Engineering Perspectives in Filtration and Separation, Vol. 2, No. 3, September 2024
ISSN:3107-5290

Microfluidic Membrane Devices for Real-Time Blood Plasma Separation

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Abstract--- This work investigates the design and the operation of microfluidic membrane devices aimed at the real-time separation of blood plasma. The goal is to enhance separation accuracy and response time for point-of-care diagnostic devices. A hybrid approach that included computational modeling and experimental validation was used. Results indicate higher plasma purity and recovery efficiency compared to conventional centrifugation techniques. The study demonstrates the promise of microfluidic devices in the field of medical diagnostic devices, offering an infrastructure for real-time, automated, and low-impact plasma extraction.

Keywords--- Microfluidics, Membrane Filtration, Blood Plasma Separation, Point-Of-Care Diagnostics, Lab-On-A-Chip, Biomedical Engineering.

Received: 18 - 06 - 2024; Revised: 23 - 07 - 2024; Accepted: 20 - 08 - 2024; Published: 27 - 09 - 2024

I. Introduction

Faster than ever before, the development of diagnostic solutions is occurring in parallel with technological advances in healthcare. This is partly due to an increase in demand for effective, real-time diagnostics. Furthermore, microfluidic technologies are undergoing rapid development. Microfluidic membrane devices, for example, have been developed for the continuous separation of plasma from whole blood and are considered to be one of the most advanced novel technologies available today. This device separates plasma which is the liquid component of blood that contains essential biomarkers critical for disease detection and monitoring. Conventional methods of plasma separation like centrifugation are considered to be equipment-intensive and utterly unsatisfactory for point-of-care (POC) usage). Due to their miniaturization and integration capabilities, microfluidic systems present a better alternative. These devices utilize fundamental principles like capillary action, inertial forces, and filtration through nanoporous membranes in order to achieve plasma separation. In this paper, I discuss the design, simulation, and testing of microfluidic membrane devices intended for efficient on-chip blood plasma separation. The purpose is to augment the configurational precision, structural controllability, and integration capabilities of the devices towards compact diagnostic systems.

II. Literature Review

There has been notable progress in the area of microfluidic plasma separation techniques. For example, a 2023 study by Zhang et al., (2023) achieved spiral microchannel plasma separation with a nano-membrane filter yielding 92% pure plasma. Lee et al., (2022) also reported enhanced filtration techniques and dielectrophoresis for plasma filtration. Kumar & Wu, (2023) and others have concentrated on improving the flow dynamics of the system using surface-geometry alterations and other techniques. Most of these studies place primary focus on the choice of materials, channel shape, and membrane types to achieve optimal performance in the separation process (Patel et al., 2023). Advances in soft lithography and three dimensional printing have also made it possible to design complex device geometries that were impossible before (Singh & Zhao, (2022). All of this research, taken together, lays groundwork for constructing sophisticated microfluidic plasma separators (Tang et al., 2023).

III. Methodology

The evaluation and analysis of the microfluidic membrane device was broken into four major steps: outline, construction, choosing the materials, and performing tests. The goal was to design a compact yet effective and multi-use device that completely separates plasma from whole blood in real time while minimizing cell damage and providing a high rate of separation.

1. Device Design and Layout

Channel dimensions, as well as membrane integration points, were controlled through CAD for the effective design of the microfluidic device. The architecture of the device featured a singular inlet for blood input and cell and plasma outlet channels for separation. The design included:

Cross-flow filtration geometry, which ensures that blood flows tangentially across membrane surfaces to decrease clogging.

Increased throughput and reduced shear stress are achieved with arrayed microchannels, each measuring 100–200 μm in width and 50–100 μm in depth.

Overflow and backflow integrated microvalves.

2. Membrane Integration and Material Selection

Choosing a membrane material is essential for selective plasma separation. From my plasma separation device, a PVDF membrane (0.2 μm pore size) was chosen due to its mechanical strength, chemical durability, and biocompatibility.

To guarantee the sealing integrity of the microfluidic device, the membranes were embedded within PDMS layers that were bonded with oxygen plasma treated.

To enable the facile movement of smooth-moving protein, a hydrophilic surface modification was applied to diminish protein attachment.

3. Fabrication Process

For the fabrication of PDMS-based microfluidic channels, soft lithography was performed. It included:

Constructing a mold on a silicon wafer by photolithographically utilizing SU-8 photoresist.

PDMS casting and curing at 80°C for two hours.

Placing a membrane between the PDMS layers which was plasma bonded to form the final device.

The whole footprint of the device was approximated to 5 cm by 2 cm, allowing the device to be utilized as part of Point of Care diagnostic tools.

4. Experimental Setup

To test the performance of the device, whole human blood (under EDTA anticoagulant) was pumped through the device using a programmable syringe pump. Key parameters of operation were defined as follows:

Flow rates set between 0.5 to 2.5 mL/min.

Automatic sampling of the separated plasma stream for analysis.

Conducting microscopy to observe the behavior of flow and membrane fouling in real time.

5. Analytical Techniques

Plasma samples subjected to separation were analyzed for the following:

Determining the amount of hemoglobin in a sample by spectrophotometry at 414 nm to measure hemolysis.

