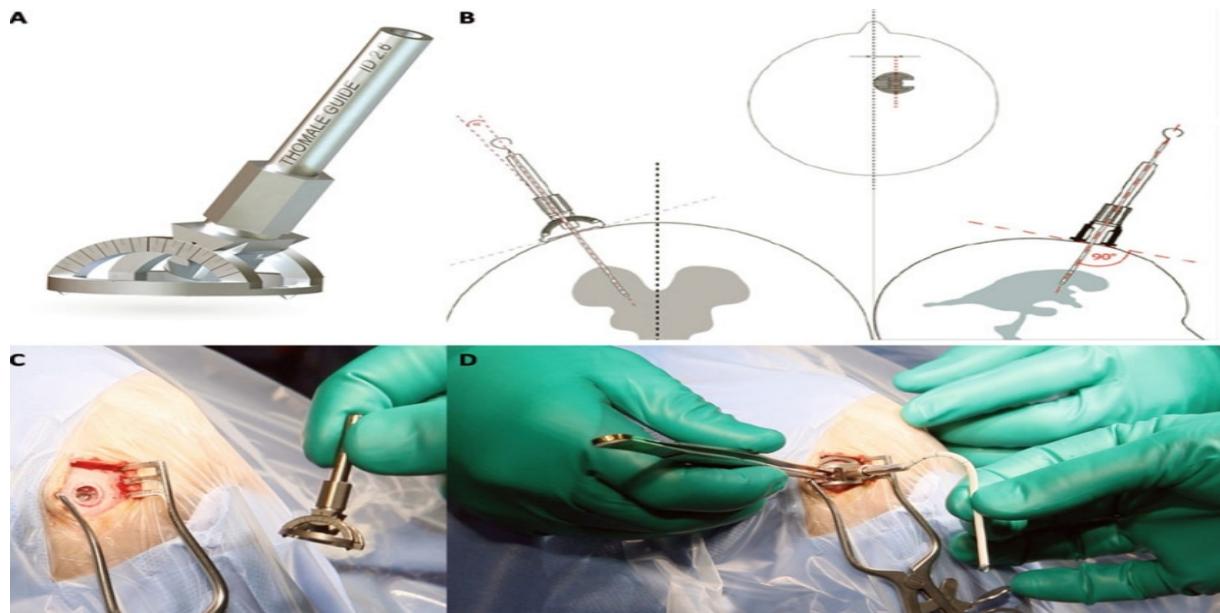


Figure 15: (a)Thomale guide (b)schematic diagram for insertion (c,d) O.R. images

8 shunt valves

a valve is a mechanism that regulate the flow depending on the pressure on our application the pressure is the difference between the ventricular pressure and the peritoneal pressure . when opening pressure doesnot work at the operating pressure that is called elbow and that happen due to deformability of the silicone rubber.

8.1 differentail pressure valves

there are 4 types according to their design : slit,diaphragm, miter valves (all made by silicone rubber), and metallic spring ball valve.

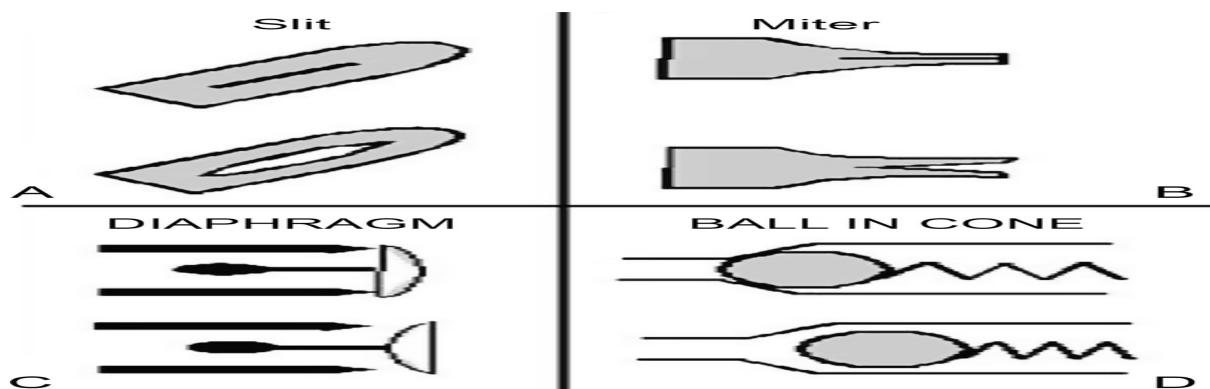


Figure 16: differential pressure valves

it can also provided with reservoir chambre . a valve can be placed anywhere along the course of the shunt but most valves are placed proximally or distally.

8.1.1 slit valve

old valves cut in a curved rubber layer and size of the opening slit depends on the pressure affecting the slit. the operating pressure (opening and closing) depends on some factors :properties of the slit, i.e., the stiffness of the silicone, the thickness of the wall, and the length of the slits it can be located both proximal and distal along the shunt line. some example of distal slit valves include the UniShunt System and the Spetzler lumbar peritoneal shunt system (Integra Neuroscience). Proximal slit valves include the Holter valve , the Chabba Slit in Spring Valve (, and the Crx valve. and in figure(26) The cylindrical side-walled slit Chabba valve is developed to maintaing operating pressure.



Figure 17: slit cylindrical valve

8.1.2 Miter Valves

The miter valve, also known as the "duck bill" valve, its orifice is rounded into two flat leaflets made of silicone that are opposed of each other at the entrance and coverage. The pressure characteristics are related to the shape, size, length, and thickness of the leaves. Some of the examples are: the Mishler Dual-Chamber Flushing valve , The Multipurpose valve , and the Ultra-VS cylindrical valve. The multipurpose valve (Figure 18), composed of one-way mitral valve which is located at the on-off control chamber, it is also available with or without an integral anti-siphon device. The Ultra-VS cylindrical valve (Figure 18), has a simple cylindrical design that incorporates with the miter valve mechanism. The

Mishler Dual-Chamber Flushing valve incorporates a miter valve mechanism that features a reservoir dome that is separated by vertical central chamber divider (Figure 19).

