Design and Evaluation of the Flexible PDMS Microfluidic Diaphragm Pump with Check-Valve

A Thesis

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Design and Evaluation of the Flexible PDMS Microfluidic Diaphragm Pump with Check Valve

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Abstract

Microfluidic pumps in the field of medicine have several applications, including cell separation, microanalysis array, and drug delivery. Among these applications, the pump's usage for drug delivery requires flow-in-one-direction. Previous attempts for this used standardized check valve from retail store, but this creates complexity in manufacturing and inconsistency of data acquiring due to the failure of manufacture. This thesis is focused on the design and fabrication of flexible micro check valve that can integrate with PDMS microfluidic pump. Both micro check valve and microfluidic channel were fabricated using replica molding, machining, and standard PDMS mixtures. Then, integrated micro pump was studied with compression test to see the performance relative to the result from pump with standardized check valve. Results indicates that integration of PDMS check valve and microfluidic channel is as effective as the one from previous research but there is room for improvement on overall design for integration. The future successful completion of the integration will serve crucial part of this project and can be further developed for drug delivery

Chapter 1
Introduction

Literature Review & Microfluidics

The concept of the microfluidic pump was established during the development of the microfluidic channel in the 1970s. The initial attempts to fabricate the microfluidic channel was done by using materials such as glass. Many channels fabricated during this era had limited applications in the biomedical field due to the material of fabrication. Nowadays, newly introduced material such as polydimethyl siloxane (PDMS) is used to fabricate the microfluidic channel and pump. These new materials are advantageous over previously used materials because of their cheaper price and biocompatibility [1]. Today, many microfluidic pumps are utilized in the biomedical field for studying cell separation, chemical synthesis, and microanalysis arrays, and particularly, fluid transport such as drug delivery[2].

When adapting fluid transport mechanism to microfluidic pump, it is important to create a flow in one direction at all time. Any reverse flow may cause decreased or zero flow rate, and this defeats the purpose of drug delivery. Many engineers achieve one-direction flow by integrating a check valve mechanism, which allows forward flow while blocking reverse flow.[3] In order to expand the spectrum of microfluidic pump designs, the current project aims to fabricate a PDMS microfluidic pump that is actuated by autonomous human body motion such as bend and compression. Therefore, the pump as well as any integrated subparts should be manufactured with flexible material so that the actuated force (by bending and compressive force) can be applied on the pump.

The goal of this project was to develop a flexible micro check valve that will be used in a bio-application for pumping purposes. The micro check valve is intended to serve the purpose of preventing the water or fluid that is to be pumped from flowing in the reverse direction and to ensure the continual forward progress of the fluid in one direction.

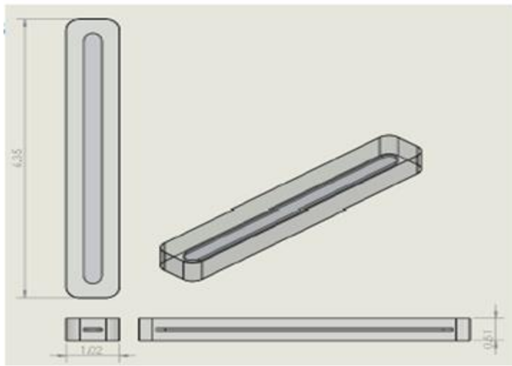


Fig. 1 Orthographic view of Microfluidic pump prototype

The current paradigm of intravenous injection (IV) apparatus functions with two premises: that this apparatus is utilizing gravity force, which only acts on vertical axis, and that patients are at static position because any active movement can potentially hinder the flow direction and cause injury, particularly when flow direction is reversed. Squeeze-chip finger-controlled microfluidic flow network proposes a new approach for fluid transport mechanism that can overcome this current paradigm by changing the actuating force to bending and compression force and integrating check valve, which inhibits reverse flow to promote one direction flow [3]. Also, this microfluidic flow network is fabricated using PDMS with 10:1 ratio between curing agent and PDMS base in order to adequately transfer actuating force to itself [4]. Although overall design of this network is theoretically viable, integrated check valve adopts an elementary design that inadequately inhibits potential reverse flow. In order to achieve successful and secure one-direction flow within the mechanism, it is necessary to integrate a new check valve design.

