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Characterization of Oxone Mediated TEMPO-Oxidized Nano Cellulose Mixed-Matrix Membranes During Ultrafiltration and Hemodialysis

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Abstract

The ninth leading cause of death in the United States is kidney disease, and hemodialysis is the process most commonly prescribed for treatment. It utilizes a selectively permeable membrane filter to remove toxins such as urea from the blood and retain necessary protein levels. However, traditional filters, such as cellulose triacetate, used during dialysis can be inefficient in terms of separation performance and reduction of fouling. Recent exploration of nanoparticles has resulted in the creation of Oxone Mediated TEMPO-Oxidized Nano Cellulose which has properties that are believed to increase hydrophilicity, increase tensile capacity, decrease membrane resistance and lower fouling, making it an ideal filter for dialysis. This study focuses on the implementation of two derivatives of these nanoparticles and how they affect the characterization of the membranes. Ultrafiltration and dialysis were performed using bovine serum albumin (BSA), lysozyme, and urea to analyze various properties of each membrane. These properties included flux, sieving coefficient, pore size, KoA, urea clearance, mass transfer coefficient, and theoretical treatment time. The first membrane, Form I, showed significant improvement in every property tested. The second membrane, Form II, showed slight improvement in each property, but it was very similar to the control, leading to the belief that it would not be much better than the traditional cellulose triacetate filters. The third membrane, 50/50, was created from a mixture of the previous two, and it showed significant improvement similar to Form I but not quite as distinct. The Form I membrane showed the most significant improvement overall and was determined to be the best option for an improved dialysis filter that can increase flux and urea clearance while preventing fouling.

1. Introduction

According to the Center for Disease Control and Prevention (1), kidney disease is the ninth leading causes of death in the United States. This does not include the amount of people who currently suffer from it. Go et. al (2) states that there are an estimated 8 million American adults who have been diagnosed with kidney disease. A multitude of health issues arise from this disease due to the inability of the kidneys to filter toxins from the blood. A buildup of these toxins can result in unpleasant symptoms such as nausea, poor sleep, fluid retention, and swelling. When left untreated, it can result in death. The CDC (1) found that in 2016, over 50,000 Americans died from kidney disease. Currently, the most common treatment to filter the blood artificially is hemodialysis. It does not cure the disease, but it performs the job of the kidneys to maintain the health of the individual. Any patient who undergoes dialysis must maintain an exhausting schedule. The majority of patients will receive treatment 3 times per week, and each treatment takes between 3 to 6 hours. This creates a difficult environment to maintain a job and social lifestyle while attending treatment every other day. Studies (3) have shown that increasing the dose, or frequency, of dialysis treatments correlates with a lower mortality rate. Lack of ability to attend every treatment increases the mortality rate of those with kidney disease, so it is vital for good health that the blood is filtered often, especially when one considers that the kidneys are constantly in use.

Hemodialysis machines operate on the principle of diffusion. The kidneys work by diffusing high concentrations of urea out of the blood while maintaining the concentration of salts and proteins. Dialysis performs the same job but does it outside of the body. Figure 1 below

demonstrates this process. Blood is pumped out of the body and passed through small, straw-like tubes that are bundled together. The tubes are made of a semi-permeable material, usually

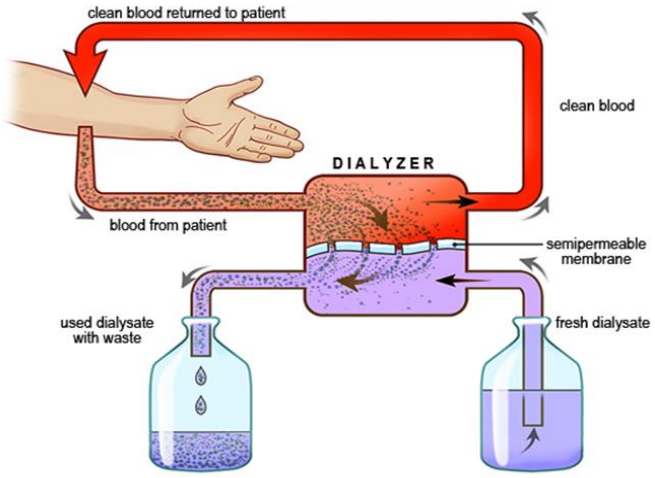

Figure 1: The process of hemodialysis. Obtained from Chris Gralapp (4).

