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Changes in Pressure-Flow Control Characteristics of Shunt Valves by Intracranial Pressure Pulsation: an In Vitro Study

Chong-Sun Lee, Joo Young Kim

College of Mechanical and Control Engineering, Handong Global University
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Abstract: Shunt valves used to treat patients with hydrocephalus were tested to investigate influence of intracranial pressure pulsation on their flow control characteristics. Five commercial shunt valves were tested in the flow loop that simulates pulsed flow under pressure pulsation. As 20cc/hr of flow rate was adjusted at a constant pressure, application of 40mmH_2O of pressure pulse increased the flow rate by 67.9%. As a 90cm length catheter was connected to the valve outlet, increase in the flow rate was substantially reduced to 17.5%. As the flow rate was adjusted to 40cc/hr at a constant pressure, increase in the flow rate was 51.1% with the same pressure pulsation of 40mmH_2O. The results indicated that pressure-flow control characteristics of shunt valves implanted above human brain ventricle is quite different from those obtained by syringe pump test at constant pressures right after manufacture. The influence of pressure pulsation was observed to be more significant at low flow rate and the flexibility of the outlet silicone catheter was estimated to significantly reduce flow increase due to pressure pulsation.

Key words: Shunt valve, Hydrocephalus, Cerebrospinal fluid(CSF), Pressure pulse, Flow control

INTRODUCTION

Shunt valves are small flow-control devices used for patients with hydrocephalus to help drain cerebrospinal fluid (CSF) accumulated in the ventricles of human brain. Ventriculo-peritoneal (VP) shunt valves, mostly used among several different types, are implanted in the scalp between neck and cupola as shown in Fig. 1. A 10 to 15 cm inlet catheter connects the ventricle to the inlet port of the valve while a 90 cm outlet catheter diverts the CSF from the valve to the peritoneal cavity.[1,2]

Fig. 2 represents a schematic diagram of a constant pressure type shunt valve employed in this study which currently dominates the market. A thin elastic diaphragm is seated in the rigid plastic base and works like a check valve to control the flow. The diaphragm opens when the ventricular pressure is increased above a threshold valve (called opening pressure), and hence prevent further increase in the ventricular pressure.

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Corresponding Author: Lee Chong-Sun, 3 Namsong-ri, Heunghae-eub, Buk-gu, Pohang City, South Korea
Tel. 054-260-1393 Fax. 054-260-1312
E-mail. cslee@handong.edu

A predeflection (height difference between surface A and B) is given in the valve design to prevent CSF drainage before the ventricular pressure reaches an opening pressure level. When the ventricular pressure exceeds this level, the diaphragm tip starts to deflect downward to form a flow orifice. Variation in the pressure level is relatively small for the constant pressure type shunt valve for a wide range of flow rate as illustrated by a small slope of the pressure-flow characteristic curve in Fig. 2.

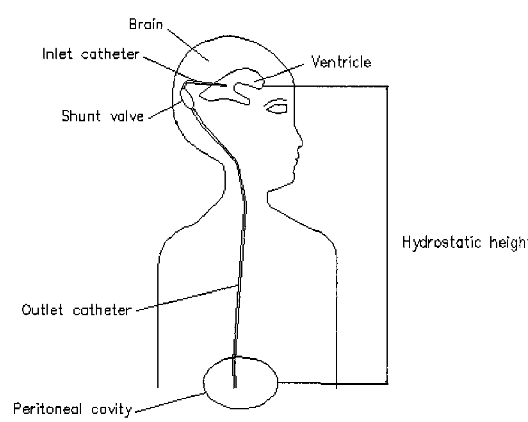

Fig. 1 Ventriculo-peritoneal (VP) shunt system (valve plus catheters)

