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Antisiphon device: A review of existing mechanisms and clinical applications to prevent overdrainage in shunted hydrocephalic patients

Dr. Meng-Fai Kuo

*An-Ping Huang, Lu-Ting Kuo, Dar-Ming Lai, Shih-Hung Yang, Meng-Fai Kuo**

Division of Neurosurgery, Department of Surgery, National Taiwan University Hospital, National Taiwan University College of Medicine, Taipei, Taiwan

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ABSTRACT

Overdrainage of cerebrospinal fluid is one of the most notorious complications after ventriculoperitoneal shunt implantation. Siphon effect plays a major role in the development of overdrainage. Various overdrainage-preventing devices have been invented to counteract the siphon effect. Though some of the devices are designed to reduce the flow instead of providing antisiphoning effect, they are generally called antisiphon devices (ASDs). The basics of siphoning, the mechanisms and physical properties of currently available devices are described in this article. The clinical efficacy, shunt survival, and considerations on patient factors are also discussed. There are three kinds of ASD design, diaphragm, gravitational, and flow reducing devices. Flow reducing ASD is always open and the flow it controls is relatively stable. On the other hand, it may not provide sufficient flow in nocturnal intracranial pressure elevations. Diaphragm and gravitational devices are sensitive to the position of the patients. Diaphragm device is sensitive to the external pressure and the relative position of the device to the mastoid process. The gravitational device is sensitive to the angle between the axis of the device and the head. Many studies showed encouraging results with gravitational devices. Studies regarding diaphragm devices either showed better or similar outcomes comparing to differential pressure valves. Clinical studies regarding flow-reducing devices and head-to-head comparison between different mechanisms are warranted. This review aims to provide a useful reference for clinical practice of hydrocephalus.

Cerebrospinal fluid (CSF) shunting is the gold standard treatment for hydrocephalus in current practices. While numerous lives are saved and quality of life is improved by the simple procedure, it is not without complications. Overdrainage of CSF is one of the most notorious complications after ventriculoperitoneal (VP) shunt implantation. It may result in postural headaches, subdural hematomas (SDH)/hygromas, stenosis/occlusion of the cerebral

* *Corresponding author*. Division of Neurosurgery, Department of Surgery, National Taiwan University Hospital, 7, Chung-Shan South Rd., Taipei 100, Taiwan.
E-mail address: mfkenator@gmail.com (M.-F. Kuo).
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aqueduct, secondary craniosynostosis, slit-like ventricles/slit ventricle syndrome (SVS), and proximal catheter obstruction, etc [1]. The reported incidences of overdrainage range from 2% to 71% due to different study populations, follow-up duration, and definitions of overdrainage [2–10]. The true incidence of overdrainage remains unknown. The Dutch Normal-Pressure Hydrocephalus Study reported subdural effusions of up to 71% in patients with a low pressure shunt [7]. Oi et al. reported slit-like ventricles in about 90% (9/10) of premature neonates (up to 36 weeks gestation) [11]. Overdrainage results from vasogenic and postural effects. In normal subjects, vasogenic effect refers to the intermittent intracranial pressure (ICP) increases related to nocturnal vasogenic events usually triggered by rapid-eye movement (REM) sleep, and CSF is shifted to the spinal subarachnoid spaces [12]. In shunted patients, the nocturnal vasogenic events and diurnal postural effect result in the shifting of CSF into the peritoneal cavity instead of maintaining them inside the subarachnoid spaces.

Siphoning is the phenomenon where fluid continuously flows through an inverted U-shaped tube connecting two containers positioned at different heights. The fluid is "sucked" from the compartment with higher potential energy, flowing upwards against gravity to the "crown" of the system, and finally into the lower compartment. The flow continues until the hydrostatic pressure reaches equilibrium. The traditional theory consisting of Pascal's principle and Stevin's law, and the novel molecular cohesion theory provide the physical basis of the siphon effect [13]. Studies on siphon utilize the Bernoulli equation as a theoretical model. The VP shunt connects the intracranial and intra-abdominal compartments, technically becoming a siphon when the system is in the vertical.

Since the 1970s, efforts have been made to overcome the postural drainage effects. Note that postural effect is the main, but not the only contributor to overdrainage. "Antisiphon", or more universally correct, "overdrainage-preventing" devices are accessories connected in tandem distal to the main valves that work with various mechanisms. To date, there is no perfect overdrainage-preventing product. In this review, we refer to all devices acting as an overdrainage-preventing device with the term *antisiphon device (ASD)* to avoid confusion. The basics of siphoning, the mechanisms and physical properties of currently available devices are described in this article. The clinical application and considerations are also discussed. This study aims to provide a useful reference for clinical practice of hydrocephalus.

Physiologic CSF dynamics

CSF is secreted with an average rate about 0.35 ml/min according to the literature. However, the actual rate may vary greatly depending on the age (0.007–0.45 ml/min in hydrocephalic children of 5–13 years old) and circadian rhythm (e.g. REM sleep) [14,15]. To maintain equilibrium ICPs, the absorption rate of CSF is obviously equal to its production in normal circumstances. In case of suddenly elevated ICP, such as coughing, crying, and vasogenic dilatation of cerebral vessels, the immense absorption reserve up to 100–200 ml/h comes into function [14]. CSF absorption involves the transdural and parenchymal routes. Arachnoid villi are believed to play a major role in transdural absorption. This type of absorption occurs passively under a CSF-dural sinus pressure gradient beginning from 20 to 50 mmH_2O [16]. In 2012, Nedergaard et al. discovered the glymphatic system where there is convective fluid fluxes into and through the brain parenchyma with the CSF and interstitial fluid continuously interchanging [17]. CSF enters the Virchow-Robin space and is subsequently transported into the dense parenchyma by AQP4 water channels expressed on the astrocytic vascular endfeet. It has been shown that the glymphatic system is turned on during sleep and dramatically suppressed during wakefulness [18]. This parenchymal route of CSF absorption also contributes to the secretion of CSF other than the choroid plexus. The equilibrium ICP may be described with Davson's equation: $ICP = R_{out}I_{form} + P_{dural}$, where R_{out} is the CSF outflow resistance, I_{form} is the CSF formation rate, and P_{dural} is the pressure in the dural venous sinuses [18].