cellulose or polysulfone, that have a pore size that is too small to allow blood cells and larger proteins to pass through. A solution containing salts and proteins called the dialysate is passed over the outside of the tubes. A lack of urea in the dialysate causes the toxin to be pulled through the filter. Additionally, if there is an excess or lack of certain salts or proteins such as sodium or potassium, the dialysate can readjust the balance to replace or remove them. After the blood passes through the filter, it is directed back into the body. This process is continuously repeated until the waste has been sufficiently removed from the blood. During treatment, patients also can undergo an ultrafiltration process to remove water from the body. Patients often experience fluid retention, so dialysis functions to not only remove excess waste but also excess water.

Cellulose is one of the most common types of materials used to create dialysis filter membranes (5). It is very effective for ultrafiltration in dialysis applications and is relatively inexpensive and easy to work with; however, improvements can be made to the material to make dialysis more efficient and improve the outcome of treatment. Modified cellulose membranes have been shown (6) to decrease the mortality rate of patients undergoing hemodialysis. Less

patients die as a result of dialysis treatment when the membrane has been modified in some way. One such method of modification is to incorporate nanocellulose particles. Collaboration with the University of Arkansas Medical School allowed for implementation of two types of TEMPO-cellulose. Using TEMPO-oxidation with Oxone® as an intermediary for nanocellulose production, two forms of TEMPO/Oxone-oxidized cellulose nanocrystals (TOOCNs) were created. Form I is partially oxidized and Form II is fully oxidized. They were both found to have a novel crystalline structure. Figure 2 shows the general chemical structure of Form I compared to Form I. The Oxone of these nanocrystals is highly water soluble and cost effective. The production of Form I and Form II was also found to be an efficient method of crystalline nanocellulose production. Prior analysis of these nanoparticles involved implementation in flat sheet cellulose triacetate membranes. Testing found that they decreased fouling and increased transport properties, hydrophilic properties, and membrane strength.

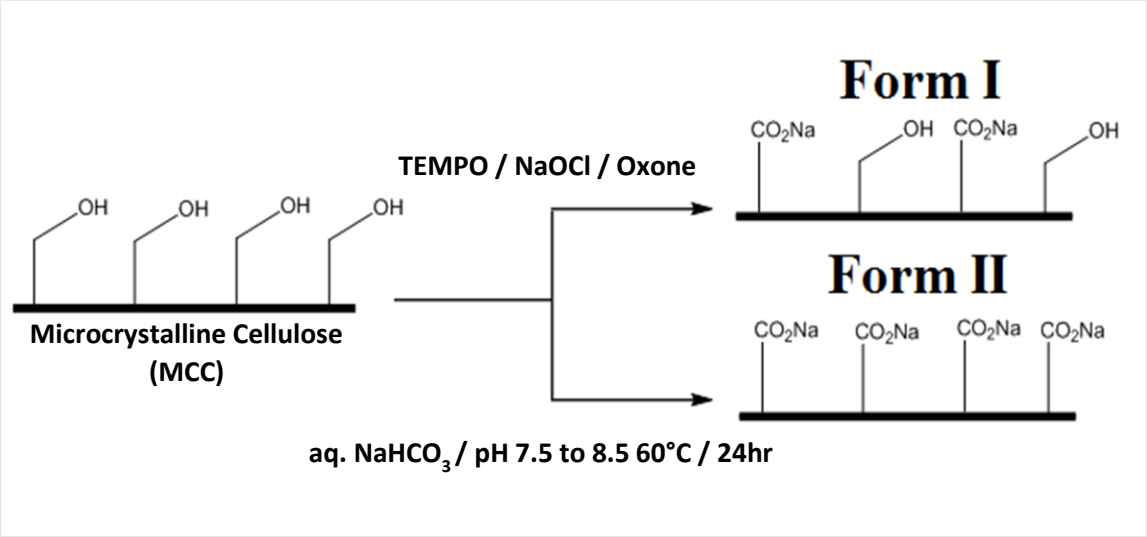

Figure 2: The structure of Form I and Form II.