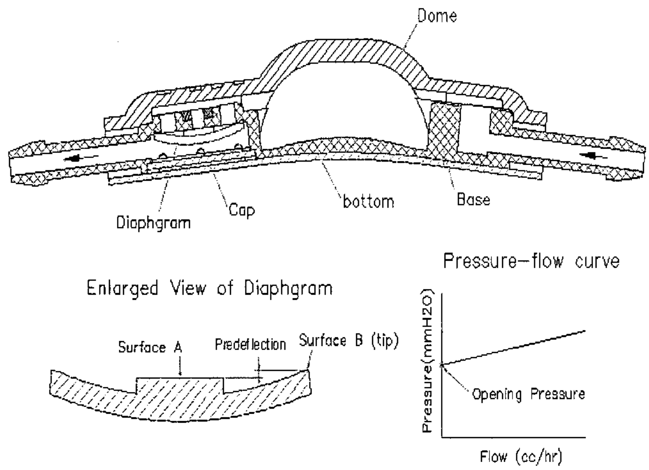

Fig. 2. Schematics of a diaphragm-type shunt valve and pressure-flow characteristic curve.

Every single shunt valve is tested for its pressure-flow characteristics right after manufacture and valves showing appropriate pressure ranges are validated and sent to the market. Medical doctors implant valves suitable to the patients' pressure conditions. A syringe pump is used for testing pressure-flow characteristics. A set of flow rates (5, 10, 20, 30, 50cc/hr) are sequentially supplied and pressures are measured at each flow rate[3,4]. Human ventricles experience pressure pulses due to cardiac pulsation, and therefore, shunt valves in vivo are exposed to the pulsed pressure rather than the constant pressure. Changes in the pressure-flow characteristics of the shunt valves by the intracranial pressure pulsation are not studied in detail yet.[1] Recently, Hong et al. performed a computational study for the flow through shunt valves and found significant increase in the flow rate when pressure pulses were added to constant pressure.[5]

Experiments were performed in the present study to investigate how flow rate changes through shunt valves as pressure pulsation is added to the constant pressure. An in vitro flow loop that simulates pulsed flow under pressure pulsation was set up and flow rates and pressures were measured to delineate influence of pressure pulsation on the flow rate. A flexible silicone catheter, which was not considered in the numerical study of Hong et al.[5], was attached to the valve outlet to investigate influence of outlet catheter.

EXPERIMENTAL METHOD

As shown in Fig. 3, constant pressure level was adjusted with water height in the water chamber, and then, pressure pulsation was added to the shunt valve by generating air pressure pulses with a three way solenoid valve. A pressure pulse of 40mmH_2O (maximum pressure minus minimum pressure) was generated at the valve inlet side using a function generator that periodically open and close the three way valve at 1Hz frequency. A Validyne DP-15 pressure transducer was connected to the NI-6024E DAQ card to measure as well as adjust the pressure pulse to appropriate ranges. Flow rates were calculated by measuring the flow passing through the valve during one minute using an electronic balance (Ohaus AV-210). Magnitude of the pressure pulses obtained in the flow loop (Fig. 4) was similar to that measured in vivo[6,7]. However, the pulse generated in vitro showed sharper variation compared to the realistic intracranical pressure pulses.

