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Modeling and simulation of biomimetic microvalves for fast injection

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ABSTRACT

This paper reports on a modelling and simulation study of a microvalve which mimics anatomic venous valves with a cone-shaped tube, allowing fluid flow in one direction while restricting flow in the opposite direction. This has potential applications in biomedicine and micro-electro-mechanical systems. A numerical study was performed by the finite element model using COMSOL multiphysics software. A fluid structure interaction method was integrated with an Arbitrary Lagrangian-Eulerian (ALE) approach. The impact of various mathematical boundaries, such as, the length of the anchor, the diameter at the base and the angle of the cone were investigated. An efficiency parameter Eff was employed to assess microvalve performance. It was found that a cone angle was the most important boundary influencing microvalve performance. For the best design, the forward flow rate was more than doubled compared to the reverse leakage rate for a given pressure.

Keywords: Fluid structure interaction; Arbitrary Lagrangian-Eulerian; COMSOL multiphysics; Flow rate

1. Introduction

Microvalves and micropumps are considered as key functional components in microfluidic systems [1]. They play an important role in the targeting transport of tracing substances [2,3]. Over the past decade there has been increasing interest in the development of biochemical microsystems [4]. There have been numerous reports on the design and fabrication of a variety of micropumps. These micropumps have emerged as a critical area of research because of their extensive potential applications in the fields of chemical analysis [5], biological instruments [6], and medical treatment [7]. Microvalve architecture is very important. Different sorts of microvalves have been widely assessed [8–10]. The microvalves can be divided into active (with actuation) and passive (without actuation) categories [11].

Up to now, few papers on micropumps with cone-molded tubes have been found in the literature [12]. The static venous valves are more complicated than cone-shaped tubes whether in parallel form or in series. Yu et al. [13] designed and manufactured soft valves based on bi-strip stimuli-sensitive hydrogels that combined the actuation mechanism of bimetallic valves and the directional liquid control of a check valve. However, these valves were limited by the nature of the fluid because the hydrogel valve not only operated like passive check valves, but also activated or deactivated autonomously based on the chemical environment of the fluid medium. By consolidating the cone-formed reported beforehand, there is the option to recreate a 3D generic biomimetic soft check valve that mimics natural systems both structurally and functionally based on the pressure gradient applicated on various liquids.

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In this work, a new design of biomimic passive microvalves inspired by natural venous valves is presented. The structure as shown in Fig. 1 will help to control the flow rate under specific pressure differences. The microvalve design was modelled and simulated utilizing COMSOL multiphysics programming. Then, the persuasive boundaries were determined based on the performance of the original construction. The simulation results were discussed.

2. Materials and methods

A three-dimensional soft microvalve was designed and modeled based on a cone-shaped structure implanted in the lower part of a miniature channel. The control stream had practically no actuators (Fig. 1). The idea was to make the microvalve – as streamlined as possible for one direction and resembling a resistant body in the other way. Mathematical boundaries affect the presentation of the microvalve. One can recognize the boundaries: diameter at the base D, throat diameter d, angle of the conical section C, length of the convex edges B, and the anchor length A, where the structure was joined to the wall of the cylindrical duct by its convex edges. Here, the cylindrical duct was a microfluidic tube that resembled a blood vein.

The objective of this study was to create soft biomimetic microvalves that operated with the same mechanism as that of venous valves (Fig. 2). The working principle of this microvalve was that the liquid moved through a cylindrical channel that was made with a flexible material. Hence, the liquid removal inside the microvalve should happen in with throat shutting and opening.

The determination of the material was very important. Here, the microvalves were formed from polymer materials. Polydimethylsiloxane (PDMS) was employed. Polydimethylsiloxane (PDMS) is an elastomeric polymer with interesting properties for biomedical applications, including physiological biocompatibilty, excellent resistance to biodegradation, chemical stability, gas permeability, good mechanical properties, excellent optical transparency, and simple fabrication by replica molding [14]. Due to these characteristics, PDMS has been widely used in micropump [15]. The flexible, soft, and highly elastic nature allowed for good sealing of a microfluidic system and minimized fluidic leakage. The transparent material also allowed for ease of optical detection of flow in the microvalves.

This microvalve was investigated quantitatively by implementing a finite element model with the COMSOL multiphysics software COMSOL, which was capable of performing fluid flow analysis, solid mechanics analysis, and coupling between both these analyses.

The boundary condition of the PDMS microvalve was fixed at its edges and considered a zero-displacement boundary condition, as exhibited in Eq. (1).

$$U_{\text{solid}} = 0 \quad (1)$$

As currently referenced, the microvalve walls were modeled as a linear elastic material; the boundary conditions for fluid model were no-slip at the fluid–wall interface. Fluid structure interaction (FSI) and pressure were characterized at both inlet and outlet of the microvalves (Fig. 3). The liquid was considered as incompressible.