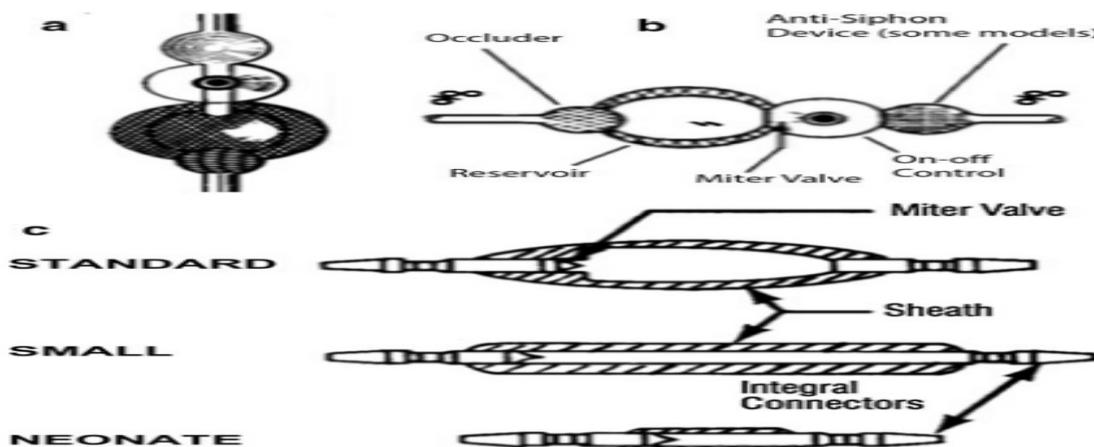


Figure 18: (a, b) Integra Neurosciences Multipurpose valve (c) The Integra Neurosciences Ultra-VS In-Line Valve is available in three models: standard, small, and neonate. The valves incorporate a unidirectional miter type silicone valve element enclosed in a silicone elastomer sheath and are available in low, medium, and high differential pressure ranges.

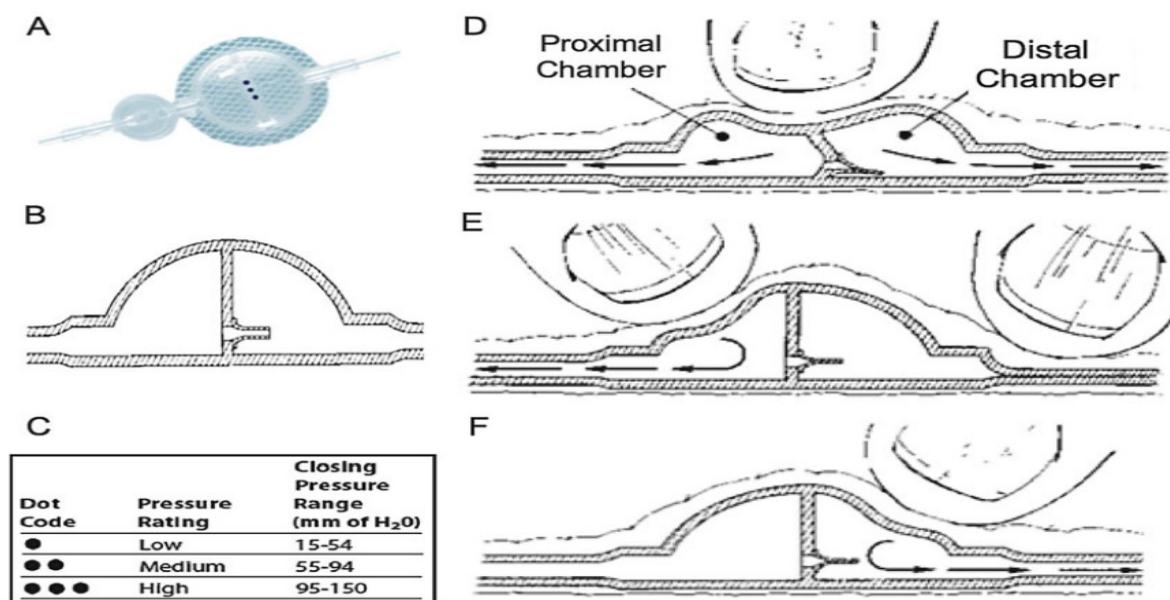


Figure 19: (a) Integra Neurosciences Mishler Dual-Chamber valve (b) The flow of CSF is controlled by a miter valve located on the vertical chamber divider (c) Pressure ranges (d) Flushing procedure: Finger pressure on the center section of the dome flushes the shunt proximally and distally (e) Finger pressure on the proximal reservoir chamber allows flushing of the proximal catheter when the distal outlet is occluded (f) Finger pressure on the distal reservoir chamber allows flushing of the distal catheter. One-way flow control provided by the miter valve prevents retrograde flow.

8.1.3 Diaphragm Valves

The Diaphragm valves has a flexible membrane that moves in response to difference in pressure with no metal parts. With the help of a central piston to move in a sleeve or to surround the piston to act like an occluder, in order to hold the membrane, which can be deformed under pressure. The diaphragm can be moved by the difference in pressure, and that is allowing the CSF to flow around it. When that difference decreases, the mechanism is sealed by the diaphragm. Some examples of the diaphragm valves are: Pudenz Flushing valve and the Integra Neuroscience Contour Flex valves (Figure 20). There is also the Medtronic delta valve which is a siphon control device that prevent the siphoning of CSF from the brain's ventricular system. The design of the valve allows it to be closed at the resting state in order to prevent the CSF flow through it down its concentration gradient, because the outlet of the shunt is being below the inlet. The valve will open and allow the CSF flow through the shunt only in the case where the pressure have a proximal value that is in excess of its opening pressure (Figure 21).