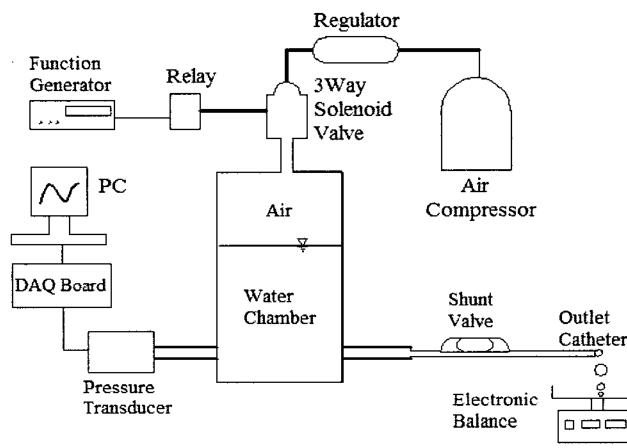

Fig. 3. Schematics of experimental setup

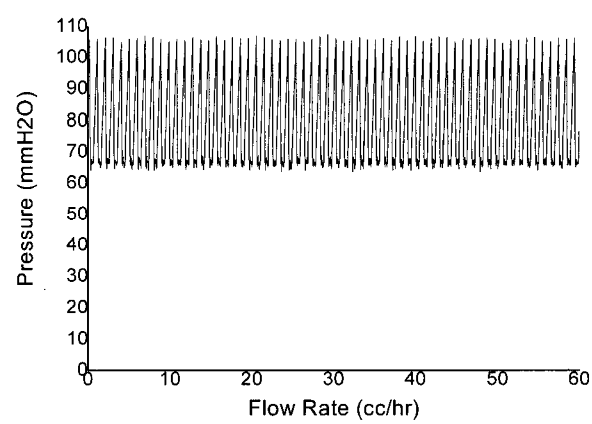

Fig. 4. Typical pressure variation generated in the experiments. Pressure pulse is estimated to be about 40mmH_2O.

The experimental system was adjusted to a constant pressure level (without pressure pulsation) causing 20cc/hr of flow rate. Then, the flow rate was measured after a pressure pulse of $40mmH_2O$ was added at the same constant pressure level. The experiments were repeated with a catheter attached to the valve outlet. Five commercial shunt valves of the same kind were tested and the tests were repeated five times for each valve. Differences in the flow rates were observed to be negligible between the tests for the same valve.

Pressure level that induced 20cc/hr of flow rate was significantly different between valves because of their inherent differences. Fig. 5 compares the pressure-flow characteristic curves of the five valves tested according to ISO 7197 protocol[3] which specifies standard procedures for testing shunt valves. One can observe pressure difference between the valves up to $20mmH_2O$. Next, constant pressure level was raised to increase the flow rate to 40cc/hr and the experiment was repeated with the same $40mmH_2O$ pressure pulse.

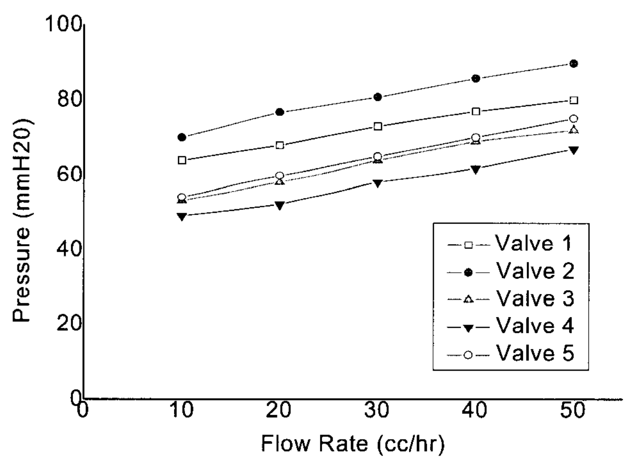

Fig. 5. Pressure-flow characteristics of the shunt valves employed in the experiments

RESULTS AND DISCUSSION

Pressure pulsation was observed to significantly increase the flow rate through shunt valves. Fig. 6(a) compares flow rates between steady and pulsed flows for shunt valves adjusted to 20cc/hr of steady flow rate. Fig. 6(b) shows the results at the same condition with a 90cm outlet catheter attached to the valve outlet. Fig. 6(c) shows the results at the increased flow rate of 40cc/hr