Check-Valve

The effective check valve design is depending on reducing or eliminating the effect of external inhibiting force on functionality of the check valve. If the design unsuccessfully reduced the effect, check valve would stop functioning while transporting fluid. This mechanism designed by Li adopted monolithic check valve design for integration. Monolithic check valve design contains three layers – middle membrane layer, top main channel layer, and bottom cavity layer. The mechanism of this design is that membrane layer is opened with high pressure on main input channel layer and closed with high pressure on cavity layer [3]. The main issue with this design is friction between membrane layer and cavity layer surface. According to the integrated check valve design, membrane layer touches the inner surface of cavity layer and so there will be frictional force between two surfaces. In other words, frictional force between two surfaces can hinder the functionality of check valve by fixed membrane surface. In order to overcome this flaw, the new research should focus on improvement of check valve design by eliminating friction force effect.

The ongoing effort to improve check valve design is incorporating cavity and output channel as one layer and input channel as another layer. The key feature of this design is that cavity is a connecting reservoir between input and output channel and the surface area of cavity is much larger than that of input channel entrance to cavity. Between these two layers, the membrane layer is integrated which will be opened with high pressure on input channel and closed with high pressure on output channel. However, currently, the proposed design has a crucial failure which is friction between the cavity and the membrane flap.

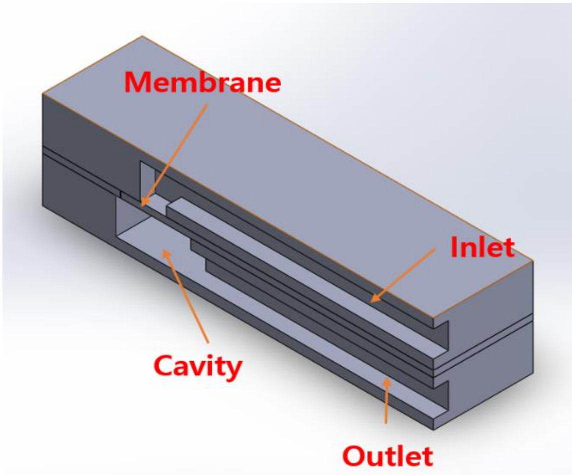


Fig. 2 Preliminary monolithic check valve design

A viable design for check valve needs to successfully eliminate the friction effect while not creating another effect that obstructs the functionality of the check valve. The most intuitive solution to this is to change the shape of membrane flap. Currently, the proposed design consists of a square-shaped membrane flap. By changing this flap design to trapezoid with inwardly curved side edges, the flap's potential to touch the cavity surface will be significantly reduced.

Materials & Methodology

Check Valve

Proposed check valve consists of three components, inlet layer, outlet layer, and membrane layer. Among these layers, primary modification is held on membrane layer.

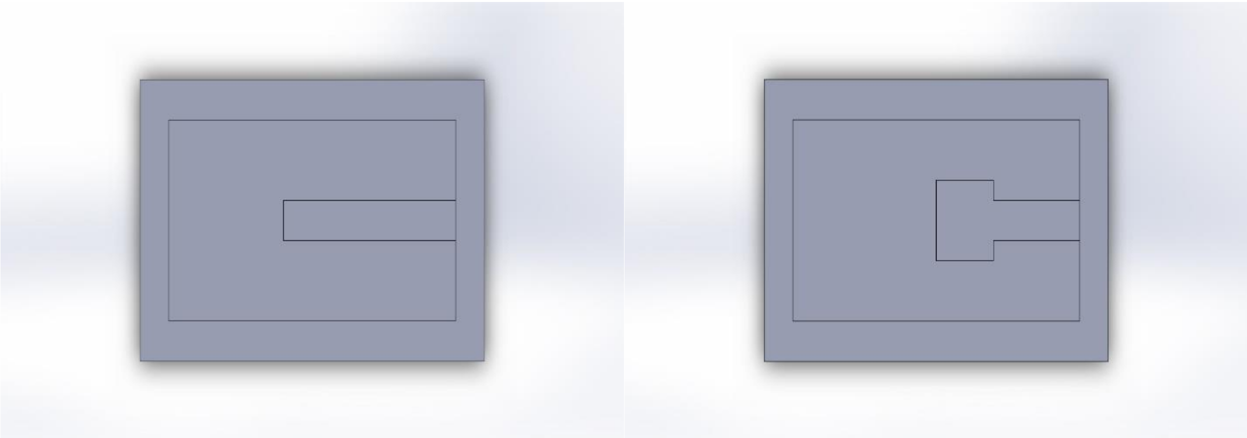


Fig. 3 3D rendered model (Left) Inlet layer mold, (Right) Outlet layer mold.