Previous studies (7) using various types of nanoparticles have also shown improvements in anti-protein adsorption and anti-fouling properties. Additional studies (8) have shown that adding

TEMPO-oxidized nanocellulose gives the cast material higher tensile strength and flux. These results lead to the belief that using nanocellulose particles can cause significantly higher flux with less fouling. A lower fouling membrane opens up the potential for an implanted dialysis filter similar to an artificial kidney. Additionally, higher flux opens up potentials to reduce treatment time. A study in the New England Journal of Medicine (9) found that patients who underwent dialysis with a higher flux rate were shown to experience lower mortality rates by eight percent. It must be noted that the goal is not to reduce the treatment time as much as possible. This study seeks to maintain membrane integrity as well as have the potential to reduce treatment time; further exploration of how the body reacts when undergoing dialysis with a higher flux must be performed to conclude how much the body can withstand. With even greater improvement expected from the addition of TEMPO-oxidized nanocellulose, it is believed that the time spent in a dialysis treatment, amount of fouling, and mortality could be reduced.

TEMPO-oxidation, or the 2,2,6,6-tetramethylpiperidin-1-oxyl oxidation method, was discovered by De Noov in 1995 (10). This method was used to oxidize cellulose, and after surface studies were performed, it was found that the oxidation did not compromise the crystallinity of the material. It simply changed the surface characteristics of cellulose (11). Further studies are needed to characterize how the cellulose nanoparticles perform in ultrafiltration and dialysis, which is what this paper aims to determine. This research aims to determine the effect of Form I and Form II on cellulose dialysis membrane filters in both pure and mixed forms. It is hypothesized that a mixture of the two forms will produce a filter that performs with increased flux and urea clearance that could foul significantly less.

2. Materials and Methods

2.1 Materials

In collaboration with The University of Arkansas for Medical Sciences (UAMS), pure TOCNs and Form I and Form II samples were prepared in the laboratory of Dr. Peter A. Crooks. These materials were used in conjunction with cellulose triacetate (CTA), N-methylpyrrolidone (NMP), and deionized water to create novel membranes for filtration. The proteins used for fouling and rejection characterization were bovine serum albumin (BSA), lysozyme, and urea. These are common proteins found in the blood. BSA was chosen to represent large proteins in the blood, lysozyme was chosen to represent medium proteins in the blood, and urea was chosen because it is the major waste product the is excreted from the kidneys. All membranes were implanted in polyvinyl chloride pipes (PVC) using underwater epoxy resin.

2.2 Preparation of TOOCN Solution

Four different solutions were created for membrane casting. The first, the control, was created using only CTA and NMP. The solution was made using 10 wt.% CTA and 90 wt.% NMP. These were mixed together in a bottle and placed on a bottle roller for 5-7 days to allow for complete incorporation of the CTA. The second solution, Form I, was created using CTA, NMP, and Form I. The solution was made using 9 wt.% CTA, 90 wt.% NMP, and 1 wt.% Form I. To incorporate the Form I nanocrystals the NMP and Form I were blended in a 500 mL beaker at 6,000 rpms for 5 minutes in a water bath. Then, the solution was placed in a sonicator at 500 watts at 20 kHz for 5 minutes with 20 second intervals of sonication followed by 10 seconds of no sonication. After sonication, the TOOCNs were fully dispersed in solution. This was run through a coarse filter using vacuum filtration to remove any large chunks. After filtration, it was

added to a roller bottle with the CTA and placed on a bottle roller for 5-7 days. This process was repeated with the other two types of solutions but with adjusted concentrations of Form I and Form II. The third solution, 50/50, was prepared using CTA, NMP, and Form I and II. The solution was made using 9 wt.% CTA, 90 wt.% NMP, 0.5 wt.% Form I, and 0.5 wt.% Form II. The same mixing procedure was followed that was used for Form I. The fourth solution, Form II, was prepared using CTA, NMP, and Form II. The solution was made with 9 wt.% CTA, 90 wt.% NMP, and 1 wt.% Form II. This solution was mixed with the same procedure as Form I and 50/50.