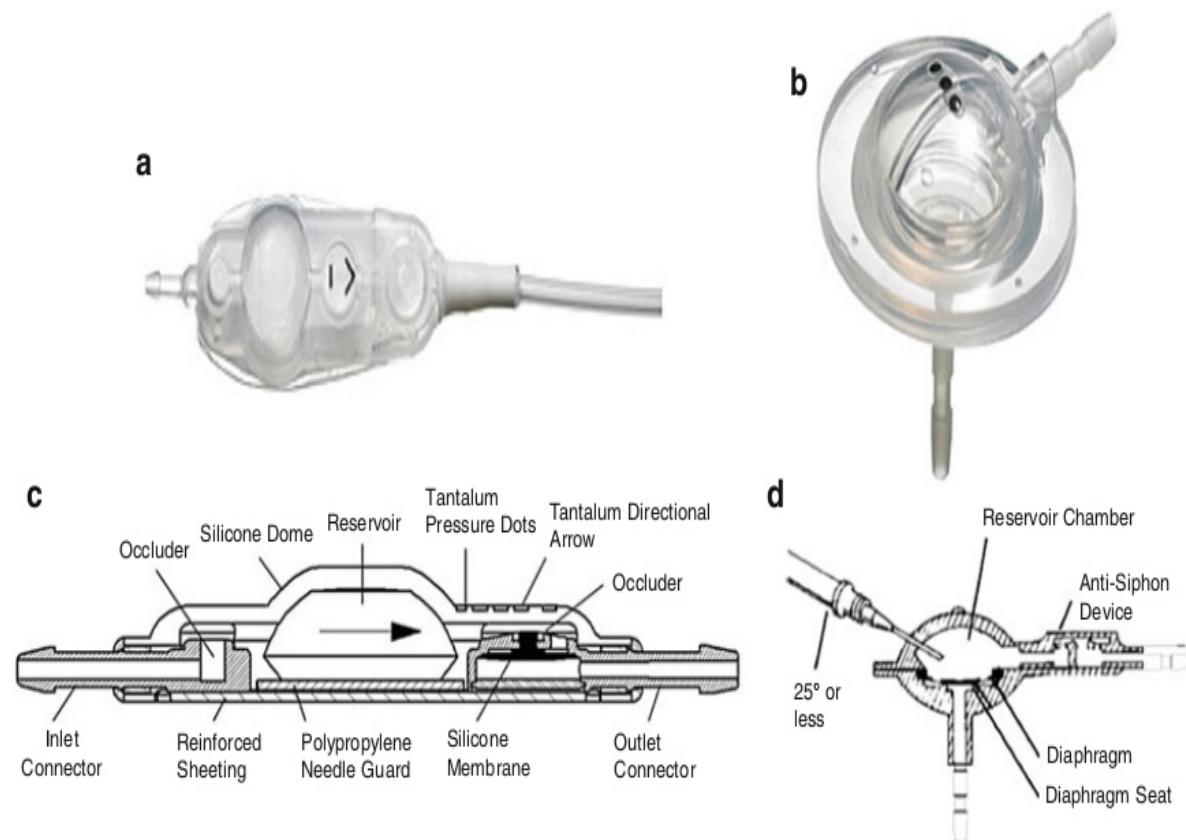


Figure 20: (a–c) The Integra Neurosciences Contour-Flex Valve design includes a flat silicone membrane, which provides resistance to CSF flow. The flat silicone membrane seats on a conical polypropylene base (b–d) Injectable reservoir for CSF sampling, distal flushing, and distal patency testing is part of the Integra Neurosciences Pudenz burr hole valve.

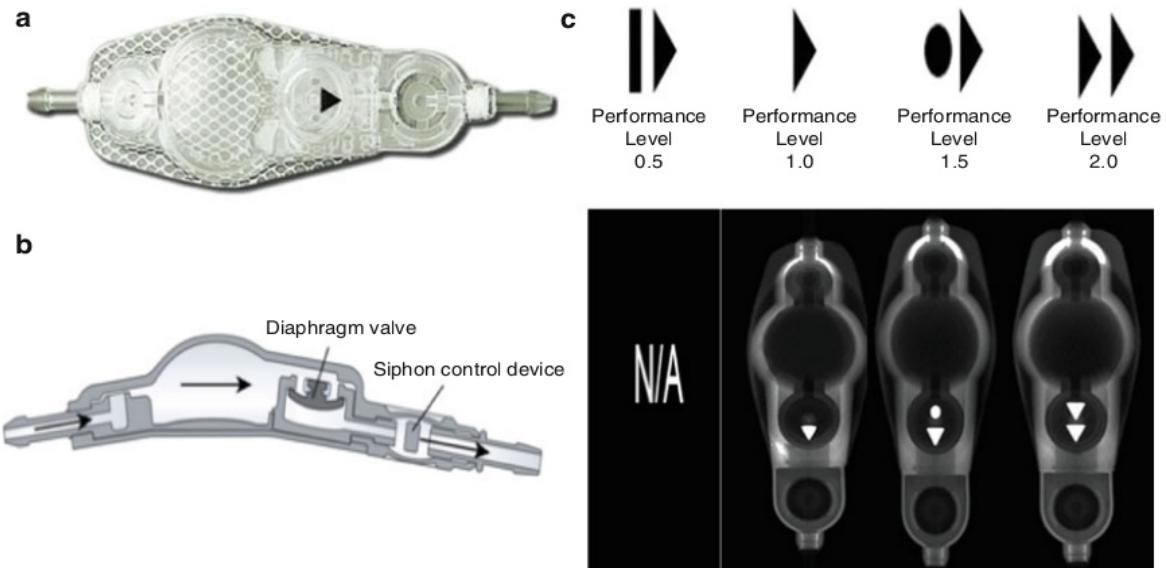


Figure 21: Medtronic PS Medical Delta Valve Regular (a and b) and radiographic appearance of the different performance levels (c).

8.1.4 Ball In Cone Valve

Flat spring with calibrated force applied on a synthetic ruby ball in a cone shaped orifice. High CSF pressure pushes the ball land open the valve to permit flow. When CSF fluid is reduced the ball return to its position and close the valve. Ball in cone valve has higher life time than miter and slit valve.