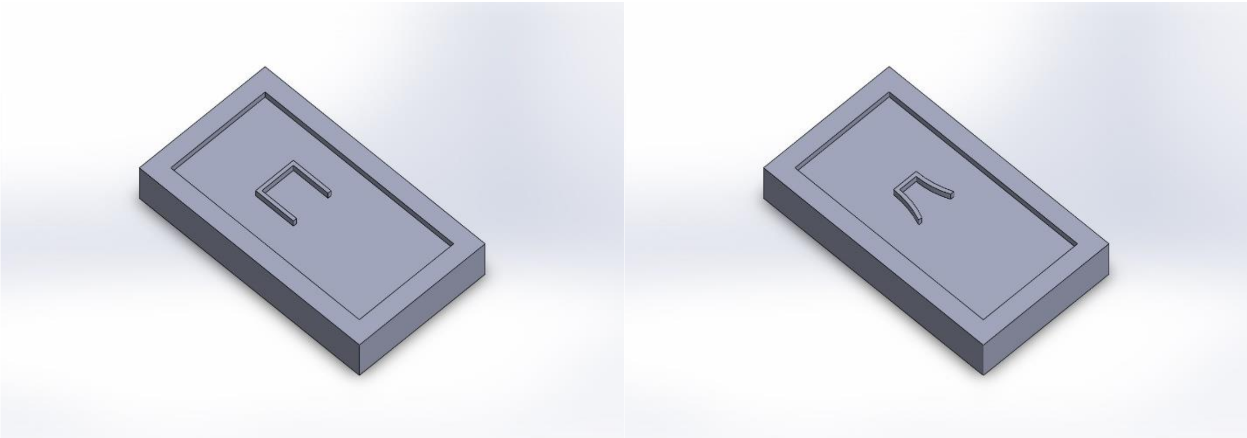


Fig. 4 Modification of membrane layer. (Left) Pre-modified membrane layer mold. (Right) Post-modified membrane layer mold.

The pre-modified membrane layer consists of a square-shaped flap. The problem with this flap is friction between flap's side edges and inner cavity surface. Shape of the membrane layer was modified to avoid this problem. A trapezoid shape with inwardly curved side edges is implemented. Also, bottom edge is shorter than cavity edge to avoid friction while top edge is longer than inlet width to inhibit leakage when flap is closed.

Check valve is fabricated with 8.5:1 ratio between PDMS base and its curing agent rather than 10:1 ratio from literature so that the membrane flap yields at lower pressure.

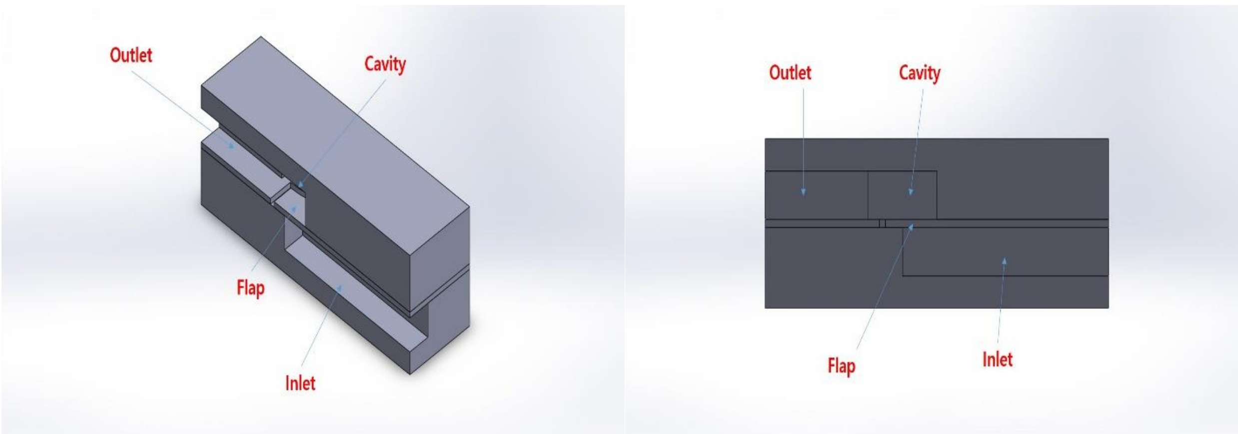


Fig. 5 Check valve prototype design: (Left) Isometric view, (Right) Front view

Integration with Microfluidic Channel

Design for both channel and check valve was changed for integration. Table 1 shows the specification of each component and Figure 5 shows the 3D rendered image of integrated device. Main aspect of design change was focused on dimensional change.

