Geometrical Modifications for Reliable 3D Printing of Microvalves in Multi-Plane Microfluidic Devices

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ABSTRACT

Three-dimensional (3D) printing has emerged as a transformative technology for fabricating complex microfluidic devices, enabling features that were previously unattainable with traditional layer-by-layer soft lithography. One key challenge in advancing 3D-printed microfluidics is the integration of functional microvalves across multiple spatial orientations. This study explores the design, simulation, and experimental realization of novel microvalve configurations to overcome the limitations of conventional, single-plane valves. We hypothesize that non-traditional valve orientations, such as those with vertically printed membranes or perpendicular control channels, present unique fabrication and operational challenges, including membrane delamination and stress-induced failure. To address these issues, we developed optimized geometries and fabrication techniques, supported by computational fluid dynamics (CFD) simulations to predict and mitigate stress concentrations. Our results demonstrate successful implementation of previously unreported valve configurations, validated through pressure testing and flow control experiments. These advancements expand the versatility of 3D-printed microfluidic systems, paving the way for more robust and adaptable devices in biomedical, chemical, and environmental applications.

I INTRODUCTION

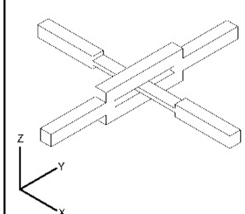
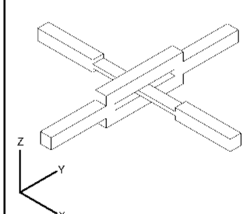
Microfluidic devices have revolutionized various fields such as biomedical diagnostics, chemical synthesis, and environmental monitoring by enabling precise manipulation of small fluid volumes within microscale channels. Traditionally, these devices are fabricated using soft lithography and layer-by-layer stacking techniques, which inherently confine the microfluidic elements—including channels and valves—to the horizontal (XY) plane. This planar constraint limits the complexity and functionality of microfluidic systems, as it restricts the orientation and spatial arrangement of critical components like microvalves.

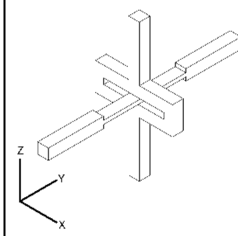
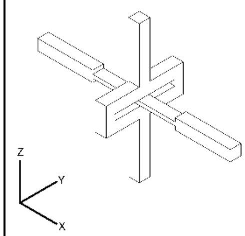
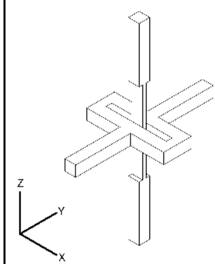
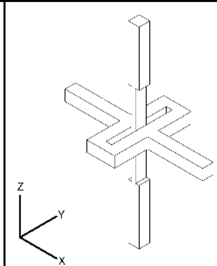
The advent of three-dimensional (3D) printing technologies has opened new avenues for the design and fabrication of microfluidic devices. 3D printing allows for the creation of intricate structures with complex geometries, enabling microfluidic elements to be oriented along multiple planes, including the vertical (Z) axis. This capability offers the potential to enhance device integration, reduce footprint, and introduce novel functionalities not achievable with traditional fabrication methods.

Despite these advantages, integrating microvalves into multi-plane microfluidic devices presents significant challenges. Microvalves are essential for controlling fluid flow, and their performance is highly dependent on the orientation and mechanical integrity of their membranes. In non-traditional orientations, issues such as membrane stress, layer separation, and reduced mechanical properties can arise.

Specifically, Table 1 summarizes the six possible configurations based on the orientations of the flow channel, control channel, membrane plane, and membrane orientation relative to the principal axes (X, Y, Z). In each configuration, the flow channel direction and control channel direction are assigned along one of the orthogonal axes, with the membrane plane aligning with the plane of the flow channel and its orientation coinciding with its longitudinal axis.