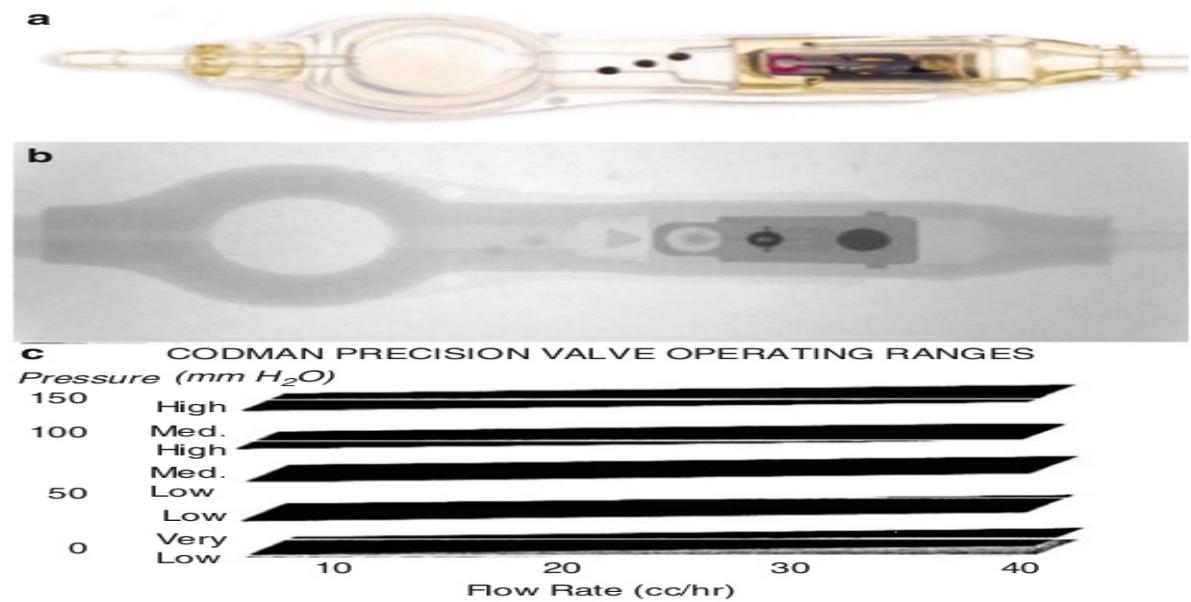


Figure 22: (a,b)codaman precision valve (c)operating ranges

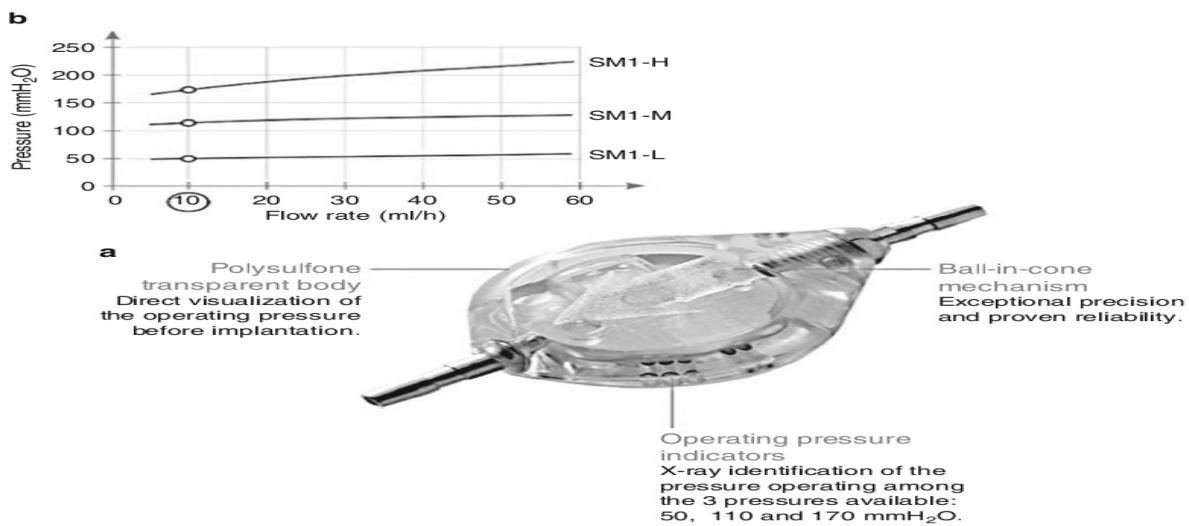


Figure 23: (a)sophsa SM1 (b) pressure flow chart for different modes

8.1.5 Multistage Flow Regulation Valves

These valves combine the features of a differential pressure valve and variable flow restrictor. The aim is to provide CSF drainage within ICP range, neglecting conditions that cause overdrainage. It has better survival rate 62% over 53% for programmable shunts[Hanlo et al. 2003; Zemack and romner 2000b]and it also limit overdrainage, controlling shunt complications, and postural and vasogenic events. Design of the valve :

- Low resistance differential pressure with mean flow 20 ml/hr.
- Variable resistance flow regulator with flow range from 20 to 30 ml/hr at pressure from 8-35 cmH₂O.
- Safety device for pressure above 35 cmH₂O to prevent acute ICP elevation.

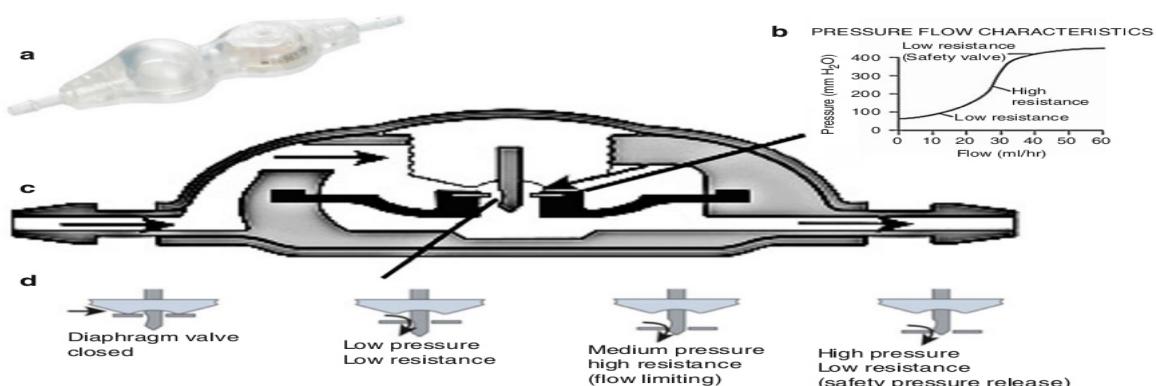


Figure 24: OSVII (a)the ring position diameter depend on pressure (b)pressure flow chart (c) cross section multistage system where pressure rise cause decrease in cross section(d)pressure-resistance relations with respect to (b)

8.2 adjustable valves

because a shunted patient's condition will often change over the course of their treatment making pressure changes necessary. in 1990s the concept of adjustable valves presents in the labs presenting more control of hydrocephalus avoid need of removal for revision . they incorporate a ball-in-cone mechanism regulated by a spring that can be adjusted noninvasively using a magnetic field transmitted through the skin.it takes many trials to set the settings to the target and once reaching the target it turns to fixed pressure shunts . the challenge was how to avoid the accidentally adjustability by another source of magnetic field like MRI for example ? so Newer valves as Polaris valve (Sophysa), ProGAV and ProSA valves (Aesculap Miethke), Certas (Codman) have mechanisms intended to prevent this accidentally adjustment

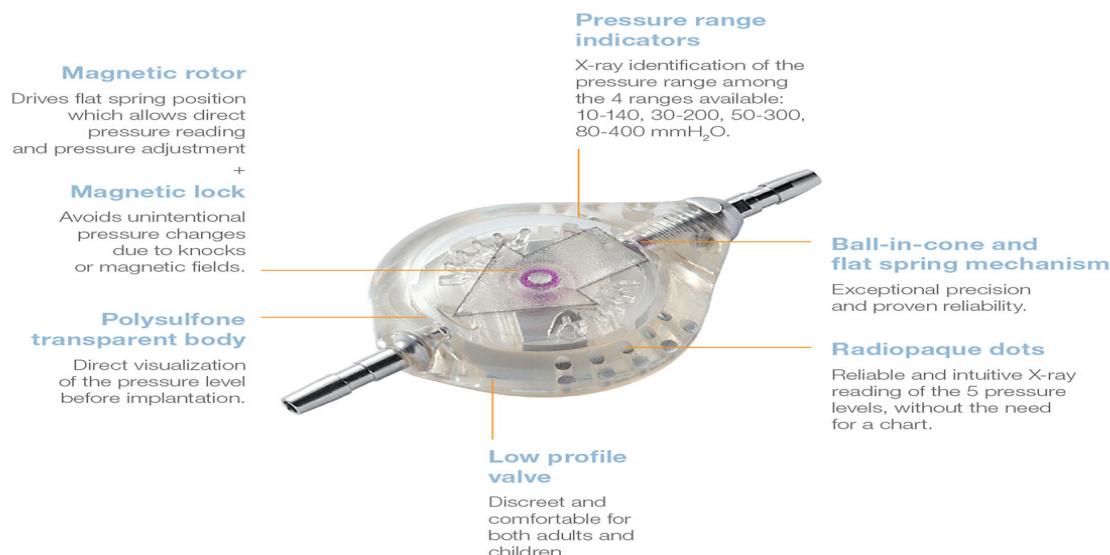


Figure 25: adjustable valves

8.2.1 The Medtronic Strata Valves

the medtronic strata valve is an adjustable ball and spring valve The tension of the valve's spring can be altered using magnetic rotor mechanism integral with the valve and the adjustment operating done noninvasively using adjustment tool to alter the rotor tension and the spring tension too.