Inlet Layer	Length	Width	Valve		
	1.5”	0.7”	0.1” x 0.6” x 0.1”		
Outlet Layer	Length	Width	Valve	Cavity	Connector
	1.5”	0.7”	0.1” x 0.9” x 0.1”	0.2” x 0.2” x 0.11”	0.1” x 0.1” x 0.15”
Membrane	Length	Width	Flap		
	1.5”	0.7”	0.2”(bottom) x 0.16”(top) x 0.1”(Length) x 0.05”(height)		
Pump	Overall Dimension	Channel Dimensions	Top/Bottom layer	Tube	
	3.5” x 0.7”	1.5” x 0.3” x 0.125”	0.08”	0.05” x 3.5” x 0.05”	

Table. 1 Integrated Microfluidic pump and Check valve specification

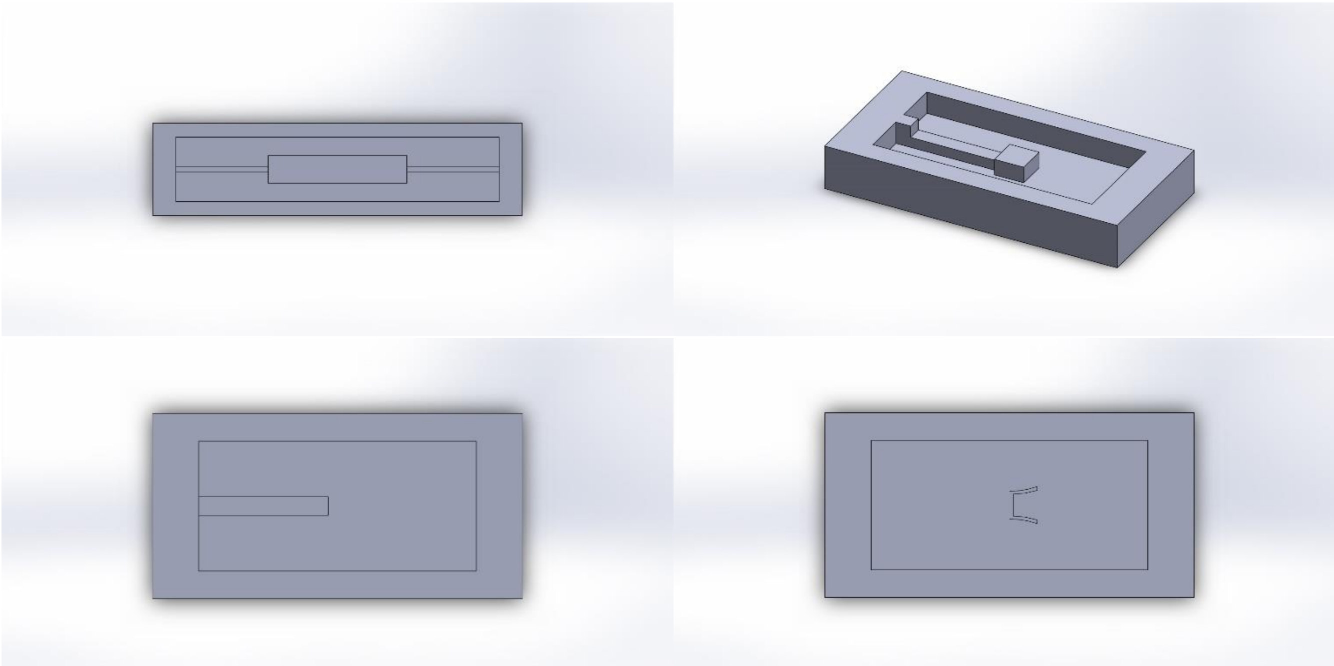
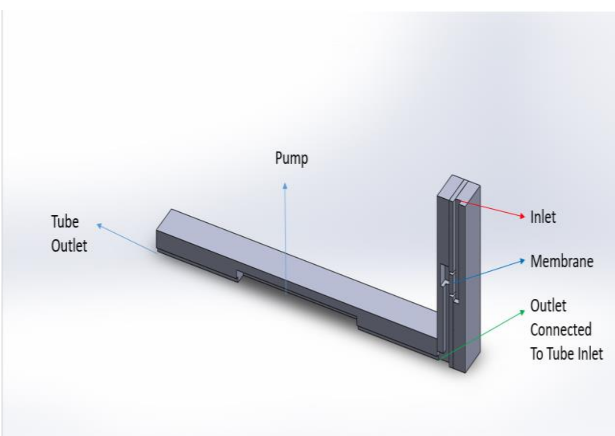


