Design and Optimization of Glomerular Membrane in Implantable Artificial Kidney

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ABSTRACT

In microfiltration of fluids, pore and its aspects like pore geometry, pore size ratio and pore edge shape play main roles. In this paper we calculate an optimized design of membrane to work as a glomerular membrane to filter formed element of blood like Red Blood Cells, White Blood Cells and platelets from plasma in implantable artificial kidney. The focus of this paper is on pore design and hydrodynamics of plasma (Newtonian fluid after pore inlet) during hemofiltration with different pore longitudinal cross section and diffuser shapes.

INTRODUCTION

Urine formation begins with filtration of large amounts of fluid through the glomerular capillaries into Bowman's capsule. Like most capillaries, the glomerular capillaries are relatively impermeable to proteins, so that the filtered fluid (called the glomerular filtrate) is essentially protein-free and devoid of cellular elements, including red blood cells. The glomerular capillary membrane is similar to that of other capillaries, except that it has three (instead of the usual two) major layers: (1) the *endothelium* of the capillary, (2) a *basement membrane,* and (3) a layer of *epithelial cells (podocytes)* surrounding the outer surface of the capillary basement membrane Fig.1[1].Current filter cartridges for dialysis machines are large and people with renal diseases need 3-4 hour treatments (sometimes up to 5 hours for larger patients) administered 3 times a week. To reduce this time patients need alternative, preferably a wearable or implantable device [2].

Developing a filtration membrane using e.g. microelectromechanical systems (MEMS) technology is a necessary step in creating an implantable, bio-artificial kidney. Successfully chosen membrane micro-machining technology helps designers to select pore geometry. In microfiltration several important filter parameters which determine the separation are flow resistance(R), pressure drop ΔP, flow rate(Q) and Reynolds number, All of these parameters depend on fluid velocity, viscosity and geometry of channel or pore.

In blood and glomerular filtration, formed element cells like RBC, WBC or platelets are separated by glomerular membrane (GBM) and blood plasma continues its path into tubule of nephron. Membrane filters can be categorized by different cross- sectional shapes such as circular, elliptical, and rectangular. In following sections we analyze and compare filter parameters like pressure drop and back wash flow. We also compare straight channels (pipes) versus diffuser (diverging) shapes.

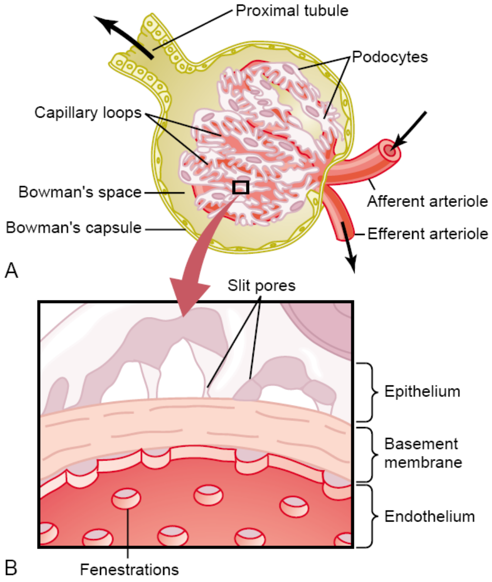

Fig1*: A,* Basic ultrastructure of the glomerular capillaries. *B,* Cross section of the glomerular capillary membrane and its major components:capillary endothelium, basement membrane, and epithelium(podocytes).

ANALYSIS OF THE MEMBRANE

Dialysis filters have short life because blood components clog their pores. In an implantable kidney the filters must operate for many years. Assuring this may be accomplished involving limited adhesion surfaces, adhesion "unfriendly" geometry, and self-cleaning mechanisms. Considering the membrane with micro channels shown in Fig.2, backwash is one of the methods to remove particles which blocked entrance. We assume that the shape to achieve the best backwash is nozzle working as a diffuser. The flow inside of micro-channel is assumed three dimensional and fully developed, steady state laminar flow. The blood is assumed to be incompressible.

For each channel geometry like rectangular, elliptical or circular diffuser, its cross-sectional area changes.