2.3 Membrane Casting

Membranes were created with non-solvent phase induced separation hollow fiber casting. A water bath set at 35 ℃ was filled so the fibers would be fully immersed as they traveled the length of the bath. A bore solution containing 15 wt.% NMP and 85 wt.% deionized water was utilized. A spinneret was used to extrude the hollow fibers. It was set to obtain a 200 μm thickness of the membranes. The polymer solutions were passed through the outer layer of the spinneret at a pressure of 25 psi and the bore was passed through the spindle at a pressure of 1-2 psi to create a hollow tube. The spinneret was set at a 5 cm height above the water level to obtain consistent time spent passing into the bath. As the solutions passed through the water bath, phase inversion occurred. The fibers were collected in a roll at a rate of 168 cm per minute until casting was complete. Immediately after completion, the fibers were placed in a hot water bath at 87-89 ℃ for 3 minutes to heat treat. This heat treatment set the membrane to strengthen them and ensure high quality. After heat treatment, they were placed in a container filled with room temperature deionized water for storage until further use.

2.4 Module Assembly

For each dialysis run, a new module had to be created. For each module, PVC pipes were assembled in the fashion shown in Figure 3 below. Figure 3 shows one of the completed hemodialysis modules created for testing. Each module contained 20 fibers. The fibers were inserted into the PVC apparatus and glued into place with underwater epoxy resin. This glue was used to seal the ends of the apparatus so no leaking would occur during testing. About 3 mL of glue was used for each end. After the glue was fully solidified, the ends were cut to create an even surface and threaded caps were added to the module to create the completed module. These were stored in a room temperature deionized water bath until ready for testing. Fiber length was measured to use in future calculations.

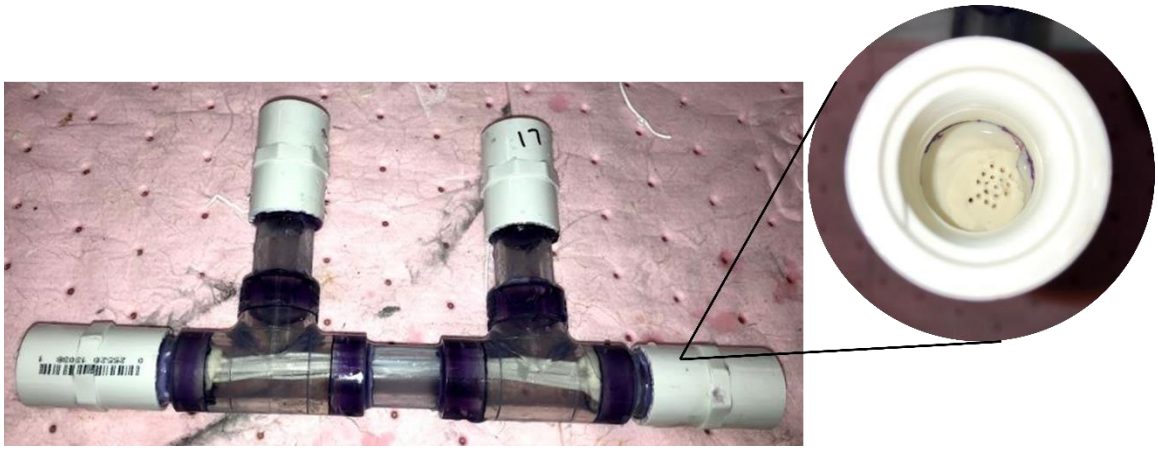

Figure 3: Example of hemodialysis module used for running tests.