The "normal" ICP ranges are 10 ± 5 cmH_2O in supine position and 0 ± 5 cmH_2O in the upright position, respectively. An overly simplified theory would argue that since the vertical distance between the external auditory canal and the top of the peritoneal cavity is approximately 50–70 cm, the expected ICP drop from supine to upright position would be about 50 cmH_2O. It is proven otherwise in reality. Cardiovascular studies suggest that a venous hydrostatic indifference point exist and is located around the top of the diaphragm. In the upright position, the venous pressure above this point is decreased, and those below this point is increased. The pressure of this hydrostatic indifference point is constant no matter what position the subject is in. The model of Magnaes postulates that there is also a hydrostatic indifference point in the CSF axis, and it is located somewhere between C6 and T5 [19]. However, it was shown that this hypothesis only applies in horizontal and vertical positions. In tilt angles in between, this model overestimates the ICP [20]. *In vivo* studies have shown ICP difference of only about 10 cmH_2O in supine and upright positions [21]. This phenomenon is attributed to the collapse of internal jugular vein (IJV) in the upright position [22]. The reference point of the hydrostatic water column is in fact the collapsed segment of IJV, which is about 10–11 cm below the tragus. This perfectly explains the moderate drop of ICP measured in human studies in vertical position. The collapsed IJV works as a Starling resistor. In vertical position, the lumen is nearly, but not totally occluded, and the venous blood flow flutters and passes through intermittently. The flow is no longer dependent of the differential pressure (DP) between the cranial vault and the venous hydrostatic indifference point, but rather dependent of the rate of blood inflow to the upstream segment. The IJVs function as natural ASDs.

Shunted CSF dynamics

The presence of a VP shunt effectively bypasses the transdural route of CSF absorption by providing a relatively low resistance pathway, especially in patients with increased CSF outflow resistances. The flow in this pathway is determined

by the perfusion pressure (PP) or the DP across the valve. If the PP is positive, then flow occurs. PP can be determined with the following equation: $PP = ICP + HP - ((OP\ or\ CP) + IAP)$, where HP indicates hydrostatic pressure, OP the opening pressure of the valve, CP the closing pressure of the valve, and IAP the intra-abdominal pressure [3,21,23]. $HP = \rho gh$, where ρ is the fluid density, g the gravitational constant (9.8 m/s), and h the vertical height of the fluid column [Fig. 1] [24]. In a valve that is normally closed, it is determined with the OP. In a valve that is normally open, it is expressed with the CP [25]. It has been shown that ICP can be as low as −15 to −35 cmH_2O in the upright position in shunted patients [21,26]. ICP is maintained at −7 to 3 cmH_2O in those with an ASD implemented [26]. As the distal compartment, the increase of IAP means a corresponding decrease in PP of the shunt. Constipation, ileus, pregnancy, and other conditions which may cause elevated IAP have been reported to cause functional underdrainage or malfunction in shunted patients [27–29]. Sahuquillo et al. demonstrated a significant positive linear correlation between body mass index (BMI) and IAP (slope 0.31, intercept −5.5, r = 0.52, p = 0.018) [30]. Elevated IAP in obese patients should be taken into consideration when selecting an appropriate pressure setting on a shunt or an ASD. Posture and activity also significantly influence IAP, such as sitting (16.7 mmHg), standing (20 mmHg), coughing (107 mmHg), and jumping (171 mmHg) [31]. The raises of IAP in sitting and standing postures contribute to the suppression of the very negative ICP measured in shunted patients. ICP in these patients would be −40 to −50 cmH_2O if IAP had not been elevated when sitting or standing.

The flow through the shunt system is determined on the DP: $Q = \Delta P/R$, where Q is the flow, ΔP is the DP across the system, and R is the total resistance of the system. The total resistance is the sum of the resistance of the individual components that make up the system, which at least includes a proximal catheter, a valve, and a distal catheter in most shunt assembly nowadays [14]. The resistance of the catheter can make up a large proportion of the total. The law of Hagen–Poiseuille states,

$$Q = \Delta P \times \left(\frac{\pi r^4}{8\mu L}\right)$$

the flow is proportional to the fourth power of the inner radius (r) of the rigid tube, and is inversely related to the viscosity (μ) of the fluid and the length (L) of the tube [32]. Common tubes with internal diameter of 1.1–1.3 mm can drain through 100 cm length with ΔP of 30 cmH_2O with flow rates of 344 ml/h and 556 ml/h, respectively. This property is beneficial in intermittent ICP crises; however ΔP easily exceeds this value in the erected posture, which leads to detrimental outflow of CSF. Internal diameter of >0.8 mm supports overdrainage [14]. The addition of an ASD increases the total resistance further even in horizontal position, though it may be subtle depending on the design.

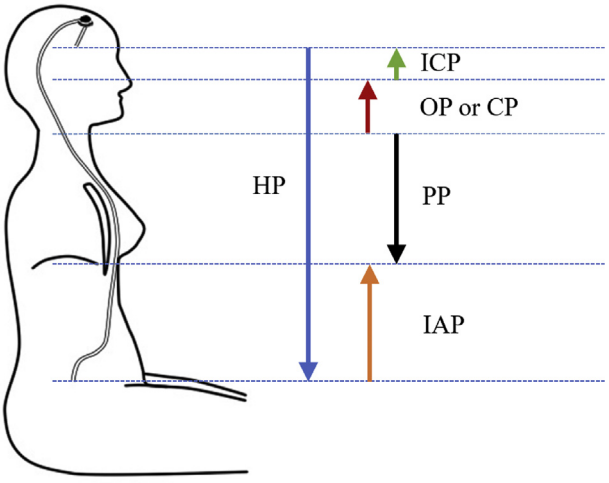

Fig. 1 Schematic illustration of the pressures involved in a ventriculoperitoneal shunt. HP = hydrostatic pressure; ICP = intracranial pressure; IAP = intra-abdominal pressure; OP = opening pressure; CP = closing pressure; PP = perfusion pressure. Arrows indicate the direction of force with which the fluid tends to flow. Since ICP is negative in the upright position, it tends to reduce the perfusion pressure, hence the upward arrow.

Mechanisms of ASDs

There are three kinds of ASD design, diaphragm, gravity, and flow reducing devices (Table 1).

Diaphragm devices (aka membrane-controlled devices)

A diaphragm device consists of one or two pressure sensitive membranes located at the upstream of the distal catheter. In 1973, Portnoy and Schulte first described the design of an anti-siphon valve [Fig. 2] [33]. The diaphragm is normally displaced from the crown seat as long as the inlet pressure, which is the ICP, is higher than atmospheric pressure, allowing CSF to flow through. When the outlet pressure drops below atmospheric pressure, resulting from the suction effect of the distal water column, the diaphragm is pulled towards the crown seat, closing the water channel. The proximal force (= ICP) required to overcome the siphon effect (= vertical length of the distal water column) is proportional to the ratio of inlet and outlet of the diaphragm device. Thus, for example, with an inlet and outlet ratio of 8:1, and the distal water column being 80 cm, it would require an ICP of more than 10 cmH_2O (= 80/8) to keep the diaphragm chamber open. This hydrodynamic leverage is an application of the Pascal's principle. It was formerly distributed by Integra NeuroSciences with the name Anti-Siphon Device until 2017, when Natus Medical acquired this asset (Natus Medical, Pleasanton, CA, USA). The Siphon Control Device (SCD, aka Delta chamber) (Medtronic PS Medical, Inc., Goleta, California, USA) has a similar design except it consists of a pair of diaphragm instead, with a larger inlet area and a smaller outlet area [Fig. 3]. It is normally closed, and opens only when the proximal pressure is greater than atmospheric pressure, unlike the Anti-Siphone Device (Natus Medical, Pleasanton, CA, USA), which is normally open. In a real subject, however, the subcutaneous pressure (5–9 cmH_2O) is needed to be overcome, instead of atmospheric