Table 1. Possible Orthogonal Configurations of Microvalves in 3D-Printed Microfluidic Devices. *Membrane orientation is along its longitudinal axis.*

Configuration	**Flow Channel Direction**	**Control Channel Direction**	**Membrane Plane**	**Membrane Orientation**	
1	X-axis (Horizontal)	Y-axis (Horizontal)	XY plane (Horizontal)	Along Y-axis (Squeezing Vertically)	
2	Y-axis (Horizontal)	X-axis (Horizontal)	XY plane (Horizontal)	Along X-axis (Squeezing Vertically)	

3	X-axis (Horizontal)	Z-axis (Vertical)	XY plane (Horizontal)	Along Y-axis (Squeezing Vertically)	
4	Y-axis (Horizontal)	Z-axis (Vertical)	XY plane (Horizontal)	Along X-axis (Squeezing Vertically)	
5	Z-axis (Vertical)	X-axis (Horizontal)	XZ plane (Vertical)	Along Y-axis (Squeezing Horizontally)	
6	Z-axis (Vertical)	Y-axis (Horizontal)	YZ plane (Vertical)	Along X-axis (Squeezing Horizontally)	

Among these, certain configurations are rotationally equivalent and can be grouped accordingly:

1. **“Conventional Valve Configuration”** (Configurations #1 and 2): Both configurations represent the traditional microvalve setup commonly used in microfluidics, where the flow and control channels lie in the horizontal plane, and the membrane is oriented perpendicular to the flow direction within the same plane. These present fewest challenges to print and have been reported by other researchers.[1-4]
2. **“Perpendicular Control Valve Configuration”** (Configurations #3 and 4): In these configurations, the control channel is oriented *perpendicular to the membrane plane*. It is positioned above or below the valve, aligned to apply pressure onto the center of the membrane to actuate it. To the best of our knowledge, the 3D printing of these valves has *not* been reported in literature. Furthermore, we hypothesize that control channel’s orientation poses a potential challenge: specifically, the membrane may experience

tearing or delamination due to uneven stress distribution when pressurization of the valve occurs.

3. **Vertically Printed Membrane Valve Configuration** (Configurations #5 and 6): In these configurations, the valve is essentially placed on *its side*. And, we have not seen reports of these valves being 3D printed either. Thus, we hypothesize that this is the case because they too are challenging to implement. However, here the difficulty comes from the fabrication of the valve. Specifically, to make a vertically-oriented membrane, a DLP (which is the leading technology in 3D printing microfluidics devices) 3D printer would have to make by fusing multiple layers together (see **Figure 1**-LEFT). This creates seams, which can lead to poor mechanical properties and are prone to separation when pressurized (see **Figure 1**-RIGHT), thus compromising the valve's functionality.

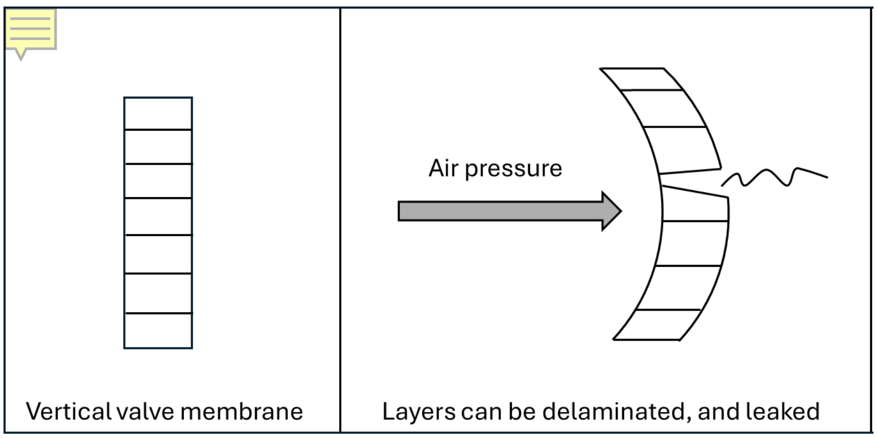


Figure 1 Diagram illustrating the hypothesized challenges associated with the Vertically Printed Membrane Valve Configuration. *LEFT - Vertical membrane constructed from multiple stacked resin layers, highlighting potential interlayer interfaces. RIGHT - Delamination at the interfaces under pressure, resulting in membrane failure and leakage.*

To address these challenges, we have developed geometrical modifications that maintain the desired orientations of flow and control channels while ensuring reliable valve operation. By systematically analyzing all possible orthogonal configurations—where the flow channel and control channel are perpendicular and the membrane lies in the same plane as the flow channel—we identified six viable orientations for microvalves in 3D-printed microfluidic devices. Our designs focus on optimizing membrane orientation and structural integrity to mitigate mechanical stresses and enhance adhesion between layers.