The Strata NSC contains the adjustable pressure differential ball and spring valve while the Strata II also contains a Delta chamber siphon control device that is a normally closed mechanism, which opens in response to positive ventricular pressure but stays closed in response to negative distal pressure.

the strata valves contain 5 settings for 5 performance levels shown in figure ranging from .5

to 2.5 and each of them has its own opening pressure programming procedure for strata valves :

- confirm exact location of valve mechanism using the help of x-ray if it is necessary
- position the locator tool over the valve with the blue arrow facing the direction of CSF flow through the valve
- set the indicator tool into the locator tool while aligning the red bands in the tool
- The blue triangle on the “indicator tool” will point to the valve’s current pressure setting.
- remove the “indicator tool.” Set the “adjustment tool” into the “locator tool” with the blue triangle facing the current pressure setting.
- rotate the adjustment tool to the desired pressure
- finally repeat the first two steps to make sure that you reached the exact pressure.

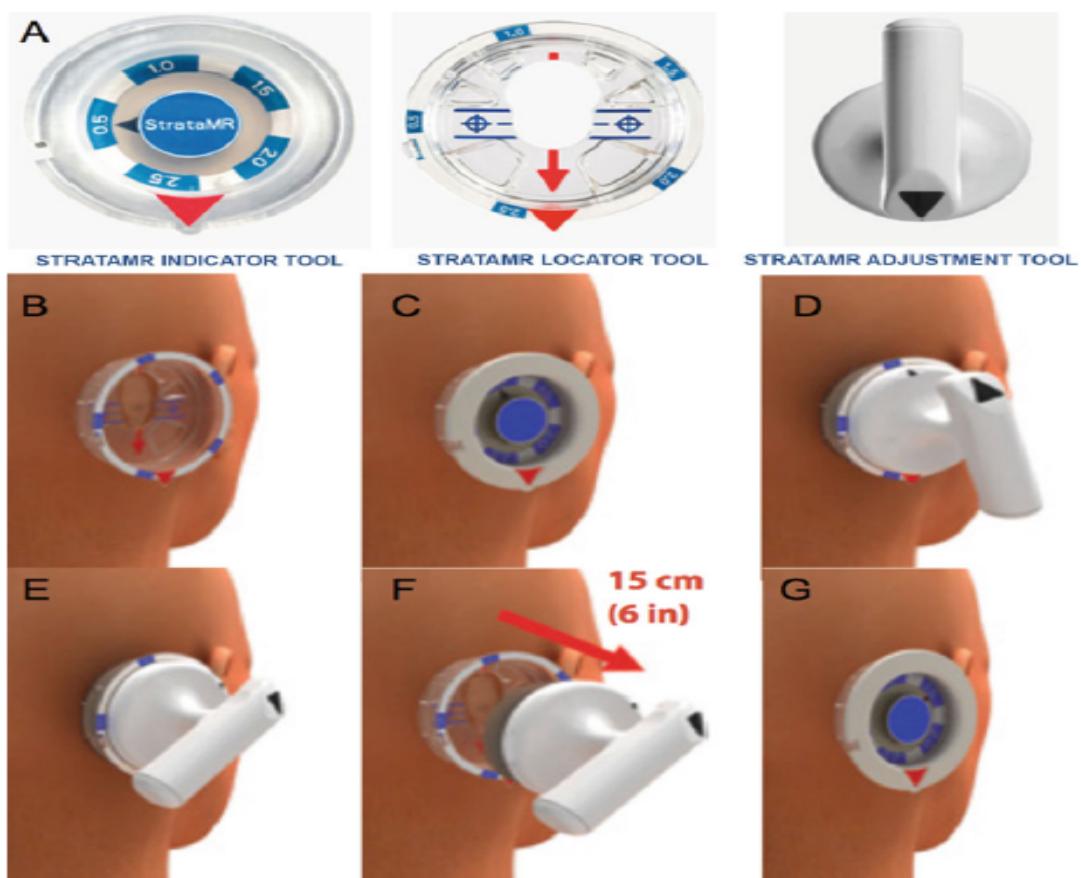


Figure 26: programming the shunt

8.2.2 The Codman Hakim Valve

The Codman Hakim valve is a programmable valve that gives you the choice of noninvasively changing the opening pressure in the range of [30-200] mmH₂O in 18 steps. A ball-spring mechanism that has a stepper motor contains a spring that sets on the top of a rotating spiral cam. In order to change the opening pressure of the valve, we can apply magnetic field to the stepper motor which in turn will cause the cam to turn slightly causing the tension in the spring to change (Figure 27).

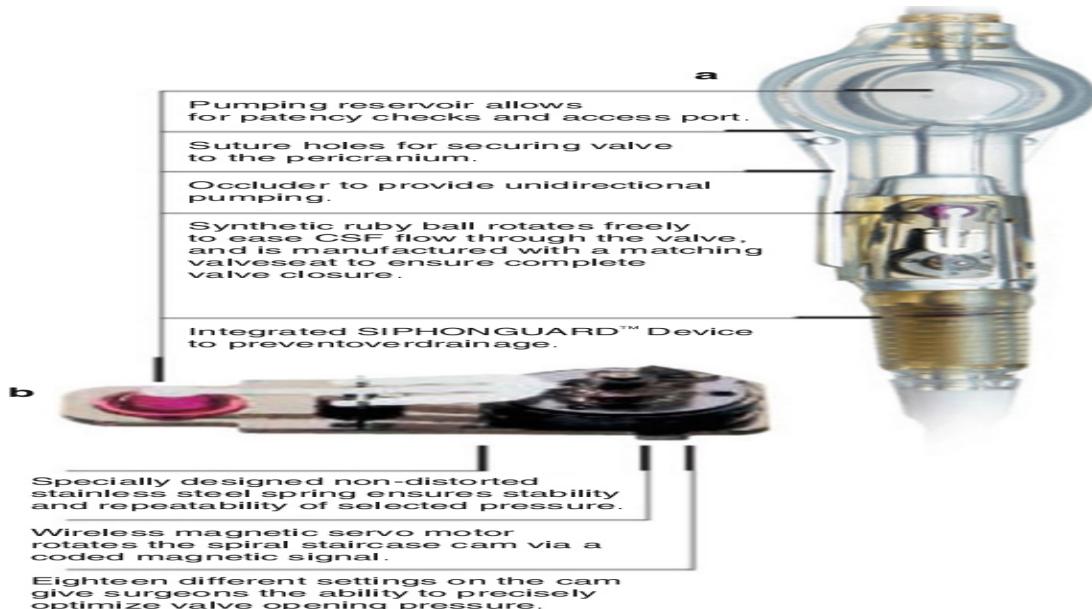


Figure 27: Codman Hakim programmable valve and inside mechanism

Programming

The programming tool has two modes: implanted and packaged valve modes. We can use the implanted valve mode whenever we want to adjust the settings of the valve after the operation. The acoustic monitoring feature is active in the implanted valve mode, also there is a sensor that is contained within the transmitter can detect valve vibration whenever the settings of it gets changed. If we want to adjust the settings of the valve before the implantation or in case of adjusting it in a recently implanted valve in a patient with skin integrity, We use the packaged valve to insure a sterile barrier and the acoustic monitoring is not active. In order to program the valve Figure 27.

