A Study on Passive Microvalve for Glaucoma

*Taeseok Sim and Yong-Kweon Kim
School of Electrical Engineering and Computer Science, Seoul National University

녹내장 치료용 수동형 밸브의 제작

*심태석, 김용권
서울대학교 전기·컴퓨터공학부

Abstract - This paper reports the design, modeling, fabrication and measurement of passive microvalves applicable to glaucoma implants. The proposed microvalves consisted of microchannels and chambers. The microchannels had a fixed fluidic resistance and generated a pressure difference. The chamber was located in the middle of the microchannels and acted as a buffer preventing an abrupt pressure change from an external variation of the fluid flow. To find optimum design parameters, six kinds of the microvalves were fabricated and experimented.

1. Introduction

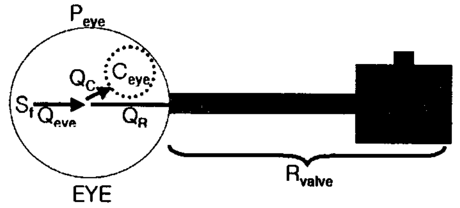
Glaucoma is an eye disease caused by abnormally high eye pressure resulted from a poor drainage of the eye fluid. It damages optic nerves and leads to visual loss and blindness. Currently an implantation surgery is known to be the most effective treatment for the incurable glaucoma patients. However, conventional drainage implants have serious problems such as a low fluidic resistance and a big size. The low fluidic resistance causes excessive drainage of the eye fluid after a surgical treatment, and this leads to be hypotonic (low intra ocular pressure state). The big size may give a fear to patients before surgical treatments [1]. The problems described above would be removed if the glaucoma implant could be fabricated more accurate and small [2,3].

In this paper, passive microvalves using fluidics and MEMS technology were proposed. Six kinds of microvalves were designed and fabricated to verify the feasibility of the proposed passive microvalve.

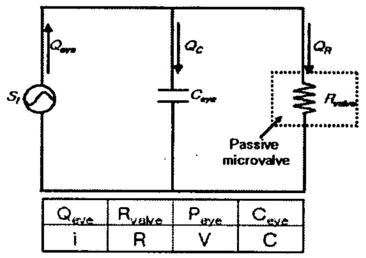
2. Theory

2.1 Modeling of valve implanted eye system

An eye fluid, called aqueous humor, is produced in a posterior chamber of an eye from circulating blood with a fixed rate, 4.167×10^{-11} m^3/sec. Thus the eye can be assumed as an universal flow source. The cornea-sclera envelop expands and relaxes according to variations in the internal volume of an eye ball. Therefore the eye can be assumed to have a compliance factor. Let P_{eye} be the pressure of eye ball, C_{eye} be the compliance of eye ball, S_f be the flow source, R_{valve} be the fluidic resistance of the valve, Q_{eye} be the flow rate of eye ball and Q_{valve} be the flow rate of channel of valve. The valve implanted eye system can be simplified as Fig 1. (a). Since pressures, flow rates, fluidic resistances and compliances of fluidic systems have similarities to voltages, currents, resistances, capacitances of electrical systems. The valve implanted eye system can be depicted by an equivalent electrical circuit as shown in Fig 1. (b).



(a) Schematic of the valve implanted eye system



(b) An equivalent electrical circuit

Fig 1. Schematic of the valve implanted eye system and an equivalent circuit

From the equivalent electrical circuit, we can formulate the following equations,

$$Q_{eye} = Q_C + Q_R = C_{eye}\frac{dP_{eye}}{dt} + \frac{P_a}{R_{valve}} \tag{1}$$

or

$$\frac{dP_{eye}}{dt} = \frac{1}{C_{eye}}\left(Q_{eye} - \frac{P_{eye}}{R_{valve}}\right) \tag{2}$$

Solving this differential equation,

$$P_{eye}(t) = e^{-\frac{t}{R_{valve}C_{eye}}} P_{eye}(0) + R_{valve}Q_{eye} - R_{valve}Q_{eye}e^{-\frac{t}{R_{valve}C_{eye}}} \tag{3}$$

Arranging Eq. (3) correspond to variable t, we obtain

$$P_{eye}(t) = (P_{eye}(0) - R_{valve}Q_{eye})e^{-\frac{t}{R_{valve}C_{eye}}} + R_{valve}Q_{eye} \tag{4}$$

In the Eq. (4), if t goes to infinity, the first term becomes zero. Thus, for the steady state, the eyeball pressure is expressed by the following simple equation [4, 5],

$$P_{eye}(t) = R_{valve}Q_{eye} \tag{5}$$

In Eq. (5), Q_{eye} has an uniformly fixed value. Hence the eyeball pressure can be thought to be varied by only R_{valve}. From the fact that an average normal intra ocular pressure(IOP) is about 2,250 Pa, 2,000 Pa seems to be the most proper and generous target for a prototype. However, in practice, the fluidic resistance becomes bigger gradually due to a fibrosis. Thus, if the fibrosis is considered, the target pressure should be smaller than 2,000Pa. From the fact that the pressure difference of currently used commercial glaucoma implant is approximately 300 Pa, 1,000 Pa was set for the prototype pressure difference. 2,000 Pa was also selected to examine a linearity of the fluidic equation for a flow rate.