In this manuscript, we present our innovative approach to microvalve design for 3D-printed microfluidic systems. We detail the limitations of traditional fabrication methods, outline the theoretical framework for possible valve orientations, and describe the geometrical modifications implemented to overcome the associated challenges. Experimental results demonstrating the effectiveness of our designs in maintaining valve functionality across different orientations are also provided. Our work expands the design possibilities for microfluidic devices, paving the way for more versatile, compact, and functional systems suitable for a wide range of applications where precise fluid management is essential.

II METHODOLOGY

II.a Materials

For 3D printing we use a custom photopolymerizable resin which consists of poly(ethylene glycol) diacrylate (PEGDA, MW258) with a 1% (w/w)phe nylbis(2,4,6-trimethylbenzoyl)phosphine oxide (Irgacure 819) photoinitiator and a 2% (w/w) 2-nitrophenyl phenyl sulfide (NPS) UV absorber.[5]

II.b Parametric Sweeps over Valve Geometry

OpenSCAD version 2021.01 was used to vary both flow and control channel sizes, as well as valve dimensions and membrane thicknesses.

II.c 3D Printing

We utilized a DLP-SL (Digital Light Processing–Stereolithography) printer, the Asiga Pro4K65 (Sydney, Australia), equipped with an LED light source operating at a UV wavelength of 385 nm and a power output of 17 mW cm^{-2}. To enhance device transparency, the devices were printed on silanized glass slides instead of directly on the build plate.

The silanization of glass slides was performed by immersing the slides in a solution of 10% 3-(trimethoxysilyl)propyl methacrylate (TMSPMA, Sigma-Aldrich, MO) and 90% toluene for 2 hours. After the silane deposition process, the slides were rinsed and stored in fresh toluene within a sealed container until use. This silanization treatment facilitated strong adhesion of PEG-DA-258 to the glass substrate.

Before printing, PEG-DA-258 was applied to the silanized glass slide, which was then affixed to the printer's build plate and exposed to UV light for approximately 3 seconds to secure it in place. After the printing process was completed, a small razor blade was used to carefully remove the glass slide from the build plate. Any residual cured PEG-DA-258 on the back of the glass slide was shaved off to ensure a clear, scratch-free view of the channels and valves under a microscope.

The use of a glass substrate offered several advantages: it minimized the risk of damage to the printed device during removal from the build plate, allowed for easier detachment due to the slide’s slightly larger size relative to the build plate, and ensured that the flat surface of the glass provided a stable, horizontal platform for microscopy. This approach resulted in devices with high optical clarity and structural integrity, optimized for visualization and analysis.

II.d Postprocessing

Following 3D printing, unpolymerized resin was initially removed from each device by manually applying vacuum to the pneumatic and fluidic ports, followed by carefully flushing the interiors of the valves and flow channels with isopropyl alcohol (IPA). A second vacuum application was then performed to extract residual IPA from the devices. The devices were subsequently optically cured by placing them in a custom curing station for 20 minutes. This curing station is equipped with a 430 nm LED (Thorlabs, Newton, NJ, USA) that generates a measured irradiance of 11.3 mW/cm² at the curing plane. The LED wavelength was carefully selected so that most of its emission spectrum lies outside the absorption spectrum of avobenzone—a UV absorber present in the resin formulation—allowing deep penetration of the curing light into the devices. Simultaneously, it remains within the absorption spectrum of the photoinitiator, enabling further polymerization during curing.

II.e Simulation

Finite element simulations were performed using COMSOL Multiphysics® version 6.2 to model laminar flow within the optimized Y-shaped microvalve. The three-dimensional geometry was constructed based on specified dimensions for the valve body, flow channel, and control channels, as detailed in Table 1. Air was selected as the working fluid, utilizing material properties from the COMSOL material library. The laminar flow physics interface was employed under steady-state conditions, applying a pressure inlet of 206,840 Pa (30 psi) and an outlet at atmospheric pressure (in order to match the lab conditions), with no-slip boundary conditions on all walls. A mesh comprising tetrahedral elements was generated, with refinement in critical regions to accurately capture flow gradients. Simulations were conducted on a workstation equipped with a 16-core Intel processor and 32 GB of RAM. The results were analyzed to evaluate velocity and pressure distributions within the microvalve, aiding in the assessment of its fluidic performance.