2.5 Dialysis and Ultrafiltration Testing

To begin testing, the module was hooked up to allow solutions to pass through the fibers. The four ends were attached to allow the direction of the solution passing through the fibers to be opposite the direction of the water passing outside of the fibers. Pressure dampers were used to keep the transmembrane pressures consistent. Once the module was hooked up, water was

passed through the dialysate side (outside) of the membranes and water was passed through the feed side (inside) of the membranes. This was run for one hour at 1-2 psi to stabilize the membrane. The dialysate was run at a flow rate of 300 mL/min and the feed was run at a flow rate of 200 mL/min. The transmembrane pressure was kept consistent. During the hour of stabilization, the feed solutions were made. For BSA and lysozyme runs, the concentration was 1 mg/mL. Each solution was made with 800 mL of water and 800 mg of protein. For the urea runs, the concentration was 2 mg/mL. Each solution was made with 800 mL of water and 1,600 mg of urea. These solutions were mixed for their respective tests and hooked up to the testing apparatus. Once the pure water stabilization was finished, the setup was switched over to ultrafiltration, which involved turning off the dialysate. The feed was maintained at a flow rate of 200 mL/min. Three water samples were collected from the permeate. Each sample was collected for 90 seconds. They were weighed for flux data calculation. After three samples were collected, the feed solution was switched to the protein solution to obtain ultrafiltration data on the protein. Three more samples were collected and weighed. After each sample collection, a microcentrifuge tube sample was collected from the feed in, feed out, and permeate to measure filtration. After ultrafiltration, the dialysate was turned back on to run dialysis with the protein. Three flow rates were used to model different rates of dialysis. The first flow rate was run at a 200 mL/min feed rate and a 300 mL/min dialysate rate. Feed in, feed out, and dialysate out samples were collected to measure filtration. The second flow rate was run at a 300 mL/min feed rate and a 500 mL/min dialysate rate. Samples were gathered again. The third flow rate was run at a 400 mL/min feed rate and a 500 mL/min dialysate rate. Samples were also gathered for this. After samples were collected, the machine was turned off and the module was disconnected. A 70% ethanol/water mixture was run through the apparatus to disinfect it.

2.6 Sample Testing

The samples collected during dialysis and ultrafiltration were tested using a BioTek Epoch Multi-Volume Spectrophotometer. A UV- transparent 96-well plate was utilized. Samples were pipetted in triplicate in 100 µL increments into the well plate. The absorbance was run at 280 nm for the BSA and lysozyme samples. The urea samples were prepared with a QuantiChrom Urea Assay Kit and run at 520 nm in a standard polystyrene 96-well plate.

2.7 ESEM Imaging

Images were taken using a Philips XL30 ESEM machine to characterize the membrane morphology. They were taken at 65X, 150X, and 350X magnification. Cross sections of the fibers were prepared using a freeze-cracking method. Images were taken of the cross sections as well as the outside of the fibers.

3. Results and Discussion

3.1 Membrane Flux, Pore Size, and Sieving Coefficient

Traditional cellulose filters do not show improvement in flux data due to a lack of improvements being made to the membranes. However, implementation of the nanoparticles improves this property greatly. Analysis of the flux data obtained from ultrafiltration was done using Equation 1 shown below, where $\boldsymbol{Q_{UF}}$ refers to the volumetric ultrafiltration rate and $\boldsymbol{A}$ refers to the area of the membrane. $\boldsymbol{P_{inlet}}$ is the pressure at the inlet of the system and $\boldsymbol{P_{outlet}}$ is the pressure at the outlet of the system. This equation was obtained from Kim et. al (12).

$$\textbf{Equation 1: } \boldsymbol{K_{UF} = \frac{Q_{UF}/A}{\frac{1}{2}(P_{inlet}+P_{outlet})}}$$