Fig. 6 Left Top) Microfluidic pump mold, Right Top) Outlet mold, Left Bottom) Inlet mold, Right Bottom) Membrane layer mold

The molds were designed using Solidworks 2016 CAD software and printed through Makerbot 3D printer. Dimensions of all molds are referred from Table 1.



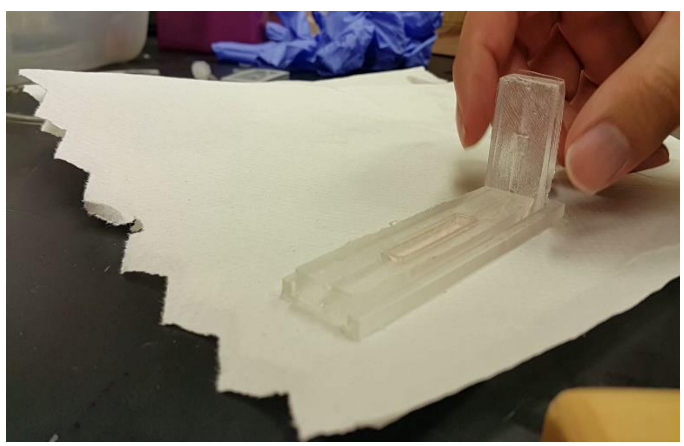


Fig. 7 Pump integrated with check valve. Left) conceptual view, Right) Actual view

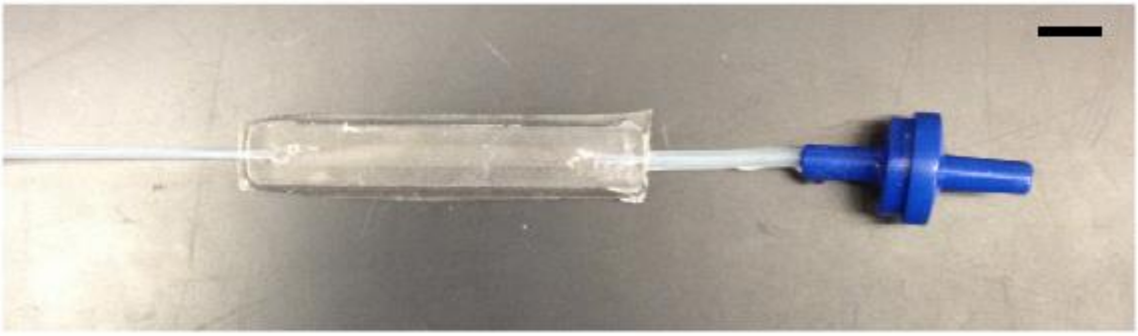


Fig. 8 Pump with commercial valve

PDMS channel & check-valve manufacture

Dow Corning Sylgard 184 silicone elastomer base and silicone elastomer curing agent were used for fabrication and integration. All components were fabricated with 8.5:1 ratio between PDMS base and curing agent. The mixture of base and curing agent was poured into the mold and placed in vacuum chamber until all air bubbles were removed. The mixture was cured in the oven with the temperature set to 50°C. Mixture was cured for 30 minutes. After curing, finished product was left to cool in room temperature for 10 minutes.

The channel and check valve were then glued, using the same PDMS solution, to the flat piece of cured thin PDMS. The glued pieces were cured again in the oven for 30 minutes with the temperature of 50°C. Once finished curing, PDMS was left to cool in room temperature.

Results

To validate the design of integrated device, fluid output vs. number of iteration test using compression force was conducted and compared with data from previous prototype which is pump integrated with commercial check valve. Total of four set of iterations were tried to resemble the instruction from previous test. Table 4 and Figure 4 shows the comparison between data from two tests. New test's fluid output is smaller than previous test's fluid output.