- Enable the programmer unit and choose the pressure of desire on the programmer panel
- Put the transmitter head over the valve
- Press on the start button and then release it while keeping the transmitter head in place until it beeps indicating completion.

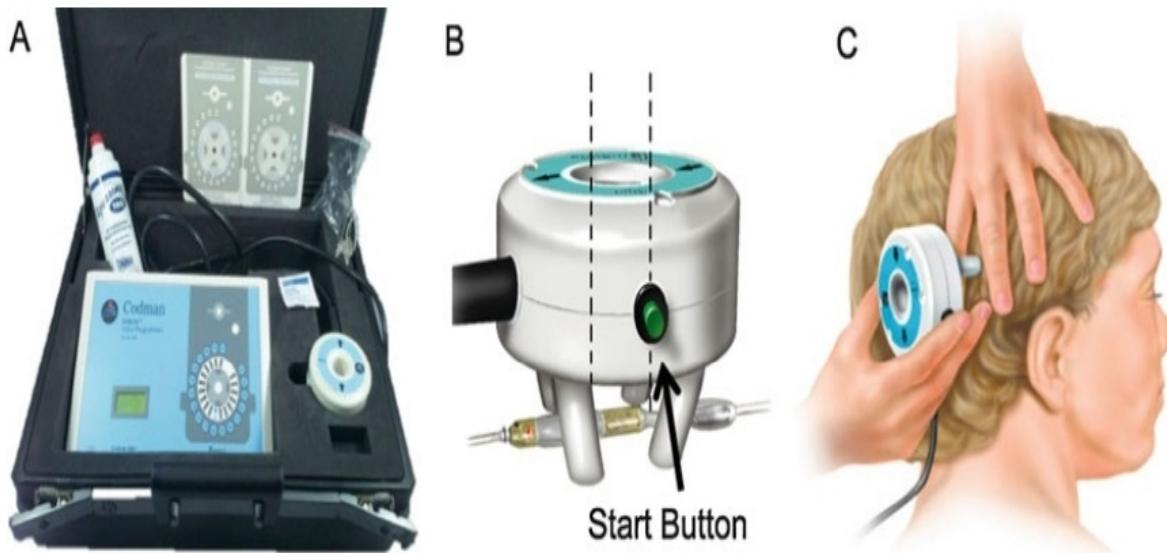


Figure 28: Programming procedure for Codman Hakim programmable valve.

8.2.3 The Sophysa SM8 And Polaris valves

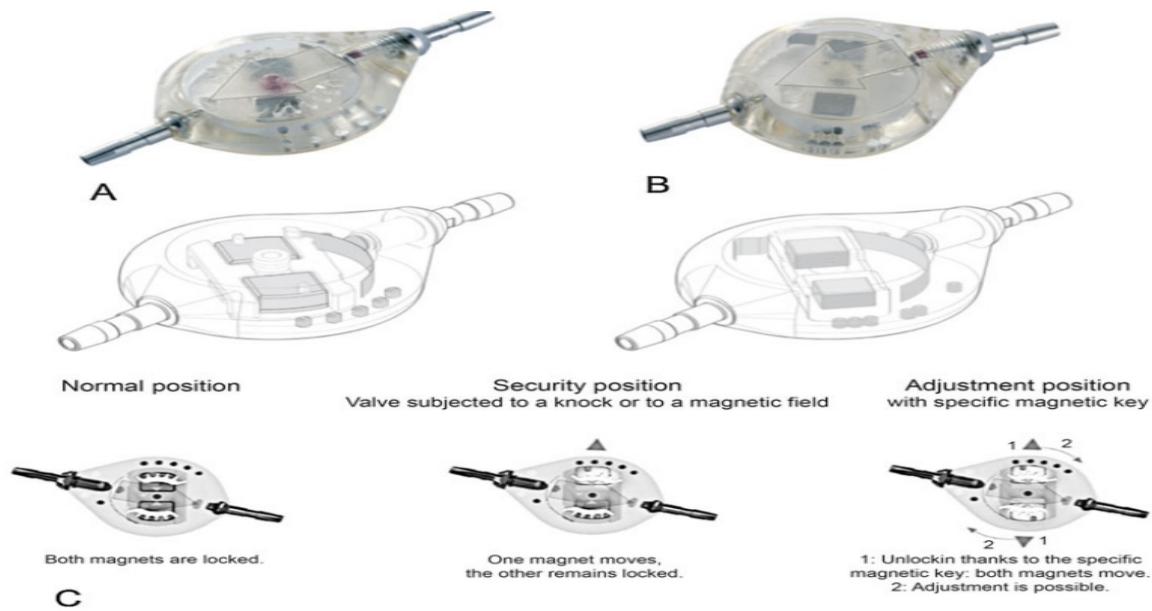


Figure 29: (a)sophysa polaris valve (b)sophysa mini SM8 ©magnetic lock security mechanism

The principle of operation depend on pressure change over a ball by semi circular spring. The spring is attached to a magnetic rotor for non invasive adjustment. SM8 has 8 positions ranges from 30 – 200mmH₂O. It also can have anti-siphon device that add 200mmH₂O in upright position same as polaris valve which has only 5 positions. It is also

designed to resist knocks and magnetic field, such as MRI. The magnetic lock depend on permanent reciprocal attraction of two micromagnets of opposite polarities. To programm polaris we follow these steps:

- Adjustment kit contain locator which is set to same operating pressure as implanted valve. Patients in horizontal posture and locator parallel to valve with green arrow with CSF flow.
- Compass aligned to locator measure current operating pressure.
- Remove compass insert magnet with central line to the current operating pressure.
- Slide magnet back and forth, then turn it slowly to highest or lowest value and check by compass.
- Remove compass, slide magnet back and forth, then turn it to new operating pressure.
- Move magnet to 0.5 m away and place compass to confirm the adjustment.

9 Over Drainage Control Devices

over drainage is a common problem either caused by posture(sitting, standing, sleeping) or caused by vasogenic conditions. Blood volume in brain increase due to cough or bowel movement which increase ICP.