The sieving coefficient ($\boldsymbol{S_O}$) of each membrane was determined using Equation 2 (12), where $\boldsymbol{C_f}$ is the concentration of the filtrate and $\boldsymbol{C_p}$ is the concentration of the permeate. The

$$\textbf{Equation 2: } \boldsymbol{S_O = \frac{C_f}{C_p}}$$

experimental data was plotted against each molecular weight for urea, lysozyme, and BSA in Figure 4 below. Additionally, the curves shown in the graph are theoretically modelled data. As

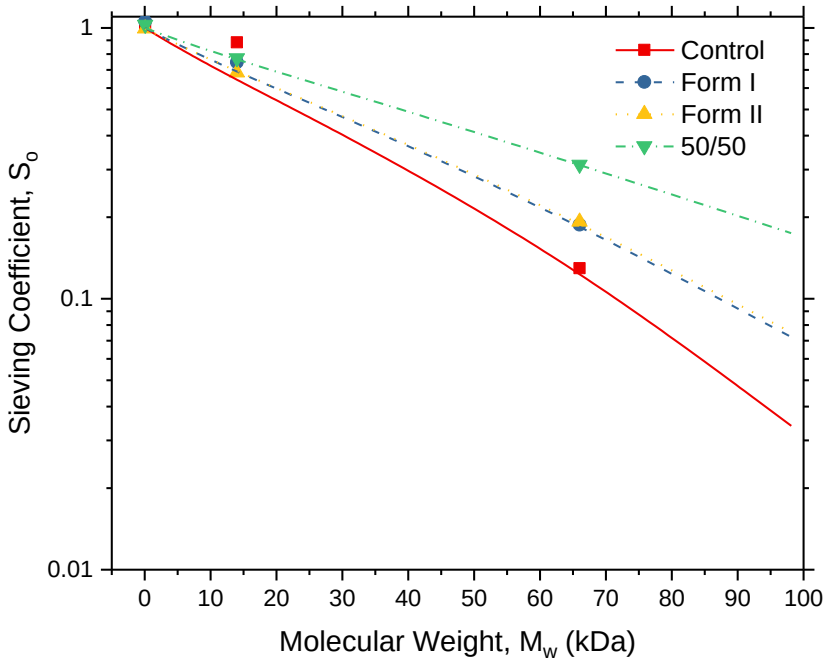

Figure 4: Experimental (points) and Theoretical (lines) sieving coefficients (S_o) plotted on the y-axis, and protein molecular weight plotted on the x-axis.

shown, the theoretical data fits the experimental data well. Forms I and II show similar characteristics to the control. However, 50/50 fell slightly short in performance with BSA. This is likely due to the increased pore size, which is calculated below. Due to these results and because BSA is such an important protein in the blood, 50/50 may not perform quite as efficiently in a dialysis treatment in this aspect. Additionally, pore size of each membrane was determined with Equations 3 and 4. Equation 3 determines the theoretical solute radius ($\boldsymbol{R_s}$) of

$$\textbf{Equation 3: } \boldsymbol{R_s = 3.1 \times 10^{-11} (M_W)^{0.47752}}$$

each protein used. $\boldsymbol{M_W}$ refers to their molecular weight. Equation 4 is a hydrodynamic model (12) that uses the values calculated from the sieving coefficient where λ is the ratio of the solute

$$\textbf{Equation 4: } \boldsymbol{S_O = (1-\lambda^2)[2-(1-\lambda^2)]exp(-0.746\lambda^2)}$$

radius to the pore radius. The pore radius was determined by the minimization of the sum of the squared residuals between the model (equation 4) and the data. The values obtained for flux data and pore size are displayed in Table 1 below. Membrane area, radius, and thickness can be found in this table as well. As determined by the table, each membrane had relatively the same area,

Table 1: Experimentally obtained values for membrane area, radius, thickness, flux, and pore size of the four variations.