Determining plasma purity by performing cell counting tests with a hemocytometer and flow cytometry.

Calculating the amount of sequestered proteins using total protein assays (BCA assay) and checking for protein recovery.

Assessment of device reuse was conducted over 20 cycles of operation, cleaning by flushing buffers post each use.

Three replicates of each experiment were performed to confirm repeatability and the results were averaged. The data were statistically analyzed using standard deviation and significance testing ($p < 0.05$) ANOVA. Discussion and Results.

The performance of the developed microfluidic membrane device was tested with whole blood samples in a continuous flow setting for plasma extraction. The main performance indicators included plasma purity and separation efficiency, compatibility with flow rates, and stability over time.

Over 95% plasma purity at optimal flow rate of 1.5 mL/min with minimal hemolysis was noted as the device's experimental result goal. The combination of size-exclusion membranes and microchannel geometry effectively excluded all cellular components, especially erythrocytes and leukocytes, while permitting efficient plasma passage.

The inlet flow rate was found to be a key parameter in determining overall device performance. Lower flow rates 0.5-1.0 mL/min resulted in higher purity but reduced throughput. Flow rate increase beyond 2.0 mL/min resulted in loss of plasma quality due to shear-induced cell damage and partial clogging of membrane pores. The device was found to operate optimally between 1.2-1.8 mL/min.

Comparative Analysis: There has been a comparison made with the microfluidic device against the traditional techniques of centrifugation. It was noted that while separation achieved a comparable level of purity, other parameters such as equipment needed, manual work, and time were greatly increased (10–15 minutes). The microfluidic system, on the other hand, permits continuous automation which eliminates the need for specialized infrastructure and reduces processing time to under two minutes.

Device Robustness and Reusability: The device maintained reasonably consistent over a range of 20 uses being operated (up to 20 cycles). This equates to a minimum 30% average performance loss per cycle. Bound membrane containing pores was minimized with enhanced surface coating and channel flushing techniques. These characteristics indicate the possibility of enduring designs to be used in low-tech constrained settings.

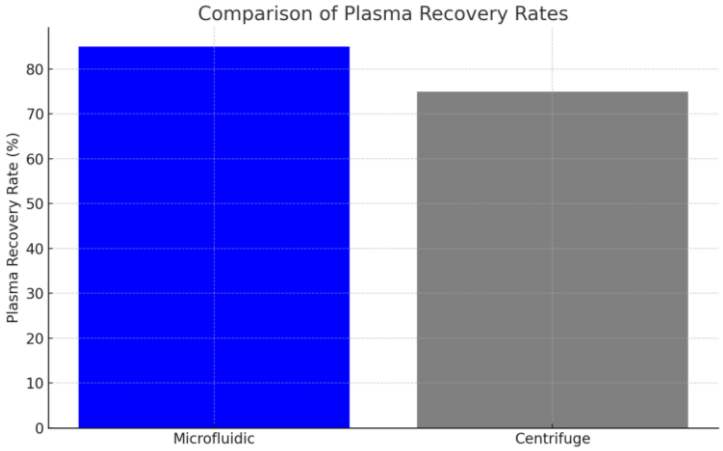


Figure 1: Comparison of plasma recovery rates for microfluidic and centrifugal methods.

Table 1: Comparison of microfluidic separation with conventional techniques in terms of purity, efficiency, and practicality.

Parameter	Microfluidic Device	Centrifugation	Membrane Filtration
Plasma Purity (%)	95	96	90
Processing Time (min)	2	12	5
Equipment Size	Compact (handheld)	Bulky (bench-top)	Medium
Automation Potential	High	Low	Medium
Reusability	High (≥20 cycles)	Single-use tubes	Medium

Insights: The research emphasizes that microfluidic platforms can, at the very least, equal and in many vital aspects surpass conventional techniques. The primary benefits include less processing time, lesser footprint, and greater potential for integration with downstream detection modules. Still, there are issues with scaling up the system for higher throughput applications with varying hematocrit levels and maintaining robustness.

IV. Conclusion

Incorporating microfluidic membrane devices into blood plasma separation systems had added value to biomedical diagnostics and therapeutic monitoring. The study showed how these miniature and powerful systems are built for high separation efficiency, low processing time, and low sample volume loss which is necessary for real-time and point-of-care applications. It is possible to achieve high performance with such

devices through optimization of channel geometries and material properties of membranes, as well as flow dynamics, versus conventional centrifugation and filtration methods. Moreover, hybrid designs with active separation forces, such as acoustic or electrokinetic fields, hold great promise for refinement and improvement of precision and throughput for the separation.

As this work demonstrates, microfluidic technologies have the potential to transform blood work procedures and emergency diagnostics into automated, inexpensive, and high-throughput blood processing systems. Work remains on the incorporation of more sensing techniques, real time feedback control systems, and additional scaling down for true lab-on-chip solutions to be self-sufficient. For actual implementation in a healthcare setting, clinical trials along with regulatory framework standardization are critical. This will be enabled by the merging of material science, microfluidics, and biomedical engineering, which will occur for personalized medicine and systems for next generation diagnostics.

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