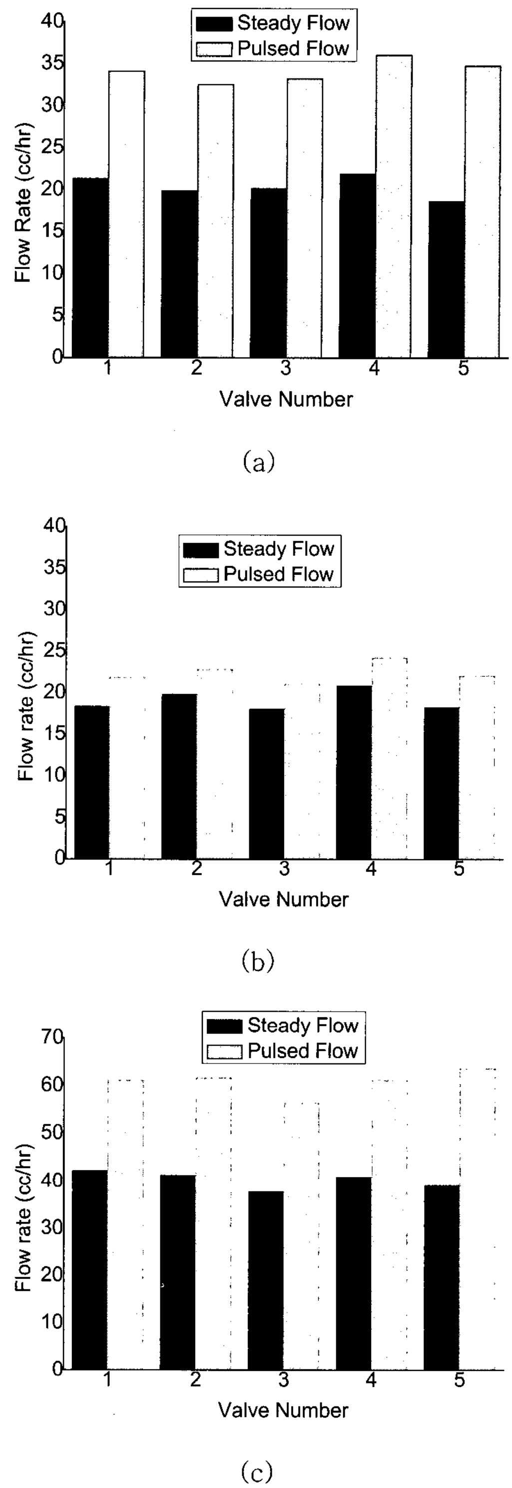

Fig. 6. Changes in the flow rate depending on the pressure pulsation
(a) valve alone at 20cc/hr (b) valve plus 90cm catheter at 20cc/hr (c) valve alone at 40cc/hr

Fig. 7 compares % increase in the flow rate by the pressure pulsation for three different cases. Pressure pulsation of 40mmH_2O induced increase in the flow rate more than 60% at 20cc/hr.
As shown in Fig. 7, about 60% of increase in the flow rate was observed for valve 1, 2, 3, and 4 while valve 5 showed increase in the flow rate close to 90% by the pressure pulsation. This difference is attributed to the difference in the characteristics of the small silicone diaphragms in the shunt valves. Jang et al.[8] and Won et al.[9] numerically demonstrated that the small diaphragm needs to be manufactured and assembled to the shunt valve with an accuracy of 10 μm in order to appropriately control the flow through the valve. Therefore, error involved in manufacture and assembly process are attributed to the differences of the pressure-flow curves observed in valve 5. On the other hand, increase in the flow rate by the pressure pulsation for the valve with an outlet catheter was reduced to 17.5% which was one fourth compared to the case without the outlet catheter. This decrease is believed to the fact that the flexible silicone catheter reduces diaphragm movement by absorbing pressure pulses.

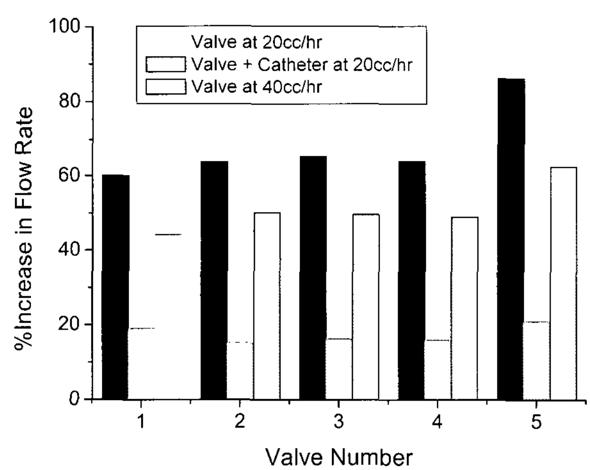

Fig. 7. *%Increase in the flow rate with pressure pulsation*

Hong et al.[5] numerically showed 48% increase in the flow rate by the pressure pulse of 40mmH_2O at 20cc/hr. They solved flow dynamics near the thin valve diaphragm rather than modeling the whole valve structure considering the major pressure drop occurs through the diaphragm.[9] Dimensions of Hong et al.'s model were obtained from manual measurement using microscope. Considering such limitations, their results are estimated to be similar to the 60% increase obtained in the present study. Fig. 8 indicates that diaphragm movement due to pressure pulsation is more significant for the increase in the flow rate than the pressure pulse itself[5]. Case 1 corresponds to a steady flow without pressure pulse and case 2 represents pressure pulsation without considering diaphragm movement.