Table 1 *Key Parameters Used in COMSOL Simulations. Width = along X axis; Depth = along Y axis; Height = along Z axis.*

Parameter	**Value**	**Unit**
Valve Height	540	μm
Valve Width	1400	μm
Valve Depth = Flow Channel Depth = Control Channel Depth	600	μm
Flow Channel Width	1100	μm
Flow Channel Height	140	μm
Control Channel Width	600	μm
Control Channel Height	0.75	μm
Inlet Pressure	30	PSI

II.f Microscopy

Visualization of fluid flow and valve functionality was performed using a Microqubic 3D MRCL700 microscope (CN Tech, Wisbech, England), with transmitted (brightfield) light source, and the stock "medium zoom" lens from the manufacturer.

III RESULTS

III.a "Perpendicular Control Valve Configuration"

We have started by fabricating arrays of the *naive* design of "*Perpendicular Control*" valves (i.e., Configurations #3 and 4 in Table 1) of varying dimensions. Specifically, we varied both flow and control channel sizes, as well as valve dimensions and membrane thicknesses (as described in Section II.b). Additionally, we also experimented with using different DLP exposure times during the printing process. However, all of the valves fabricated according to the naïve design failed to be functional once 3D printed due to leaking.

We hypothesized that the observed valve malfunction was a result of its membrane being torn by asymmetrically high stresses applied to its center when the valve is pressurized. To that end, we performed a COMSOL computational fluid dynamics (CFD) simulation to confirm our assumption and the results shown in Figure 3-LEFT confirmed our belief.

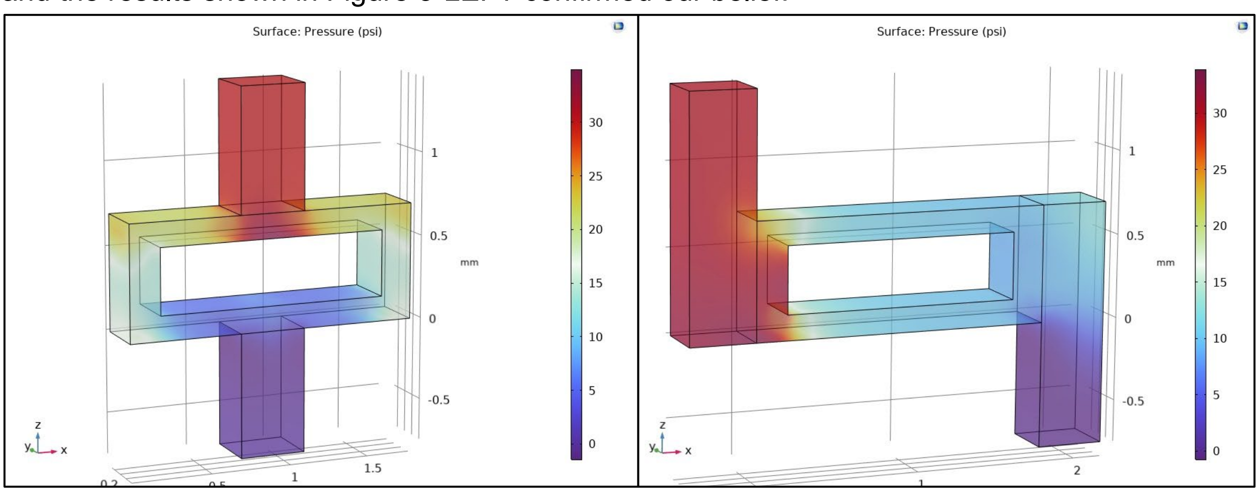


Figure 2 COMSOL CFD Simulation showing the pressure distribution on the membrane for the "Perpendicular Control" Valve. *Left: Pressure distribution on the membrane of the naive design under actuation, highlighting unevenly high stresses at the membrane center, potentially leading to rupture or mechanical failure. Right: Pressure distribution on an optimized design, demonstrating how stresses are shifted away from the membrane's center—the weakest part—toward more structurally robust regions.*

However, this was difficult to validate experimentally, because there are a number of other ways that the valve damage could have occurred: namely, i) Something could have gone wrong during the printing process (e.g., bubbles trapped in the resin), but this is nearly impossible to image due to the presence of the uncured material in the valve that has identical optical properties with the rest of the device; ii) The membrane could have been damaged by the flow forces exerted on it during the washing process prior to the curing; iii) The post curing process could have resulted in the adversely affecting the membrane's material properties (e.g., leading to shrinkage or being made too stiff) which could have subsequently resulted in its tearing. Unfortunately, such defects are also difficult to detect using 2D microscopy.