Iteration	Fluid Output (mL) – Previous	Fluid Output (mL) – New	Percent decrease(%)
25	1.7	1.5	11.76
50	3.7	2.4	35.13
75	5.1	4.1	19.60
100	7.2	5.9	18.05

Table. 2 Difference of fluid output. Left is acquired from previous paper, Right is acquired from current setup

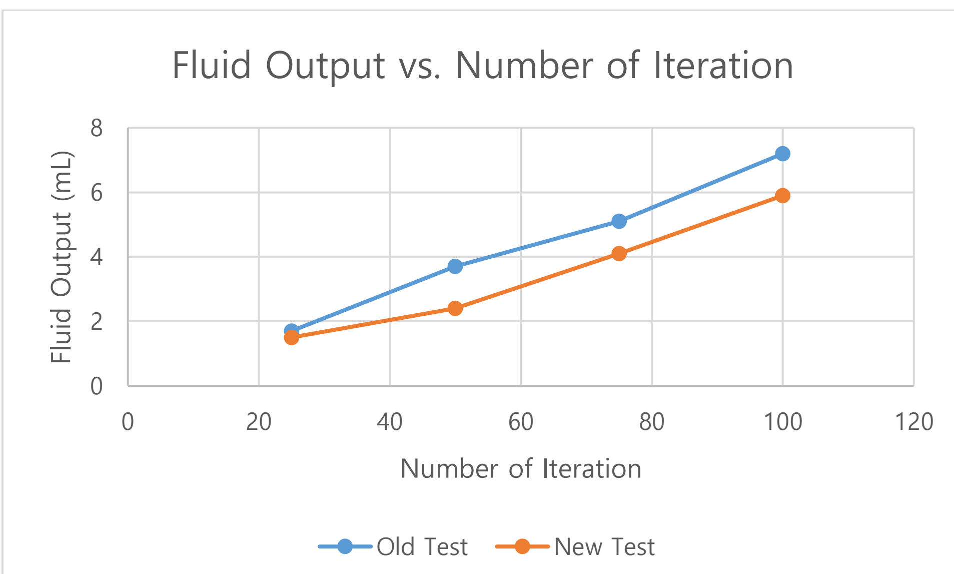


Fig. 9 Fluid Output vs. Number of Iteration

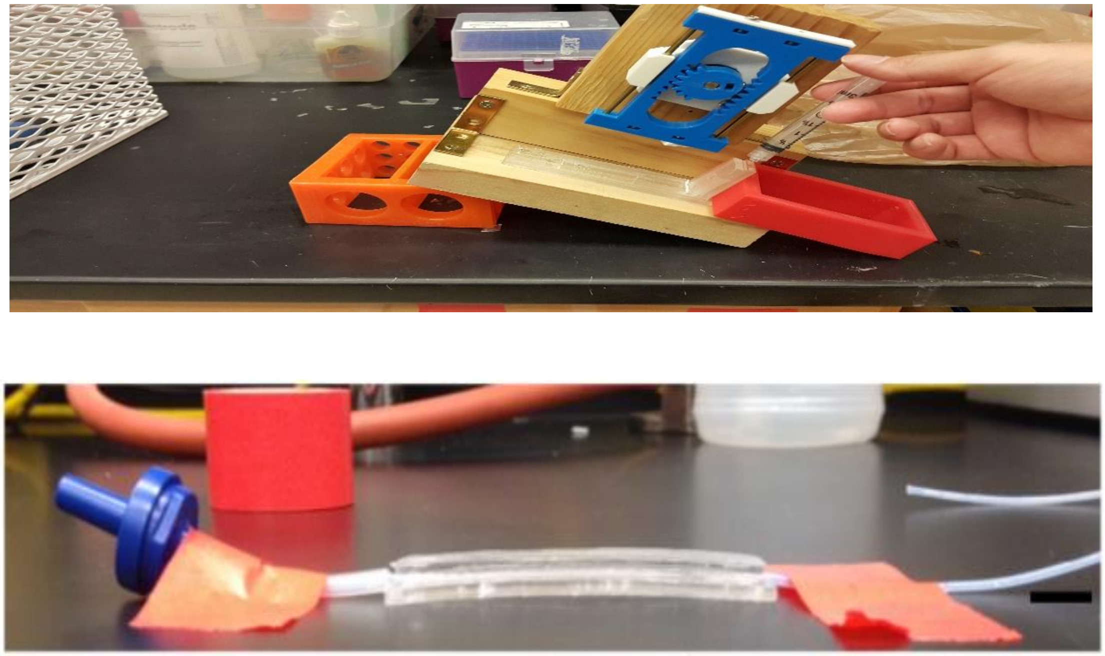


Fig 10. Comparison of test setup Up) Integrated check-valve, Down) Commercial check-valve