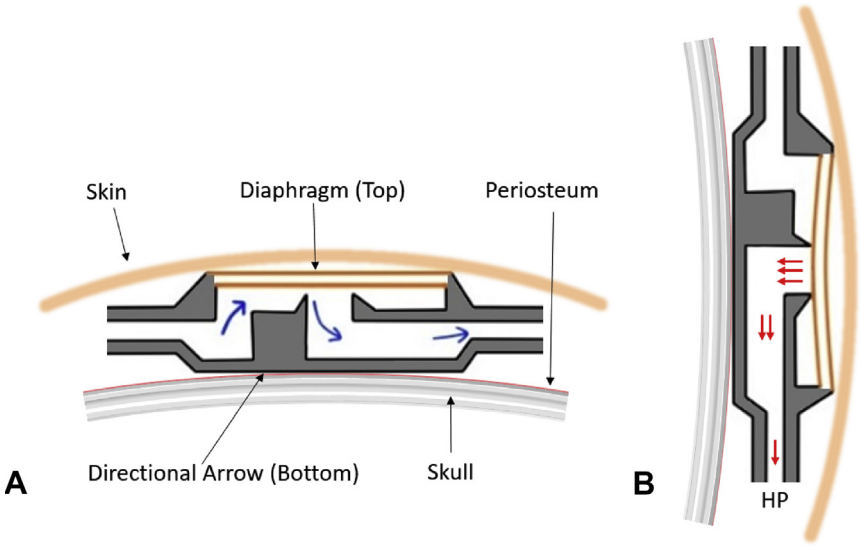

Fig. 2 Schematic illustration of the Anti-Siphon Device (Natus Medical, Pleasanton, CA, USA). (A) Device in horizontal position. The diaphragm is normally displaced from the crown seat, as long as intracranial pressure is larger than the external subcutaneous pressure (slightly higher than atmospheric pressure). (B) Device in vertical position. In vertical position, the negative hydrostatic pressure sucks the diaphragm towards the crown seat, thus preventing cerebrospinal fluid flow.

pressure [34]. The hydrodynamic leverage ratio is about 20:1, which theoretically leads to about 1.2–2.5 cmH_2O increase in OP when the device turns vertical. Note that a diaphragm device distal to the main valve decouples the valve opening from the IAP and negative HP column. Thus the only driving force is the ICP instead of the sum of ICP and HP [35]. Medtronic distributes Strata II (with the SCD), Delta Valve (with the SCD), and Strata NSC (without the SCD).

Comments

1. The ability of the diaphragm device to counteract siphon effect depends on the vertical length of the distal hanging water column. This is automatically adjusted in growing children, since the distal catheter is gradually pulled out from the peritoneal cavity along with increasing body height [14]. Some authors proposed that many children are not tall enough to generate sufficient negative hydrostatic pressure to keep the membranes closed [36,37]. However, this statement has not been clinically proven.
2. The ideal location of the diaphragm device seems to be at the level of mastoid process, or approximately 10 cm below the level of the foramen of Monro. This results in physiologic ICP (0–10 cmH_2O) and optimal flow initiation in erect positions [34,38]. Placement of the device below this level may lead to overdrainage, and vice versa. In some iNPH patients, however, deliberately implanting the diaphragm device at the clavicle or upper thoracic level may be considered for the goal of lowering the ICP [34,35].
3. The conceptual resemblance to the collapsible IJVs may sound appealing. However, the IJV is present on both sides, and avoids most compressions by the protruding head and shoulders in the lateral decubitus position. The diaphragm device is susceptible to external pressure from the subcutaneous tissue. Although an offset ring is implemented at the circumference of the diaphragm, avoiding direct compression from the scalp, studies have shown significant reduced flow and increased closing pressure of the valve as the external pressure increases [34]. During sleep, the head could be rotated such that the diaphragm is compressed between the skull and the underlying bed. This could lead to functional occlusion of the device and underdrainage [14]. The diaphragm device is best placed in the loose subgaleal space, instead of the neck, chest or abdomen. Subcutaneous implantation causes capsule formation and is likely to result in increased resistance to flow [39].
4. As mentioned above, a positive inlet pressure (i.e. ICP) is required to open the diaphragm device. Since the shunted ICP in the erect posture is negative, it virtually prevents all flow until CSF accumulates and the ICP increases above the OP [35].
5. Studies have shown an increase of 3–6 cmH_2O in inlet pressure with DP valves (DPVs) assembled with a diaphragm device compared to DPVs only in the supine position. This works as if the DPV is upgraded in the pressure setting. Thus, it is suggested that the diaphragm device be assembled with a DPV of low pressure setting, instead of a medium or high one [40].
6. With a simulated CSF production rate of 20 ml/h, the diaphragm device effectively reverses the negative inlet pressure of about −50 cmH_2O from the siphon to a positive inlet pressure of 12–21.5 cmH_2O with in-line low-pressure DPVs. The results were 17–25.4 cmH_2O with medium-pressure, and 19.8 to 37 cmH_2O with high-pressure DPVs [40].

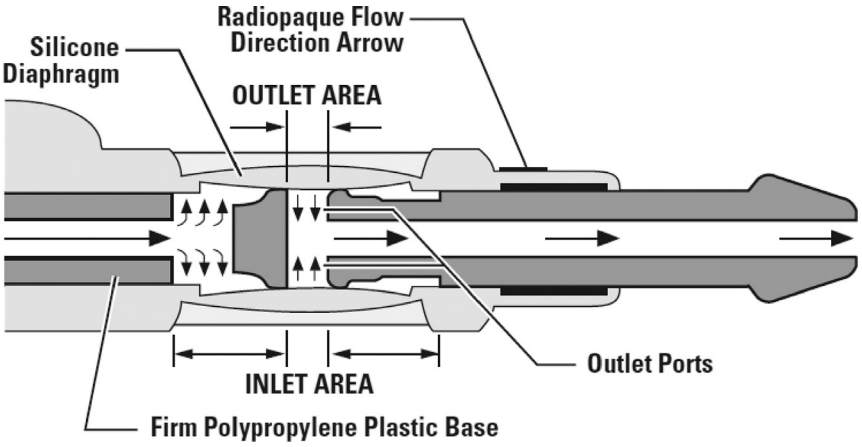

Fig. 3 Schematic illustration of the Delta chamber, a kind of diaphragm device. The silicone membranes are normally closed. They are displaced from the crown seat when the inlet pressure overcomes the external pressure. The external pressure in a real patient is the tissue pressure of loose subgaleal space or the subcutaneous space, which is slightly higher than the atmospheric pressure. When the device is in vertical position, the negative hydrostatic pressure of the distal water column pulls the diaphragms towards the crown seat, keeping them closed. The area ratio of the inlet area and outlet area is 20:1. Note the slightly higher ring surrounding the diaphragm. It is supposed to prevent some of the direct external pressure (Image adopted from Medtronic Delta® Chamber Instructions for Use, https://www.medtronic.com/).