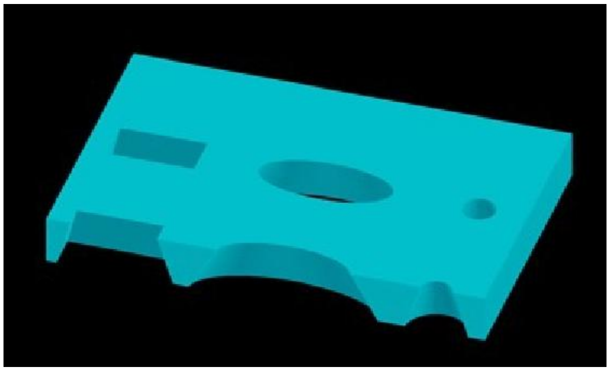

Fig2: 3D schematic of rectangular, elliptical and circular pores and their cutting view

As shown in Fig3 effective width and height of the diffuser in the z position are:

$X_{(z)} = X_{(1)} + 2z\,tan(\theta)$ (1) $Y_{(z)} = Y_{(1)} + 2z\,tan(\theta)$ (2)

Where X_1 and Y_1 are width and height of the diffuser element at entrance respectively. Θ is the divergence angle of the diffuser. The hydraulic diameter at z axis is:

$$D_{h(z)}=\frac{4A(z)}{P(z)} \qquad (3)$$

A(z) and P(z) are the cross section area and the circumference at z location, respectively.

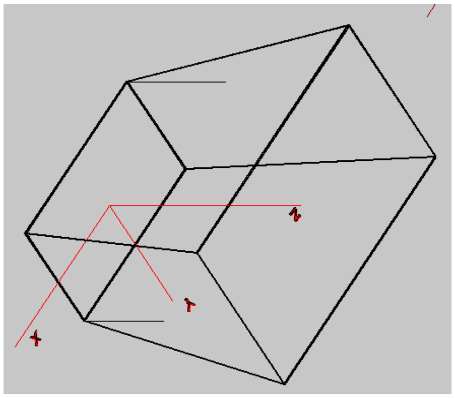

Fig3: schematic of Rectangular diffuser microchannel

The average velocity at z location can be defined from continuity equation as

$$V_{(z)} = \frac{\dot{m}}{\rho A_z} = \frac{A_1\, v}{A_z} \qquad (4)$$

Where $\dot{m}$ is mass flow rate and A_1 and v are the cross section and velocity at entrance (throat), respectively. Therefore, the Reynolds number at z position is

$$Re_{(z)}=\frac{\rho V_{(z)} D_{h(z)}}{\mu} \qquad (5)$$

μ is viscosity and ρ is densityof fluid. Pressure drop in channels is function of velocity, diameter, length, density and friction and it defines by

$$\Delta P= \frac{2\, f_{(z)} \rho V_{(z)}^{2}\, Z}{D_h(z)} \qquad (6)$$

Where f is Fanning friction factor [3].Fanning friction factor depends on geometry of channel cross section and for rectangular channel can be calculated as follows [4]

$$f\, Re_{\sqrt{A}}=\frac{4\,\pi^2(1+\varepsilon^2)}{3\,\sqrt{\varepsilon}(1+\varepsilon)} \qquad (7)$$

Where ε is aspect ratio of channel. Fanning factor for elliptical shape is defined by

$$f\, Re_{\sqrt{A}}=\frac{4\,(x^2+y^2)\,\sqrt{A}}{xy\,(\sqrt{\frac{1}{2}(x^2+y^2)})} \qquad (8)$$

where $Re_{\sqrt{A}}$,Reynolds number, can be calculated as

$Re_{\sqrt{A}}=\frac{\rho Q}{\mu\sqrt{A}}$[4](9)

Q is flow rate and A is cross section area regarding to z position.