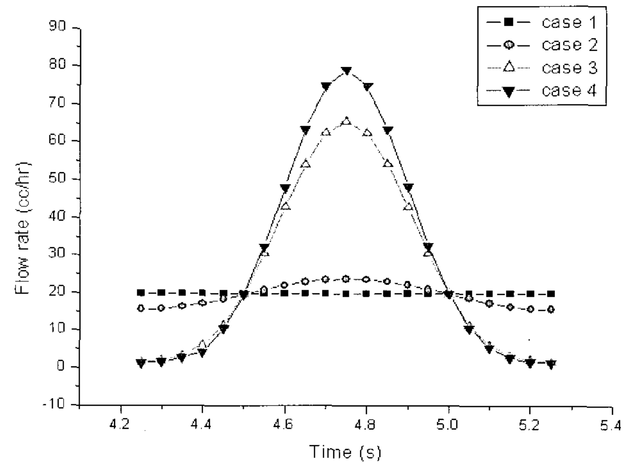

Fig. 8. Comparision of flow waveforms during a pulse cycle at 20cc/hr (Redrawn from [5]. case 1: steady state, case 2: pressure pulsation without diaphragm movement, case 3: diaphragm movement without pressure pulsation, case 4: diaphragm movement with pressure pulsation)

Case 3 represents diaphragm movement without considering pressure pulse and case 4 takes into account of both diaphragm movement and pressure pulse. Increase in the flow rate is observed to be much larger in case 3 than in case 2. Therefore, diaphragm movement is considered to be more responsible on the increase in the flow rate than the pressure pulse itself.

Relationship between pressure and flow rate in the shunt valve were compared in Fig. 9 for steady flow and pulsed flow cases. Marks in the graph are observed to be located in the lower pressure side for the pulsed flow case compared to the steady flow case. Although the present experiments were conducted at only two flow rates (20cc/hr and 40cc/hr), Hong et al.'s numerical study[5] supports the results of the present study over the range of flow rate. Therefore, shunt valves in vivo are believed to have pressure-flow curves with much lower pressure values than those tested at constant pressure levels right after manufacture.

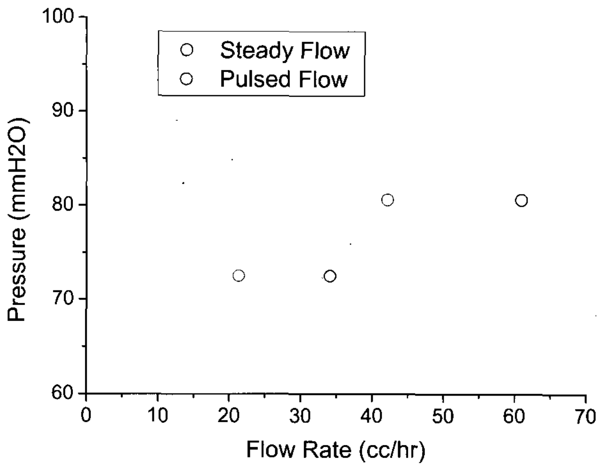

Fig.9. Relationship between pressure and flow rate for steady and pulsed flows.

CONCLUSION

Every single shunt valve is tested for its pressure-flow characteristics right after manufacture and valves showing appropriate pressure ranges are validated and sent to the market. In the above test, pressures are measured by sequentially supplying five predetermined constant flow rates using a syringe pump. However, human ventricles are subject to pressure pulses due to cardiac pulsation. The present study showed that implanted shunt valves would drain much more CSF by the pressure pulsation added to the constant pressure. Therefore, shunt valves in vivo are believed to have pressure-flow curves with much lower pressure values than those tested at constant pressure levels right after manufacture. Influence of pressure pulsation was observed to be more significant at low flow rate. The flexibility of the outlet silicone catheter was estimated to significantly reduce flow increase due to pressure pulsation.

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