Gravitational devices (aka ball-in-cone devices and g-valves)

This type of device involves one or several metal spheres contained in a titanium cylinder with a cone shaped seat [Fig. 4]. The middle column of the water channel is with an inverted direction. In horizontal position, the metal balls roll away from the inlet, allowing CSF passage. When the device turns vertical, the metal balls seat on the cone. Thus adding additional pressure (ΔOP) depending on the weight of the balls against the entering flow of CSF. The pressure setting of the gravitational device does not affect the OP at all in horizontal position. In combined valves, the OP in vertical position is the sum of the DP unit and the gravitational unit. Theoretically, the relationship of the added OP (ΔOP) and the angle (α) of the device with respect to horizontal may be expressed with the following equation: $\Delta OP(\alpha) = \Delta OP(90)\sin\alpha$, *if* $0° \leq \alpha \leq 180°$; $\Delta OP(\alpha) = 0$, $-180° < \alpha < 0°$ [41].

Examples of gravitational devices are Gravity Compensating Accessory (GCA, Natus Medical, Pleasanton, CA, USA), Miethke ShuntAssistant (Aesculap, AG, Tuttlingen, Germany) (comes in six ranges, 10 (Paedi-ShuntAssistant), 15, 20, 25, 30,

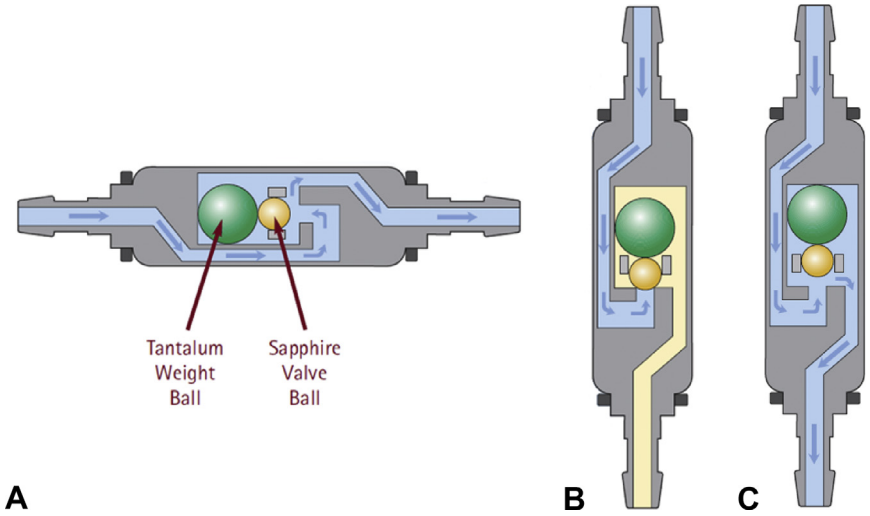

Fig. 4 Schematic illustration of the ShuntAssistant, a kind of gravitational device. (A) Device in the horizontal position. (B) Device in vertical position, closed. (C) Device in vertical position, open. The device consists of a titanium casing, a tantalum ball, and a sapphire ball. The weight of the tantalum ball provides the additional opening pressure in vertical position. When the differential pressure does not overcome the weight of the tantalum ball, the sapphire ball seats in the ball seat, preventing cerebrospinal fluid flow (Image adopted from Christoph Miethke paediShuntAssistant/ShuntAssistant sales brochure, https://www.aesculapusa.com/).

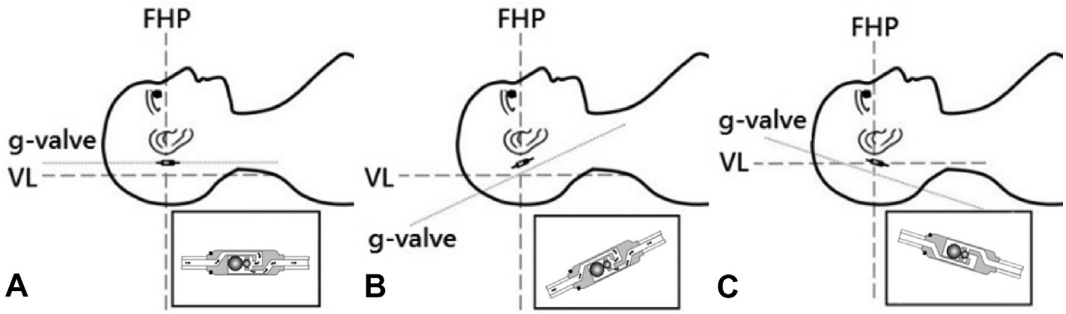

Fig. 5 Schematic drawing of the direction of inclination (the angle between the axis of the gravitational device and the head). (A) Vertical. (B) Posterior inclination. (C) Anterior inclination. FHP: Frankfort horizontal plane; VL: vertical line. Note that in the case of posterior inclination, the tantalum and sapphire balls roll *away* from the ball seat when the patient is supine. In the case of anterior inclination, the balls roll *onto* the ball seat in the supine patient, adding pressure to the cerebrospinal fluid pathway (Image of the device design is adopted from Christoph Miethke paediShuntAssistant/ShuntAssistant Instructions for Use, https://www.aesculapusa.com/).

35 cmH_2O), and Siphon X (Sophysa, Orsay, France). The ShuntAssistant is available as a single valve or incorporated with a main DPV (GAV, PaediGAV, ProGAV, ProGAV 2.0, and M. blue). A programmable version of the ShuntAssistant, ProSA, also became available on the market. The pressure setting of combined DP and g-valves is referenced as follows (cmH_2O): OP of horizontal position/OP of vertical position. Other examples of gravitational valves (instead of accessories distal to the main valve) include Chhabra Z-flow valve (G. Surgiwear Limited, India) and Miethke Dual Switch Valve (Aesculap, AG, Tuttlingen, Germany).