3. Results and discussion

To assess the effect of pressure variation on the flow rate; the various parameters of the microvalves were compared according to various directions (i.e., forward and backward). When a microvalve is used to control the amount of drug delivery, the efficiency between inlet and outlet would be a key control parameter for regulating and controlling the micro channel (opening/closing).

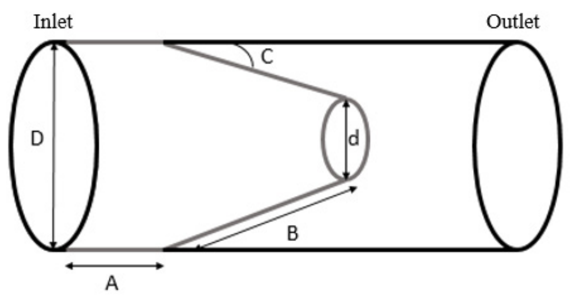

Fig. 1. 2D schematic design of the microvalve.

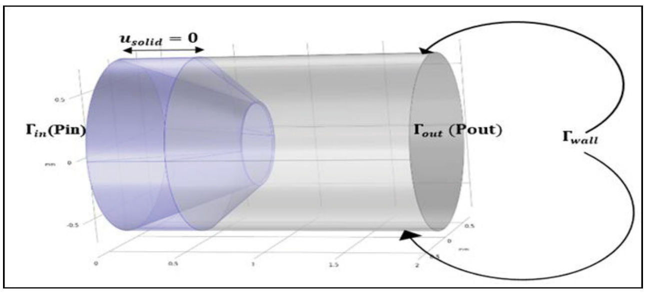

Fig. 3. Microvalve geometry constructed on COMSOL multiphysics.

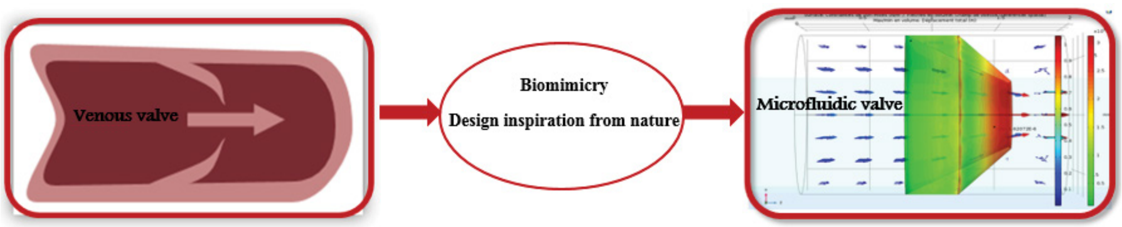

Fig. 2. Biomimetic microvalves mechanism.