Functionality test was conducted to ensure proper operation as check-valve. Using a syringe filled with colored water, water was pumped through the valve by pressing down on the syringe plunger with very little force. When the color water was forced into check-valve, the intended ease of water flow direction, the water was qualitatively observed to flow through the valve very easy and quickly. When the reverse testing was performed, it was observed that the membrane flap did in fact shut and close channel preventing the liquid from flowing backwards through the device. [8][9]

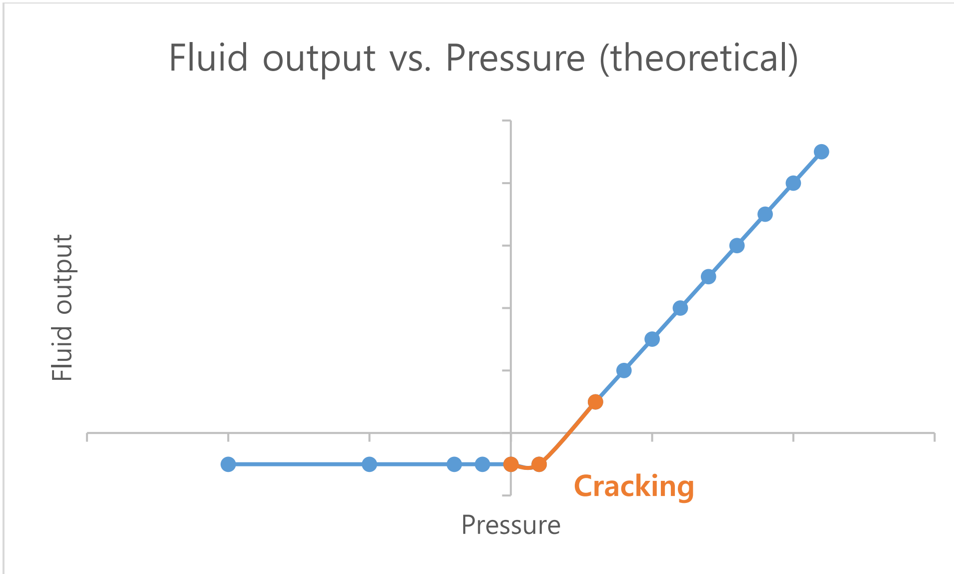


Fig. 11 Fluid output vs. Pressure representation

Discussion

Result Analysis

Quantitative assay shows two peculiarities of integrated device. One is the decrease in fluid output at all trials. At each trial, the output was decreased by 11.76, 35.13, 19.60, and 18.05% respectively. One aspect of this outcome is the increased dimension of the device. Microfluidic channel's length in previous study was 2 inches while current device's length dimension was 3.5 inches. The other aspect of this outcome is inconsistence of applied force. When conducting compression test on the pump with check valve, the testing device was break down and incapable of further testing. Therefore, testing was done manually with index finger. Therefore, percent decrease in fluid output at each trial is not consistent with the number of iteration due to human error.

On top of this, the other peculiarity is the graph trend. Even though the data was inconsistent, the graph shows resemblance in terms of trend. This means that, with large numbers of sample, this device can be validated. Thus, it is crucial to acquire more data with different iteration.

Limitation & Improvements

Although human errors and other outliers can be neglected with additional numbers of iteration trials, consistent compression device is still needed for acquiring accurate data. Original testing setup has linear actuator device which serves to create continuous flow through the pump, but it lacks durability because it was built with medium density ABS from 3D printer. To overcome this issue, new compression device should be built with extra durability for further uses.

Conlcusion

In conclusion, proposed PDMS check valve functions in conjunction with PDMS microfluidic channel adequately based on the compression force test. The result and data analysis both validates our design as well as gives room for improvement to complete the design. The future successful completion of the integration will serve crucial part of this project and can be further developed for drug delivery.

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