Comments

1. The gravitational unit must be placed vertical, or perpendicular to the Frankfort horizontal plane. Anterior inclination of more than 20° in the sagittal plane poses serious risk of underdrainage in supine position, especially in bedridden patients [41]. Posterior inclination of any realistic degrees or anterior inclination within 10° in the sagittal plane seems to be safe [Figs. 5 and 6] [42]. Inclination in the coronal plane has no correlation with ventricular volume change.
2. Even if implanted correctly, placement at the commonly used retroauricular site may still cause under- or overdrainage in specific situations when the neck is flexed (discrepancy between the axis of the head and the body), such as reading, using the mobile phone, or sleeping on a thick pillow. Thoracic implantation guarantees the axis between the g-valve and the body to be parallel. However, in growing children, adhesion at the pocket may cause subsequent disconnection of the shunt. Thus, thoracic implantation in adults and retroauricular implantation in growing children is suggested [14].
3. Vertical and oscillatory movements such as jogging and jumping may have unexpected effect on the g-valve [14].
4. G-valves should not be used in bedridden patients. Underdrainage will likely occur [41,43].
5. The amount of siphon effect, hence the required pressure setting with a g-valve, depends on the individual. Supplementary Table 1 gives a quick reference based on the suggestion of the manufacturer and reports from the literature [36,44]. It is however not a strict rule and should be tailored individually. Note that a typical person is sitting or standing in about 2/3 of the time in a day [35,45]. The effect of the additional OP only takes place in about the same proportion. When following up a patient with a neuroimaging study, the size of the ventricles only represent the net effect of the g-valve with 2/3 of the time being vertical and 1/3 of the time being horizontal. The physical condition and activity should be taken into consideration when choosing the appropriate setting of a g-valve. Most importantly, a g-valve may not fit the needs of a growing child who has changes of physical activity. An adjustable g-valve or pressure-valve may be considered in the growing children.

Flow reducing devices (aka "flow regulated", "flow regulating", "auto-regulating", "flow controlled", "low flow", and "variable-resistance" devices.) [14]

These terms may be seen in the literature or on commercial brochures. Whatever term used, this type of device aims to reduce the flow depending on the DP instead of postural changes, thus technically not an "antisiphon" device. This mechanism is often discussed together with true antisiphon devices because they share a common goal of preventing overdrainage. The SiphonGuard (Codman & Shurtleff, Inc., Raynham, Massachusetts, USA) consists of two CSF pathways: a large caliber primary pathway at the center (mean resistance 1.5 mmHg/ml/min), and a spiral secondary pathway surrounding it (mean resistance 42 mmHg/ml/min) [Fig. 7] [46]. The spiral channel is 40 mm long with a diameter of 0.4 mm. This secondary pathway is always open [14]. A ruby ball sits between two opposing springs in the primary pathway. During normal flow, the ball is balanced off the seat, allowing CSF to enter the primary pathway with lower resistance. In the case of excessive flow, the ball seats and blocks the primary pathway, forcing CSF to flow through the secondary pathway with higher resistances, resulting in a low flow state. The DP required to achieve a CSF flow of 0.3 ml/min would be

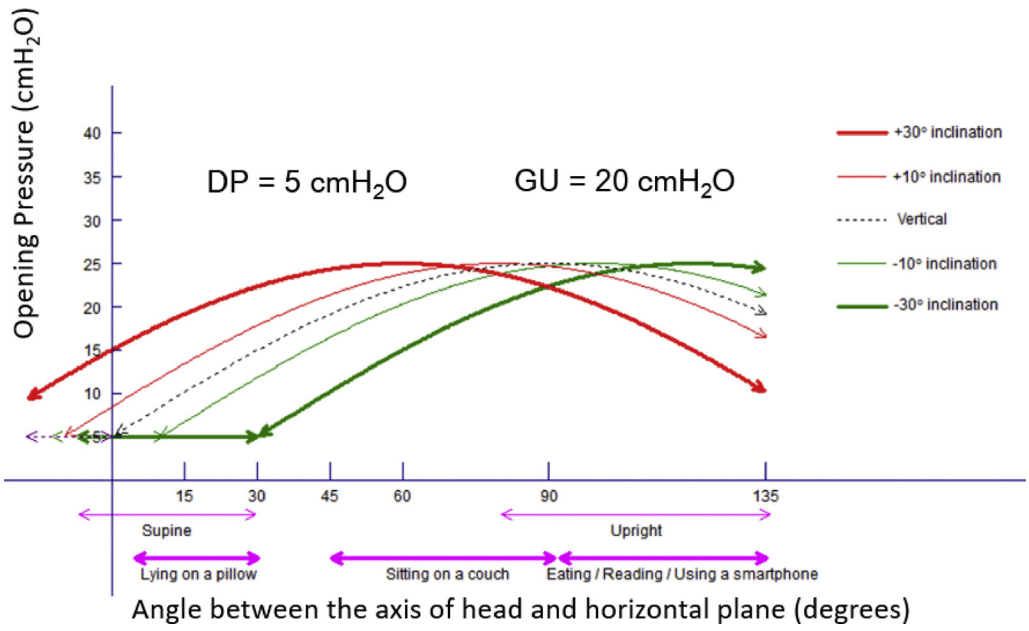

Fig. 6 Shift of pressure curve depending on the inclination (the angle between the axis of the gravitational device and the head). The given pressure setting of the differential pressure (DP) unit is 5 cmH_2O, and the setting of the gravitational unit (GU) is 20 cmH_2O. Anterior inclination (positive degrees) leads to left shift of the pressure curve, and posterior inclination leads to right shift. An anterior inclination of 30° results in an actual opening pressure (OP) of 15 cmH_2O when the patient lies supine, leading to underdrainage. Anterior inclination also results in undesired low OP when the patient is upright with the head flexed (95° to 135°), leading to overdrainage. Note that an anterior inclination of only 10° results in an OP of 8.47 cmH_2O instead of 5 cmH_2O in supine position. Posterior inclination (negative degrees), on the other hand, doesn't affect the draining function significantly as shown in the diagram. It could even be beneficial in certain circumstances.