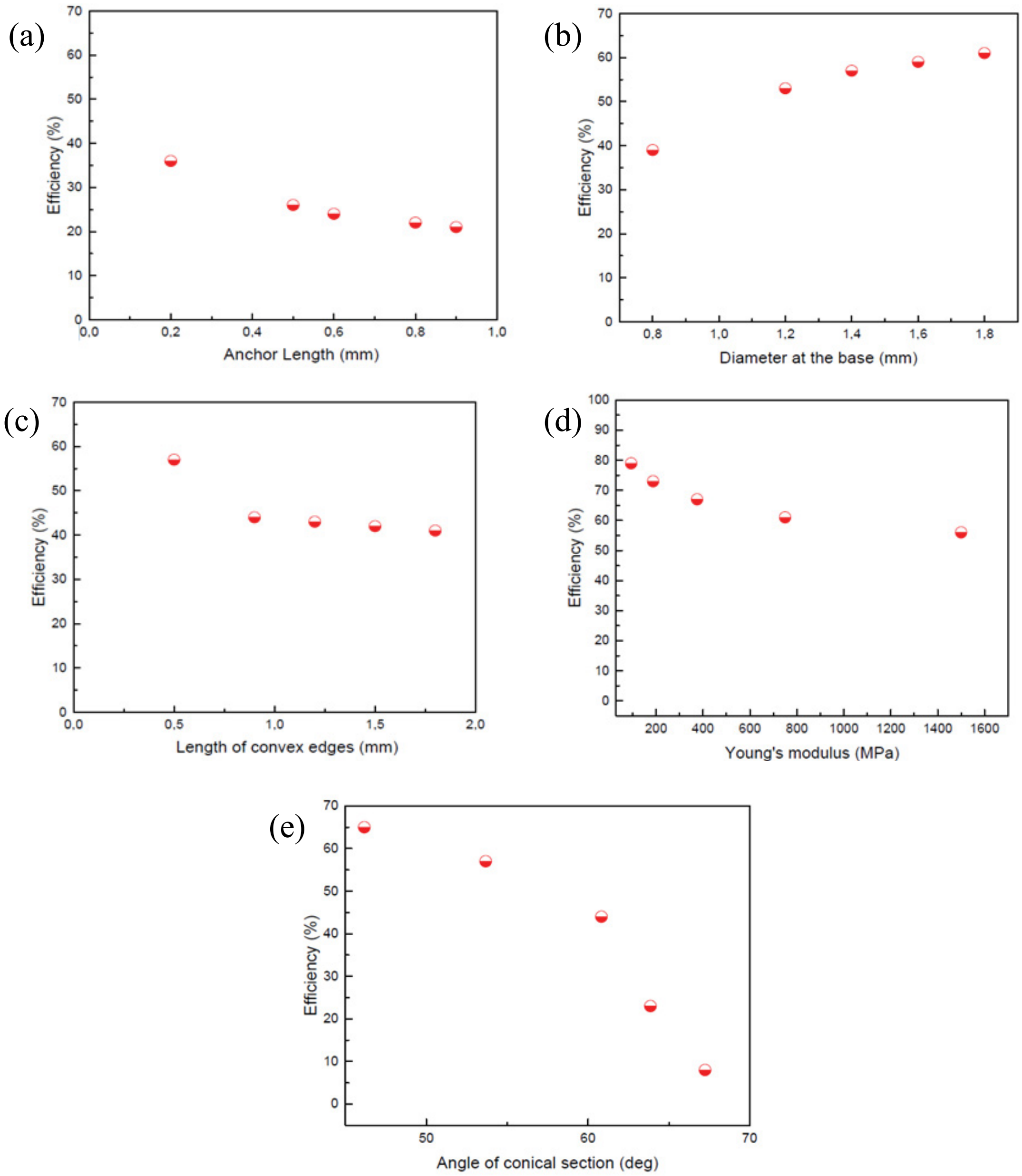

Fig. 4. Microvalve efficiency as a function of: (a) anchor length A, (b) diameter D, (c) convex edges B, (d) Young's modulus and (e) conical angle.

The behavior of the fluid in both directions was investigated using an efficiency term [Eq. (2)]:

$$\text{Eff} = \frac{Q_p - Q_r}{Q_p} \quad (2)$$

where Q_p and Q_r were the flow rates, respectively in the positive direction and the negative direction.

The principal objective of this parameter was the determination of the ideal geometric construction, which allowed for a minimum in the return of flow. The performance of various models was investigated by plotting different geometry parameters against the quality parameter Eff.

The curves (*a*, *b*, *c*, *d*) showed a small variation in efficiency corresponding to each parameter. However, from the graph (*e*) it can be deduced that, the maximum value of Eff decreased with increasing angle of the conical section with an important gap from each angle. It started from 8% and continued to 65%. It was also clear that the variation of Eff with geometry parameter *A*, *B* and *D* was very small compared with the angle of conical section *C*. Hence, angle *C* was the key parameter in microvalve characterization.

4. Conclusion

A new generation of valve was designed and demonstrated quantitatively by implementing a finite element model using COMSOL multiphysics. In this work, a biomimetic soft microvalve was designed based on a cone shaped structure that responded to liquid moving through a tube-shaped lead. It was apparent that the liquid displacement inside the microvalve and the flexibility of the design should occur at opening and shutting of the throat. The impact of geometric parameters of the microvalve was assessed by calculating the forward and reverse direction of flows for various pressures. The efficiency parameter was utilized to analyze the various geometries. It was seen that the angle of the conical section was the critical parameter for determining the performance of the microvalve compared with other parameters. The current study was focused on the effect of the geometric parameters on the flow rate and did not concentrate on high-pressure activity, which is fundamental for utilizing the ideal construction in microfluidic areas. From the results, it can be deduced or inferred that the new microvalve can be incorporated in micro devices for multiple applications.

Symbols

A	—	Anchor length
B	—	Length of the convex edges
C	—	Angle of conical section
D	—	Diameter at the base
E	—	Young's modulus
Eff	—	Efficiency
p	—	Pressure
Q^+	—	Inlet flow rate
Q^-	—	Outlet flow rate
U_{fluid}	—	Velocity
Γ_{in}	—	Boundary inlet
Γ_{out}	—	Boundary outlet
Γ_{wall}	—	Boundary on the wall

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