2.2 Design of passive microvalve

In the laminar flow system, the fluidic resistance for arbitrary shape is expressed by Eq. (6) [4].

$$R=\frac{f\mathrm{Re}}{2}\frac{\mu l}{D_h^2 A} \tag{6}$$

In Eq. (6), *f*Re, μ, l, D_h and A are shape constant for arbitrary non-circular channel, absolute viscosity of water, channel length, hydraulic diameter and area of channel cross section, respectively. In Eq. (7), *f*Re for arbitrary rectangular channels is expressed.

$$f\mathrm{Re}=96(1-1.3553\alpha+1.9467\alpha^2-1.7012\alpha^3+0.9564\alpha^4-0.2537\alpha^5) \tag{7}$$

where,

$$\alpha=\frac{b}{a},\quad \text{in case of } a\geq b \tag{8}$$

Variables a and b are the length of rectangular sides of the channel cross section. Since the target pressure difference is already known, using Eq. (6) six kinds of channels were designed. The design layouts are shown in Fig 3 and design parameters are summarized in Table 1.

Model ①, ② and ③ were designed to examine the feasibility of the Eq. (6) for the various channel shape in microscale fluidic system. Model ①, ④ and ⑤ were designed to examine the effect of a size of chamber. Finally, model ⑥ was designed to examine the relation between fluidic resistance and channel length.

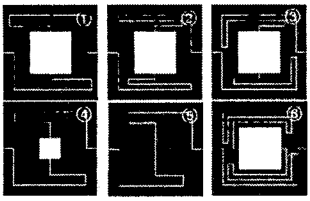


Fig 3. Mask layouts

Table 1. Design parameters

Model #	Target pressure difference	Channel cross section	Channel length	Chamber size
①	1000Pa	80×80μm^2	34.6mm	4×4× 0.08m^3
②	997.3Pa	90×80μm^2	43.3mm	4×4× 0.08m^3
③	995.5Pa	90×80μm^2	52.5mm	4×4× 0.08m^3
④	1000Pa	80×80μm^2	34.6mm	2×2× 0.08m^3
⑤	1000Pa	80×80μm^2	34.6mm	none
⑥	2000Pa	80×80μm^2	69.2mm	4×4× 0.08m^3

3. Fabrication

The fabrication procedure of passive microvalves is depicted in Fig 4. Thermal SiO_2 was patterned to define a hard mask. Then Si was etched to a depth of 80 ㎛ by DRIE (Deep Reactive Ion Etching) with the patterned hard mask. DRIE was performed using 535 bosch process in an ICP reactor (Plasma Therm SLR-10R-B). The inlet and outlet of the microvalve were defined by dicing process. Finally, an anodic bonding was done to close the channel with a glass wafer. The fabricated valve is shown in Fig 5.

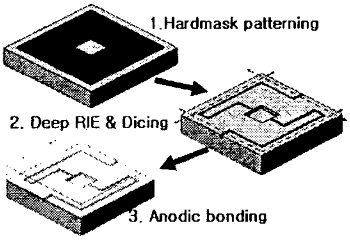


Fig 4. Fabrication process of microvalve

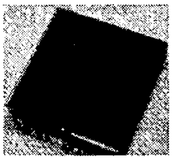


Fig 5. A fabricated passive microvalve

4. Measurements

4.1 Measurement system

The schematic of measurement system is depicted in Fig 6. The microvalve was filled by deionized water to prevent air bubble generating in the middle of microvalve before measurement. A syringe pump was used to supply deionized water to the microvalve at a rate of 2.5 ㎕/min. A pressure sensor was connected between the syringe pump and the microvalve. Data from the pressure sensor were acquisited using NI-DAQ, PCI-MIO-16E-1 board and LabVIEW program.

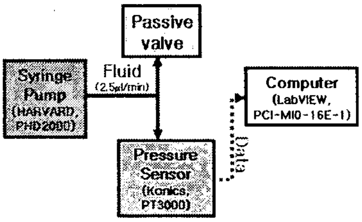


Fig 6. A schematic of measurement system

4.2 Measurement results

The measured pressures of each model and their standard deviations are shown in Fig 7. Data fluctuations of the results are mainly generated by a nonuniform flow rate due to a stepwise motion of the syringe pump. Since the stepwise motion of syringe pump was inevitable, a curve-fitting was achieved for easy analysis.