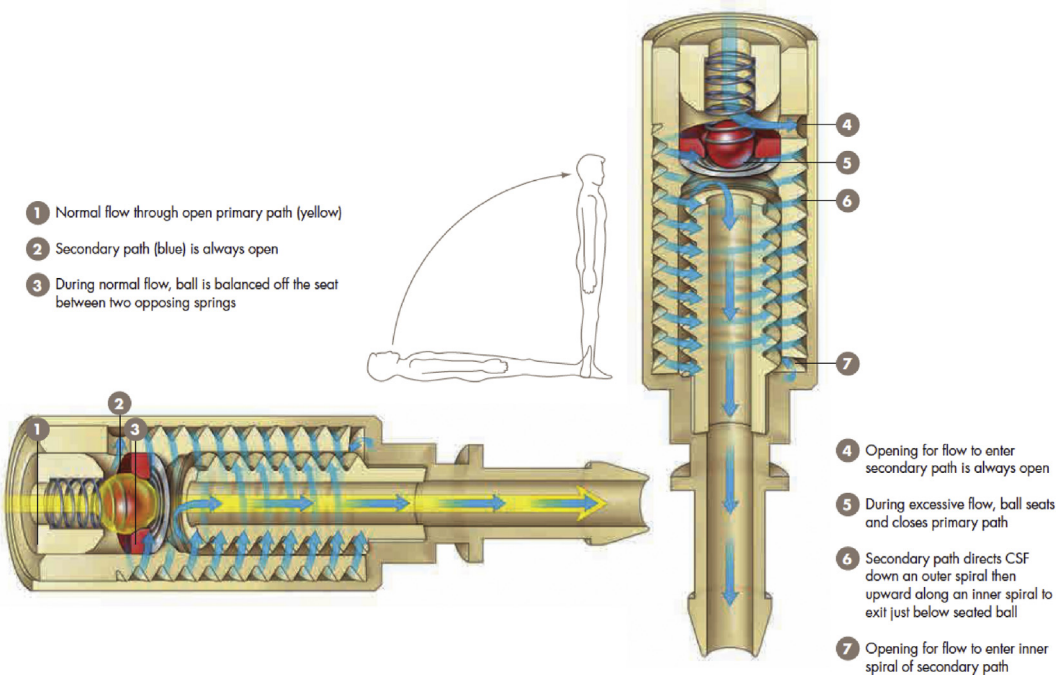

Fig. 7 Schematic illustration of the SiphonGuard, a flow-reducing device. The ball and spring mechanism is encased in a polyethersulfone shell, making it impervious to scar tissue encapsulation or external pressures (Image adopted from CODMAN® SIPHONGUARD® brochure, https://www.integralife.com/).

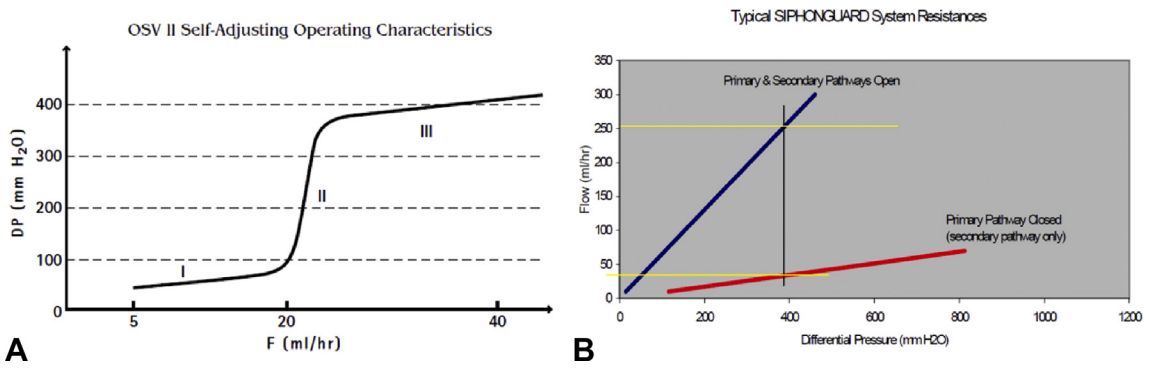

Fig. 8 Flow-pressure curves of (A) OSV II and (B) SiphonGuard. There are three stages in OSV II. DP: differential pressure; F: flow. (A) When DP is about 40–120 mmH_2O, Stage I begins and the flow rate will be between 5 and 18 ml/h. Stage II begins when the DP is between 120 and 300 mmH_2O. The valve operates as a variable-resistance flow regulator, and the flow is restricted between 18 and 30 ml/h. Stage III is the pressure relief mode. It takes place when DP rises above 300 mmH_2O, allowing rapid flow rate. This design enables management of postural and vasogenic ICP changes. (B) The SihponGuard is always patent and the concept of opening pressure does not apply. The resistance is different however, when the primary pathway is open or closed (Image adopted from OSV II brochure and Codman Siphonguard FAQ, https://www.integralife.com/).

0.45 mmHg and 12.6 mmHg, in low- and high-flow states, respectively [46]. Examples of flow reducing devices include SiphonGuard (Codman & Shurtleff, Inc., Raynham, Massachusetts, USA), Orbis-Sigma OSV II valve (Integra LifeSciences, Plainsboro, NJ, USA), CRx Diamond valve (Phoenix Biomedical Corp., Valley Forge, PA). The latter two are generally classified as "valves" with integrated flow reducing function instead of an antisiphon device per se. A "valve" is a mechanism that regulates flow and opens when DP exceeds OP. The Orbis-Sigma valve and the CRx Diamond valve (also a slit valve) are multistage flow-regulating valves with their own unique flow–pressure curves. Their opening pressures are about 5 mmHg [47,48]. They are able to function as independent valves in the VP shunt system and usually not implemented in tandem with other valves. SiphonGuard, on the other hand, has virtually no opening pressure. It is utilized as an accessory in tandem with a main valve [46]. The flow–pressure curves of the OSV II and SiphonGuard are presented in [Fig. 8].

Comments

1. The most distinct feature of this group is that it does not sense body posture. Its function is not "anti-siphon" by nature, but generally flow reducing and not counteracting siphon effect. This mechanism is the only one that is able to reduce excessive CSF flow caused by nocturnal vasogenic events. In another sense, it cannot differentiate standing up from an ICP crisis [14].
2. It is demonstrated that the SiphonGuard shifts to the low flow state when flow exceeds 1.39 ± 0.42 mL/min (= 83.4 ± 25.2 mL/h), or when ΔP exceeds 15–17 cmH_2O [35]. Aschoff's laboratory demonstrated flow peaks of up to 160 mL/h or as low as 50 mL/h before shifting to the low flow state, suggesting a large discrepancy in performance between individual products. In the range of 8–15 cmH_2O, the valve permits non-physiologic high flows (>20 mL/h), which may not be a significant problem since the ΔP well exceeds this value when in vertical [14]. Laboratory studies show large hysteresis in flow reducing devices. Wide variations in flow–pressure curves are observed [14,35]. This may be due to the very narrow passageways in this type of devices.
3. In those with slit ventricles, there may not be enough CSF to produce flow above the threshold of state switching. Shorter patients, obese patients, or those who rest persistently in a semisitting position, the drainage rate of 1–1.5 ml/min may cause overdrainage while not activating the flow reducing function. The threshold for switching back to low flow state is below 4–6 mmHg. In a patient with relatively high ICP, the device may not switch back to high flow state when the subject lies down. The device is thus "locked" in the low flow state and continues to drain CSF with a sub-physiologic rate, resulting in underdrainage [35,46].
4. In contrast with the OSV, the SiphonGuard does not provide a safety stage for drainage in higher ICP circumstances. The OSV on the other hand, may permit excessive drainage and thus non-physiologic low ICP in the upright position, since the hydrostatic pressure easily exceeds the 300 mmH_2O threshold.
5. Despite the aforementioned concerns, the SiphonGuard showed relatively stable flow and physiologic ICP compared to the Delta chamber and ProSA in studies using a test bench simulating physiologic situations [35,45].
6. The housings of OSV and SiphonGuard prevent influences from scar tissue encapsulation or external pressure. They can be placed at any level (unlike diaphragm devices) and require no particular orientation (unlike gravitational devices) [37].