Overdrainage may cause proximal shunt obstruction, small ventricle syndrome, and subdural & extradural collections. This effect is reduced by anti-siphoning devices(ASD), gravitational devices(GCD), and flow regulating devices(FRD).

9.1 Flow Regulating Devices

FRD maintain constant flow at different pressures. When the flow increase by a certain limit(20 ml/h) the the high resistance pathway is active that return the flow rate to its nominal value

9.2 Anti-Siphon Device (ASD)

It is characterized by having a silicone membrane which reacts to hydrostatic pressure across both ends of the catheter and then close the valve, when the patient is vertical it increases the opening pressure. It has got two chambers with membrane that is responsive to pressure that separate the compartments (Figure 30). The device is an integral component of: Pundez, Multipurpose, and Mishler Dual Chamber. ASD can also be connected to any flushing reservoir in series. There is a difference in the area of pressure sensitivity, one

compartment is greater than the other: the device has an open pathway between chambers in relaxed state. In case of the dependent distal catheter, suction in the pressure-sensitive membrane is caused by the negative siphoning action and that obstruct the flow. Whenever the pressure in the proximal chamber increases, the membrane can be lifted by the fluid pressure, and restoring the flow of CSF . Because the device is referenced at atmospheric pressure, there will be a hydrostatic pressure difference between the inlet to the shunt and the device – if the device is located too cephalic, so that the intracranial pressure will have to be elevated in order to overcome the negative pressure added to the device. In case of placing the device too caudal, and when the body is vertical, the added hydrostatic fluid will keep the device open and prevent the anti-siphoning effect from occurring.

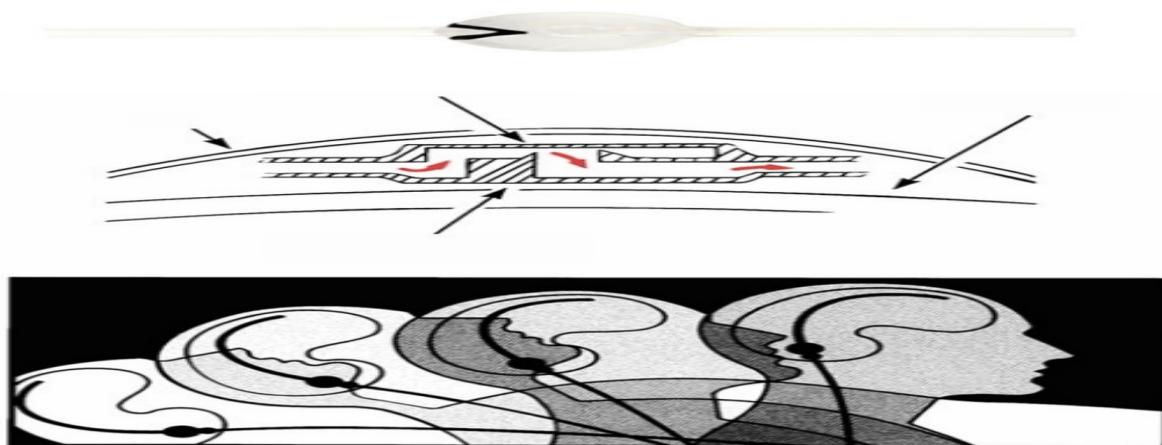


Figure 30: Integra Anti-Siphon Device.

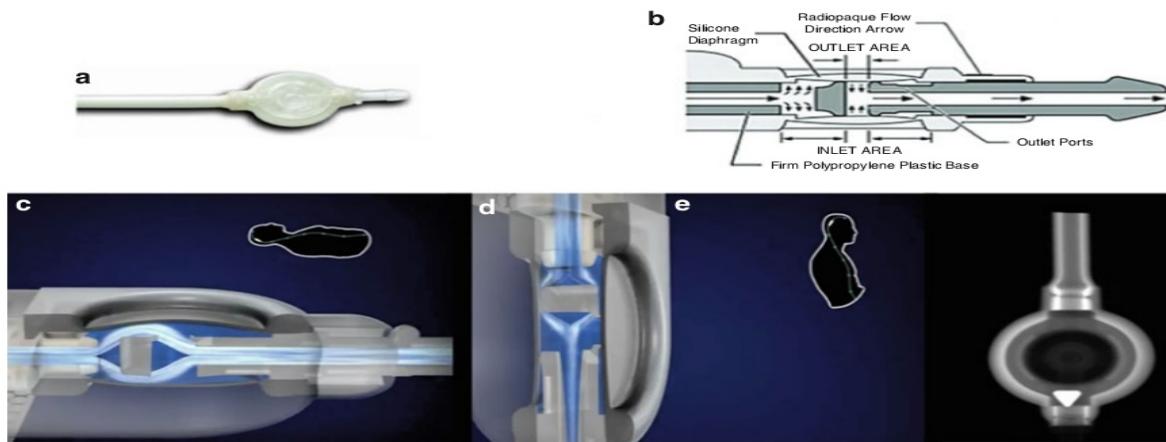


Figure 31: (a, b) Medtronic Delta Chamber (c) The normally closed Delta chamber mechanism (d) opens in response to positive intraventricular pressure. Working with the membrane valve, this mechanism minimizes over-drainage by utilizing the principle of hydrodynamic leverage (e) X-ray appearance.

9.3 Gravitational devices

These devices add extra weight that elevate the opening pressure in upright position. The resistance to flow equal the height of hydrostatic column.

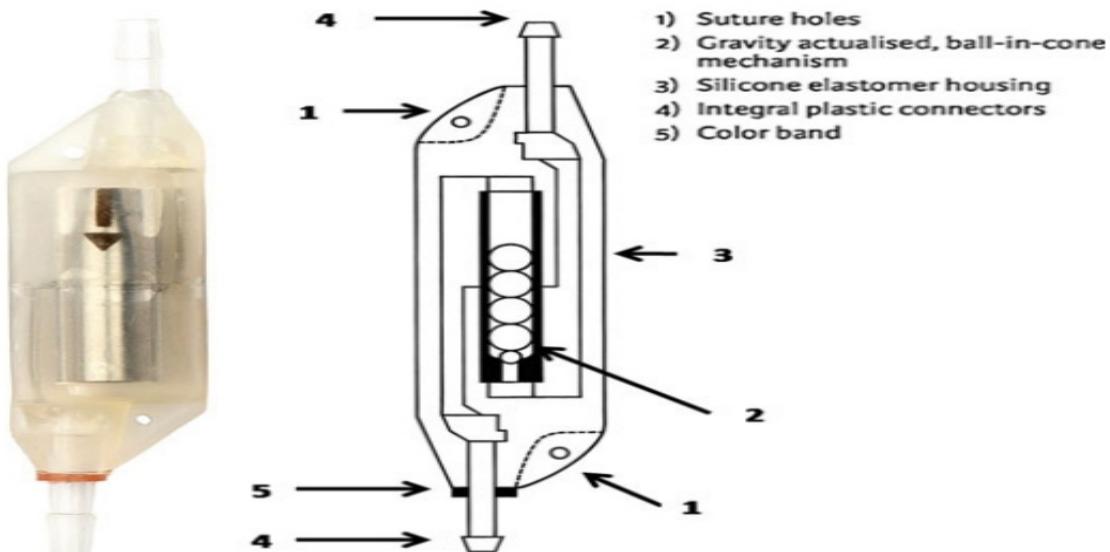


Figure 32: integra neuroscience gravity compensation accessory

Number of balls in cone determine the resistance to flow less than 30 mmH₂O at 5 ml/hr. Sternum is a preferable site for Z shunt, except in ventriculo atrial shunting. This site is preferable in babies as skin erosion is less likely to occur.