All measured pressure differences showed good agreements with the target pressure differences. From the results of (a) (target pressure: 1,000 Pa)and (f) (2,000 Pa), it was shown that the pressure difference is proportional to the channel length. In the case of variation of channel cross section size ((a), (b) and (c) in Fig 7), all the results were near to the expected pressure difference (1,000 Pa). Therefore, it seems that Eq. (6) is reliable for various channel shapes. In the case of comparison of chamber size ((a), (d) and (e) in Fig7), it was expected that by buffering effect of the chamber, data fluctuation would decrease and time response would increase in proportion to chamber size. For the time reponse, it was observed that the bigger chamber size becomes, the slower response time becomes (Fig 8). However, the inclination of decreasing data fluctuation was not observed.

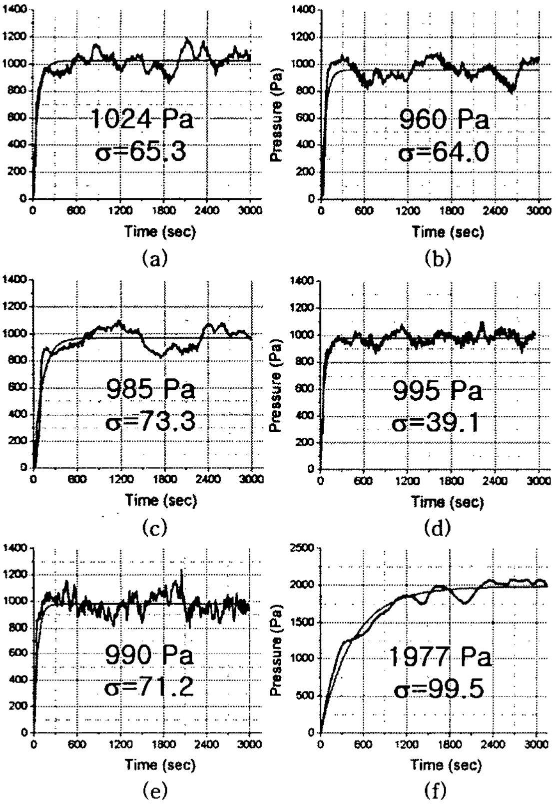


Fig 7. Pressure change of microvalve by the time
(a) model ①, (b) model ②, (c) model ③,
(d) model ④, (e) model ⑤ and (f) model ⑥

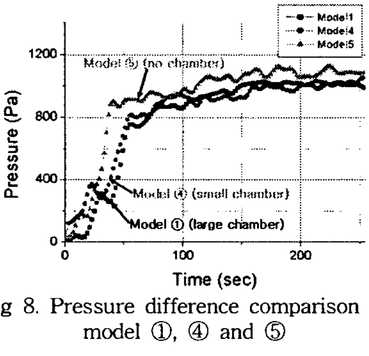


Fig 8. Pressure difference comparison of model ①, ④ and ⑤

The pressure difference of model ① was measured for about 9.17 hours to verify the reliability of the valve for a long time, The measurement result is shown in Fig 9. It was observed that the fabricated microvalve successfully operated without pressure drift.

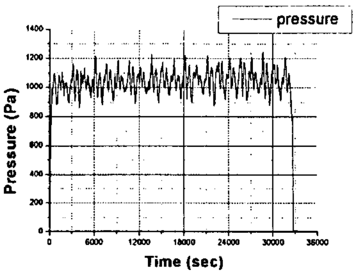


Fig 9. Measurement result of model ① for 9.17 hours

5. Discussion

Chamber was designed to act as a buffer to make microvalve insensitive against the external influence.

The chamber seems to only have small influences on time response and fluidic resistance. Since microvalve will be implanted for a long time, the early time response characteristic is not important.

And the change of pressure difference induced by chamber can be also negligible, because the amount of pressure change is relatively small compared to data fluctuation range. Thus, to be optimized for glaucoma implant, the microvalve should consist of only microchannel and the size of channel cross sect
should be as big as possible to be insensitiv
fibrosis within the total device size. From th
that the chamber has a negligible influenc
microvalve, if there needs an expansional spa
actuator, the chamber can be used as an expan
space regardless of the influence on the micro
characteristic.

6. Conclusion

The passive microvalves applicable to glau
implant have been fabricated and investigated.
measured pressure differences of the fabri
microvalves showed good agreements with the t
pressure differences and it was also shown tha
fabricated microvalve operated well for a long
Thus the proposed passive microvalve may
applicable to glaucoma implant. In vitro measu
is needed to verify the feasibility of the microva
practice.

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