To address these problems, we tried to degas the resin and discard samples with any observed bubbles after the printing process but before the postprocessing; use slow flowrates (1-5 μL/min) to wash the uncured resin out; and experiment with different exposure times (including using grayscale DLP to make the membrane receive less crosslinking energy relative to the rest of the device). Yet, none of these approaches resolved the membrane leakage issues that we kept observing once the valve is pressurized.

Consequently, we decided to redesign the valve in such a way that would minimize the stress asymmetry experienced by its membrane. Figure 3-RIGHT demonstrates the idea: the control channel's inlet that originally connected to the top center of the valve is moved to its side, which results in most of the high pressure being applied to the flow channel's side wall rather than to the top one (which serves as one of the two valve's membranes). Likewise, the bottom control channel is moved to the opposite side of the valve to maintain symmetry. The COMSOL results in Figure 3-RIGHT confirmed that this updated configuration results in a more uniform pressure distributions along the valve's two membranes.

Furthermore, originally, we tried to return the control channels to be centered above and below the valve, as shown in Figure 3-LEFT. This may be desired in cases where side channels might interfere

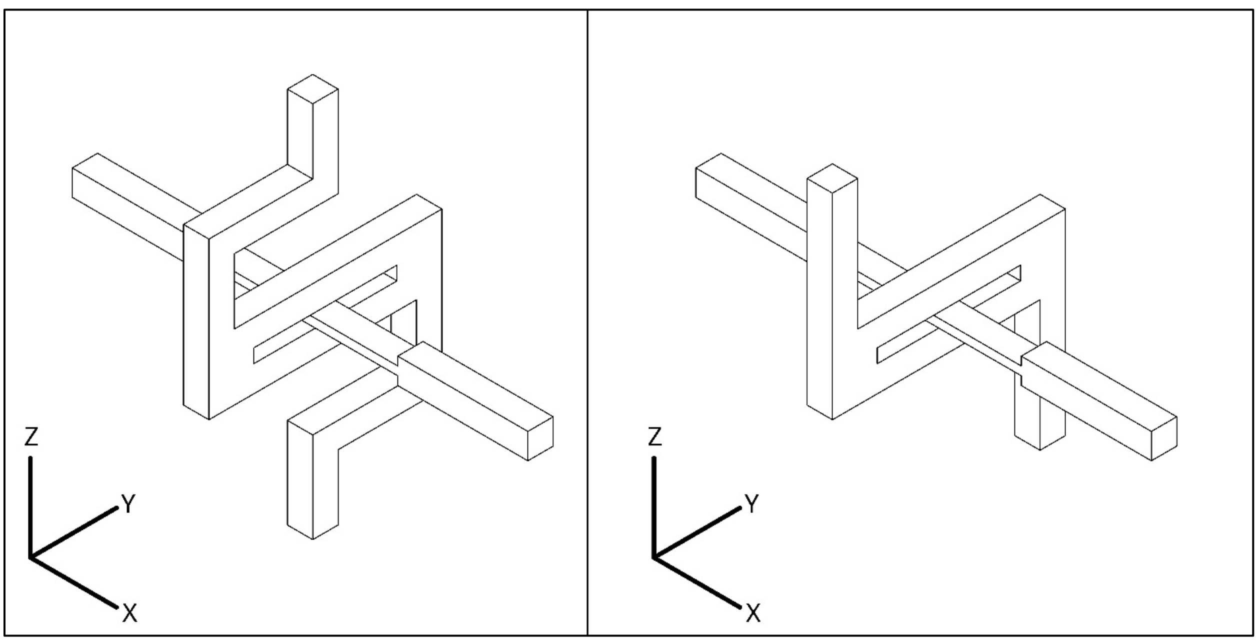


Figure 3

III.b "Vertically Printed Membrane Valve Configuration"

IV CONCLUSIONS

V ACKNOLWEDGEMENTS

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