The Aesculap Miethke shunt programmable assistant(proSA) is a technical advancement with values range from 0 – 15 – 20 – 25 – 30 – 35 – 40cm H₂O.



Figure 33: Aesculap miethke shunt and x-ray marker code

Individual adjustment could be made by proSA

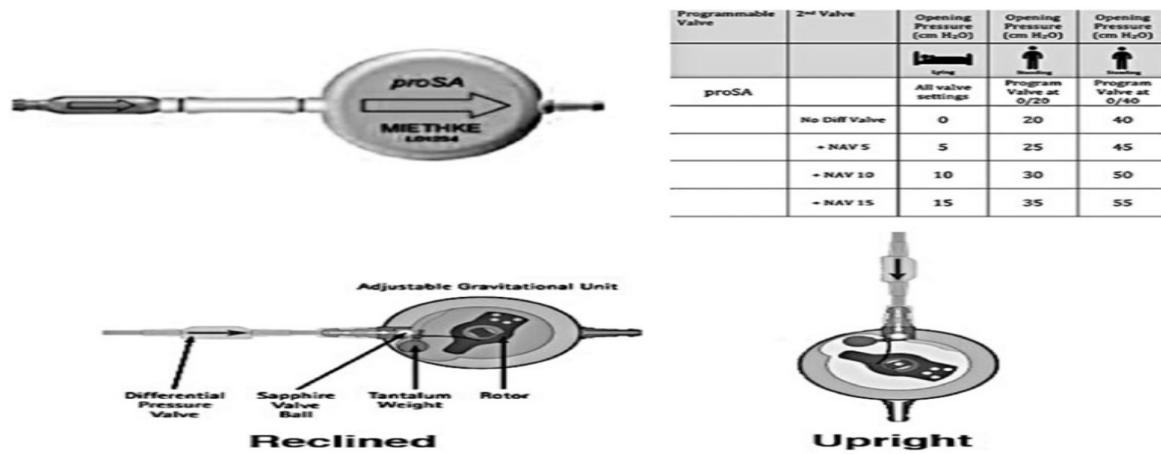


Figure 34: proSA with differential pressure valve

It also has active lock for protection from external magnetic fields with MRI up to 3T.

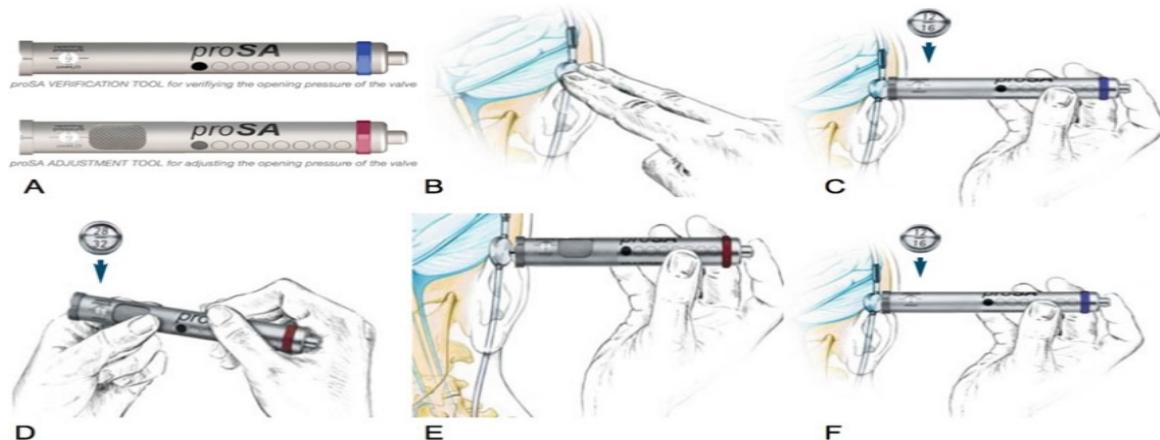


Figure 35: (a)proSA

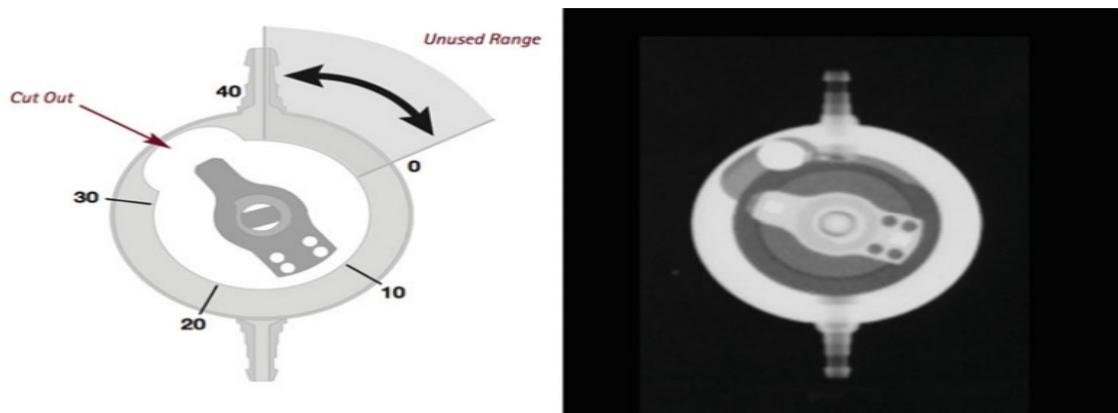


Figure 36: proSA x-ray verification

10 Future Development

A smart shunt is a device capable of measuring conditions such as ICP or drainage rate and adjusting the CSF flow rate through the shunt based on this information. In contrast to mechanical valves, This may solve overdrainage problems.

It may allow open pressure adjustments, adaptation to patient growth, personalized control). Sensor based control could inform the patient and the doctor with data and allow for remote adjustment by transmitting real-time data to the healthcare system.

10.1 new biomaterials

have great potential to reduce obstruction with nanotechnology, it is possible to self-cleaning shunts or early warning systems that detect shunt failure to lower risks of unpredictable failure.

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