RESULT AND DISCUSSION

If we consider particle sizes in blood, table1[5], maximum width of micro-channel (x) must not exceed 1.5 μm.Aspect ratio varies between 0< $\varepsilon \leq 1$ and diffuser opening angle $(\theta) = 0{,}5{,}10$. flow rate for each glomerulus is around 62 nl/min[1]

Table 1: Blood cells diameter in human whole blood

Cells diameter of whole blood	
Erythrocytes	7-8 μm
Leukocytes	7-20 μm
Platelets	2-4 μm

Figures 4 to 7 illustrate functions expressed by equations 6 to 8, for rectangular, elliptical, and circular pores. In $\varepsilon = 0.1$ for straight micro-channel (pipe), rectangular shape, the maximum pressure drop is 81993 Pa and in $\varepsilon = 0.5$, it is 4480.5 Pa and for diffuser shape with opening angle of 5 and 10 degree and same aspect ratio the pressure drops are 4483.82 Pa and 4479 Pa, respectively (Fig 4). In the same condition (aspect ratio and angles) for elliptical shape maximum pressure drop was$1.03 * 10^5$Pa, and for diffuser shape they are 5120 , 5123.8, 5119.2 Pa (Fig 5). In straight circular shape, maximum pressure drop in 0.1 μm diameter is $4 * 10^5$ Pa and in 1.5 μm is 2048 Pa, in diffuser shape with opening angle 5 and 10 degree pressure drops are 2049 and 2047.8 Pa respectively (Fig 6).

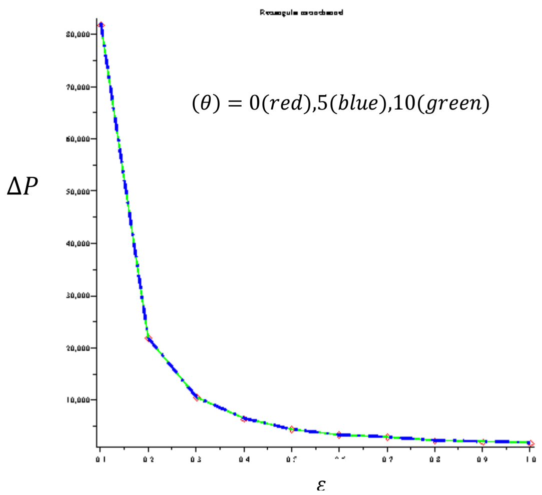

Fig 4: Maximum pressure drop as a function of aspect ratio in rectangular micro channel for $(\theta) = 0(red),5(blue),10(green)$.

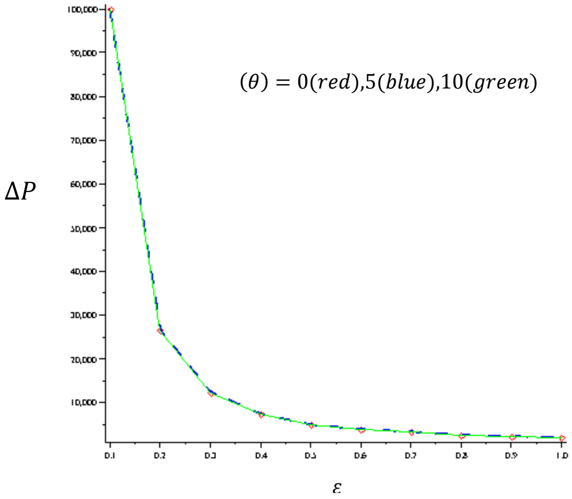

Fig 5: Maximum pressure drop as a function of aspect ratio in elliptical micro channel for $(\theta) = 0(red),5(blue),10(green)$.

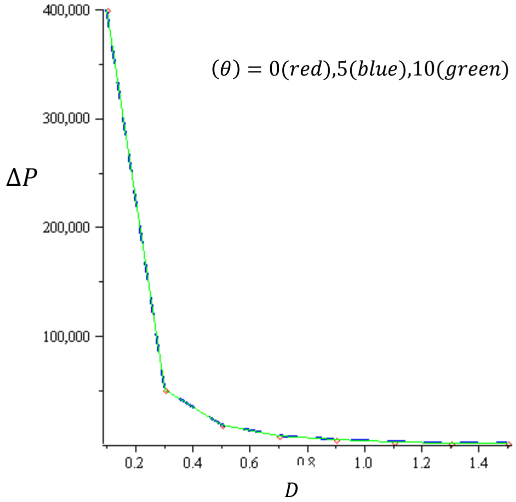

Fig 6: Maximum pressure drop as a function of diameter in circular micro channel for $(\theta) = 0(red),5(blue),10(green)$.