Clinical efficacy of ASDs in shunt-induced overdrainage conditions

Overdrainage rate

All currently available ASDs have been proven to be able to counteract the negative suction pressure of siphoning to some extent. The definition of overdrainage varies greatly in the literature and results should be interpreted carefully. The determination of superiority of one device over another is difficult owing to the paucity of *in vivo* comparison in the literature. In a randomized multicenter control trial (SVASONA) in iNPH population, ProGAV, a kind of g-valve was shown to be superior to programmable DPVs in terms of cumulative overdrainage rates (5% and 39% at 6 months, 12% and 59% at 12 months, respectively). It also demonstrated less underdrainage rates at 12 months (2% and 14%, respectively). The Short-Form 12 health survey (SF-12) Mental Component Scores was significantly better at 6- and 12-month clinical visits [9]. An observational study with pediatric and young adult population who suffered from clinical and/or radiological overdrainage treated with adjustable gravitational valve ProSA reported 91% symptom-free at 1 year follow-up [49]. A prospective multicenter study (PROSAIKA) reported an overdrainage rate (SDH/SD effusion on neuroimaging studies in patients with symptoms) of 7.9% in adult patients who underwent primary or secondary implantation of ProSA [50]. The authors stated that the somewhat negative patient selection (2/3 were revisions) and imaging in only symptomatic patients resulted in the seemingly higher rate of overdrainage. Other clinical studies regarding g-valves reported overdrainage rates ranging from 0% to 9%, with the exception of one report with 15.6 and another with 21% [9,50–60]. Underdrainage rates ranged from 1.8% to 10.6%, with one exception of 40%. Many studies support the use of a g-valve for overdrainage control [9,49,50,53–58,61,62]. Most studies regarding a diaphragm device date earlier than those regarding g-valves. Outcomes vary among studies. Kondageski et al. reported resolution of severe overdrainage symptoms (19/24 (79.2%) pre-treatment and 1/24 (4.17%) at one year post-treatment) in pediatric population with mixed hydrocephalic etiologies treated with secondary implantation of a programmable valve with diaphragm SCD (Strata valve). The rate of radiologic slit ventricles seemed similar before and after treatment [63]. A prospective cohort study reported less overdrainage rates in the siphon control (Delta valve) group than simple DPV (PS Medical Medium pressure) group [64]. However, there are also studies reported no significant differences in overdrainage rates between SC and NSC [65–67]. Clinical reports regarding the efficacy of SiphonGuard is lacking. Nearly all studies regarding SiphonGuard were laboratory studies [Supplementary Table 2].

Subdural (SD) collections: SD hematomas (SDH)/hygromas

The SVASONA study demonstrated less subdural effusions in the g-valve group than the programmable DPV group (6% and 36%, respectively) [9]. A retrospective chart review with adult population of mixed etiologies concluded that there was no difference in the rate of SDH between siphon control and non-siphon control groups (4% and 6%, respectively). The valve type was not specified [67].

Slit ventricle syndrome (SVS)/proximal catheter obstruction

This condition is typically observed in older hydrocephalic children who are shunted in infancy [68]. The addition of or replacement to an ASD or a programmable valve is the most popular and reasonable method for treatment. The secondary or primary placement of a diaphragm ASD have shown a dramatic reduction in the incidence of SVS and ventricular catheter obstruction. Better intellectual outcomes are also observed [69]. G-valves have been shown to be able to reduce the rate of proximal obstruction (43%–66%) in pediatric population [61], and also slit ventricles (75% radiological improvement at 1 year) in pediatric and young adults [49].

Shunt survival

Reports on shunt survival regarding ASDs should be interpreted carefully because the valve and catheters also play a role in the system. Other factors such as young age [70], etiology of hydrocephalus [71], entry point [1], shorter interval of revision since the primary shunting, number of revisions [72], and complexity of the assembly also have negative effects on shunt survival [73]. Populations vary among studies. Most studies either did not have a control group or the control group was DPVs instead of another type of ASD. G-valves generally perform well in this respect. One year survival ranges from 53% to 90% [49–52,54,56,57,59,62,74,75]. One year survival of diaphragm devices was about 54%–70% [10,64,65,76–78]. One year survival of the OSV was about 61%–71% [10,76,79,80]. Clinical study regarding the survival of SiphonGuard is lacking. Many studies reported similar shunt survival in the antisiphon group and the DPV group [10,64,65,73,76,81]. However, proximal obstruction may be reduced in shunts with ASDs [49,61,62,69,81] [Supplementary Table 3].

Discussion

Knowing the basics of physiologic and shunted CSF dynamics, the siphon, and the mechanisms and physical properties of currently available ASDs, three questions emerge. First, should an ASD be implemented in all primary shunts? Second, may ASD play a role in the management of overdrainage induced by shunting? Third, what is the role of programmable valves in the management of overdrainage?

A survey was conducted to evaluate the understanding and management preferences among the members of American Society of Pediatric Neurosurgeons. As the choice for primary shunt valve, 41% chose DPVs, 29% DPV + ASD, 27% programmable valves, and 3% OSV. As for the treatment for chronic shunt overdrainage, 45% of members reported often or always placing an ASD, 41% adjusting valve settings, 30% replacing the valve, and less than 20% considered adding an additional valve or shunt assistant. Valve preference was reported as

follows: 50% programmable valve ± ASD, 25% DPV + ASD, 19% OSV, and 3% DPV [82]. Although outcomes have been encouraging in pediatric population, reports showed the contrary argue that the placement of an ASD may result in underdrainage and subsequent alarming neurologic symptoms. This included pediatric patients [61,69,83,84]. Bedridden patients most likely benefit from a DPV only. It is not necessary to place an ASD. Integration of a g-valve has been shown to be harmful in this population [41,43]. Some patients with poor brain compliance may actually need siphoning to achieve adequate treatment effects [85]. As a general guideline, ambulatory patients (older children and most NPH adults) may most likely benefit from the decreased overdrainage rates by implementing an ASD in the shunt configuration. On the contrary, bedridden patients and those with poor consciousness do not need an ASD. Clinical considerations of each type of ASD are summarized in Table 2.