Maximum pressure in entrance of renal arteries in human kidney is around 100 mmHg or 13300 Pa and pressure drop bigger than this amount is out of design limits. Fig7 compares rectangular and elliptical micro-channels and it illustrates in same aspect ratio rectangular shape has less pressure drop.

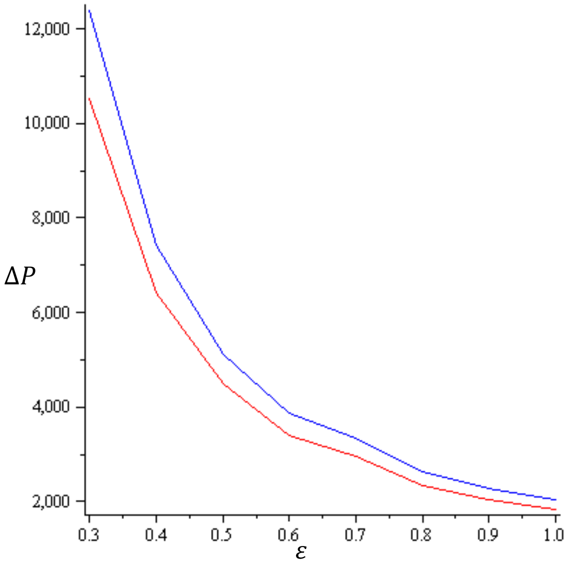

Fig 7: Comparison of pressure drop as a function of aspect ratio in rectangular (red) micro channel versus of elliptical (blue) microchannel in $(\theta) = 10$

According to fluids mechanics, flow rate depends on velocity and cross sectional area of channel, with friction factor affecting velocity. Eq. 7 and Eq.8 show dependence of Fanning friction factor and Reynolds number on aspect ratio, Fig 8 illustrates a comparison between rectangular and elliptical shape in equal area.

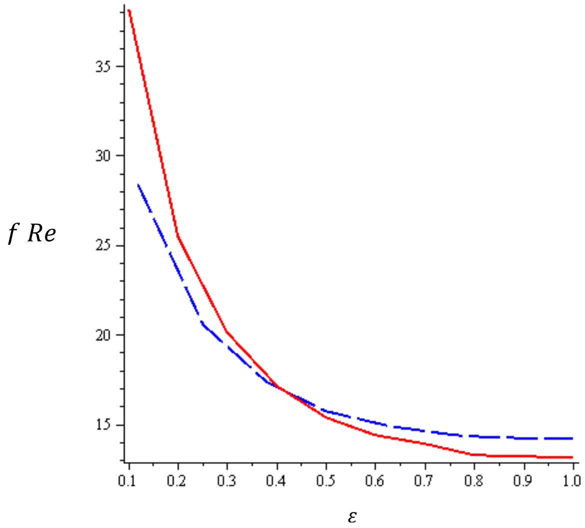

Fig 8: Comparison of f Re as a function of aspect ratio in rectangular (red) micro channel versus of elliptical (blue) with equal cross-sectional areas

CONCLUSIONS

The pressure drop in micro-channels with cross section of rectangular, elliptical and circular shape is studied. Frictional pressure drop was measured for three opening angle for varieties of aspect ratio $0.1 \leq \varepsilon \leq 1$and maximum length 1.5 μmregarding to formed element dimensions of whole blood.

According to maximum pressure in main renal artery (13300 Pa), the pore design should be between $0.3 \leq \varepsilon \leq 1$for elliptical or rectangular shape and for circular shape, it is $0.5 \leq \varepsilon \leq 1$The results and figures, specially Fig7 and Fig 8, indicate that micro-channel with rectangular cross-section has about 10 to 13% better performance than one of elliptical shape for the same cross-sectional area if only Fanning friction factor is considered. The pressure drop results proving that diffuser shaped micro-channels do not differ from pipe shaped micro-channels favor selection of a diffuser channel, as the clogging and blocking has lower probability for this geometry.

The next step is to evaluate potential flow resistance changes due to adhesion of blood components on inner filter channel walls and propose remedies that will extent filter functioning for several years.

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