Secondary implantation of an ASD onto the pre-existing shunt has been proven to be effective with the treatment of shunt-induced overdrainage symptoms, SD collections, and slit ventricles [49,50,57,62,69]. It should be considered as long as no contraindications exist.

The Dutch Normal-Pressure Hydrocephalus Study showed that low-pressure valves lead to better neurological outcomes than medium pressure valves, but low-pressure valve were associated with 3.3-times higher relative risk of SD effusions [7]. Programmable valves have been widely used especially in iNPH patients since the 1990s. The 2005 iNPH guidelines stated that they can manage over- and under-drainage noninvasively instead of surgical revisions [86]. Symptoms and signs of overdrainage may resolve by adjusting the valve to a higher pressure setting. However, the treatment effect of CSF diversion is reduced. Studies comparing g-valves and programmable valves without anti-siphon function showed better clinical outcomes in the former group. Improvement in gait imbalance is observed in both groups, but only the g-valve group showed improvement in cognition and bladder functions. The presence of the gravitational unit allows a low pressure setting of the DPV, which leads to better outcome [9,58,87,88]. The hydrostatic pressure in vertical position is larger than the OP of the valve even with the highest pressure setting (200 mmH_2O in Codman Hakim Programmable Valve) [89]. In horizontal position, the patient may suffer from underdrainage with high OP. Theoretically, a higher pressure setting to prevent overdrainage is by no means physiologic. Programmable valves are actually DPVs with fixed, but adjustable OP. The original theory of Hakim advocating an adjustable valve uses the function to correct mechanical mismatching due to continuously shrinking ventricle sizes after the initial implant of a shunt. A higher pressure setting is needed to maintain the SD stress after the sizes of ventricles decrease. The ventricles collapse if the intraventricular expansive force (= CSF pressure x ventricular area) is insufficient [90]. Viscosity of CSF may change by time due to degradation of blood products and protein. CSF production rate increases in growing children. The function of programmable valve should be used to fine-tune the OP to match the required IVP according to the aforementioned factors, but not to counteract the siphon effect [89].

Table 1 List of some of the available ASDs on the market.[a]

Product	Combination valves	Manufacturer/Distributor	Mechanism
SiphonGuard	- Codman Hakim Precision Fixed Pressure Valve with SiphonGuard (In-Line, Right Angle) - Codman Hakim programmable valve with SiphonGuard (In-Line, Right Angle) - Codman Hakim programmable valve Lumbo-Peritoneal (L-P) with SiphonGuard (In-Line) - Codman Certas Plus Programmable Valve with SiphonGuard (In-Line Regular, In-Line Small, Right Angle)	Integra LifeSciences, Plainsboro, NJ, USA[c]	Flow reducing
Siphon Control Device (SCD, Delta chamber)	Strata II, Delta valve	Medtronic PS Medical, Inc., Goleta, California, USA	Diaphragm
Anti-Siphon Device (ASD)[b]	Pudenz Valve, Multi-Purpose Valve, Novus Valve	Natus Medical, Pleasanton, CA, USA[c]	Diaphragm
Miethke ShuntAssistant, ProSA	GAV, PaediGAV, ProGAV, ProGAV 2.0, M.blue	Manufacturer: Christoph Miethke GmbH & Co. KG, Potsdam, Germany Distributor: Aesculap, AG, Tuttlingen, Germany	Gravitational
Gravity Compensating Accessory (GCA)[b]	Horizontal-Vertical (H–V) Lumbar Valve	Natus Medical, Pleasanton, CA, USA[c]	Gravitational

[a] Availability may vary among countries/regions.
[b] Only available in the USA.
[c] Natus Medical Incorporated acquired certain neurosurgery business assets including the ASD and GCA from Integra Life Sciences in 2017. Integra LifeSciences acquired Codman Neurosurgery from Johnson & Johnson in the same year.

Table 2 Clinical implementation of various antisiphon devices (ASDs) considering different mechanisms of ASD and the condition of patients.

ASD	Diaphragm	Gravitational	Flow reducing
ASD orientation	–	Vertical ± 10°, or posterior inclination	–
ASD location of the body	Level of Mastoid *Clavicle/Upper thoracic: for iNPH and poor brain compliance *Above mastoid: tend to underdrain	*Retroauricular: growing children *Thoracic level: adults	–
ASD encapsulation	Avoid tight pocket	–	–
ASD setting	–	*Refer to Supplementary Table 2	–
Patient conditions			
Obese	Y	Y *Refer to Supplementary Table 2	Δ The DP may not be enough to deactivate the high flow pathway
Bedridden	X	X	X
Poor consciousness	X	X	X
Infant and young children	Δ	*Refer to Supplementary Table 2 *Consider programmable device in difficult cases[a]	Δ The DP may not be enough to deactivate the high flow pathway
Older children, shorter adults	Δ	Y *Refer to Supplementary Table 2 *Consider programmable device in difficult cases[a]	Δ The DP may not be enough to deactivate the high flow pathway
iNPH	Δ Clavicle/Upper thoracic location	Y	Δ May not provide sufficient flow in nocturnal ICP elevations
Slit ventricle	Y	Y	Δ
Subdural collection	Y	Y	Y
Patient education			
Sleeping	Avoid lying on the side of the ASD	–	–
Exercise	–	Rest if discomfort	–
Posture	May occasionally lie down (An erect position may prevent any CSF flow)	Keep the axes of head and body in-line if symptoms develop (Discrepancy of the two axes may lead to over- or under-drainage)	Avoid semisitting position for too long (Try to stand up or lie down totally to ensure the device switches to the correct state)

Abbreviations: Doesn't matter; *: note; iNPH: idiopathic normal pressure hydrocephalus; Y: consider to use; Δ: may consider to use; X: not be used; DP: differential pressure; ICP: intracranial pressure.

[a] Difficult cases: The setting of gravitational device may need to be adjusted in growing children, those with activity changes, and those who underwent multiple revisions.

Conclusions

ASDs may be used in the management of overdrainage induced by shunting; however, the use of ASDs may hinder the improvement of some functions in patients with iNPH or poor brain compliance. In addition, the implanted level and angle of ASD, the age, physical activity, and BMI of the patients may affect the function of the ASDs that were designed with different mechanisms. There is no ideal ASD, which is as physiologic as IJV. Neurosurgeons should be familiar with the mechanisms and physical characteristics of the implants they use. The indication of placement of an ASD and the type of ASD should be determined according to the patient's need. The ideal location of the ASD should also be considered carefully according to the patient's age and the characteristics of the ASDs.

Conflict of interest

All authors declare that they have no competing interests.

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Appendix A. Supplementary data

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