	A (m^2)	**R (μm)**	**δ (μm)**	**$K_{UF\ Pure\ Water}$ ($L/hr/m^2/PSI$)**	**R_p (nm)**
Control	0.0115	568	192	109	9.0
Form I	0.0112	578	211	144	9.8
Form II	0.0118	554	229	111	9.9
50/50	0.0105	513	226	121	11.6

radius, and thickness with some variation in sizes. This uniformity was produced by casting all membranes with the same spinneret; however, some human error can occur when adjusting the spinneret, which may have caused the slight variations. These values were used to calculate the flux and pore size of each membrane. Form I and 50/50 had a significantly higher flux than either the control or Form II. Both would be able to perform dialysis with an increased flow rate to speed up the process. Additionally, 50/50 had a larger pore size than any of the other membranes. A larger pore size would allow for increased filtration without clogging of the pores, resulting in a decrease in fouling. However, this also may result in more passage of larger molecules such as BSA, which is what appeared to occur in Figure 4. It was plotted against each

molecular weight for urea, lysozyme, and BSA, respectively. Forms I and II show similar characteristics to the control. However, 50/50 fell slightly short in performance with BSA. This is likely due to the increased pore size. Due to these results and because BSA is such an important protein in the blood, 50/50 may not perform quite as efficiently in a dialysis treatment in this aspect.

3.2 Urea Characterization

Although traditional cellulose triacetate membranes are able to filter urea, they tend to do so at a lower clearance. $\boldsymbol{K_{oA}}$ is the mass transfer area coefficient, otherwise known as the theoretical clearance at infinite blood and dialysate flow rates. $\boldsymbol{K_{oA}}$ is determined using Equation 5, Fick's Law, below. $\boldsymbol{N}$ represents the solute transport rate, which was calculated using Equation 6, where $\boldsymbol{Q}$ represents the flow rate and $\boldsymbol{C}$ represents the concentration. Subscript $\boldsymbol{f}$ represents feed, subscript $\boldsymbol{d}$ represents dialysate, subscript $\boldsymbol{o}$ represents out, and subscript $\boldsymbol{i}$ represents in. $\boldsymbol{A}$ represents the area, and $\boldsymbol{\Delta C_M}$ represents the log mean concentration difference, which was calculated using Equation 7. Subsequently, the clearance $\boldsymbol{K}$ can be determined from Equation 8. The values calculated for each membrane can be found in Table 2 below.

Equation 5: $$\boldsymbol{N = K_{oA} A(\Delta C_M)}$$

Equation 6: $$\boldsymbol{N = Q_f(C_{fi} - C_{fo}) = Q_d(C_{do} - C_{di})}$$

Equation 7: $$\boldsymbol{\Delta C_M = \frac{(C_{fi} - C_{do}) - (C_{fo} - C_{di})}{ln(\frac{C_{fi} - C_{do}}{C_{fo} - C_{di}})}}$$

Equation 8: $$\boldsymbol{K = \frac{N}{(C_{fo} - C_{di})}}$$

Form I and 50/50 both had a significantly higher KoA value than the control and Form II. They would both perform well during high-efficiency dialysis where the flow rate is increased

Table 2: Experimentally determined values of urea clearance (K) and the mass transfer coefficient (k_o) for each membrane derivative. $\boldsymbol{K_{oA}}$ is the mass transfer area coefficient. ε/τ is the porosity/tortuosity and was calculated using Equations 8-10.

	$\boldsymbol{K_{oA}}$	$\mathbf{K_{experimental}}$ **(mL/min)**	$\mathbf{k_o}$ **(μm/s)**	**ε/τ**
Control	968.3048	9.431863	14.02224	3.1
Form I	1995.788	20.81781	32.80209	7.9
Form II	1176.942	14.50435	21.31135	5.6
50/50	1527.56	16.21754	26.90686	6.8

significantly to perform filtration within the typical 4-hour time period. Additionally, the experimentally determined urea clearance was calculated with Equation 5 using the respective data that was collected. It can also be found in Table 2. Form I had the highest urea clearance. Form II and the 50/50 membranes both had improved urea clearance as well when compared to the control. All three filters would be able to filter out urea more efficiently than the control while fouling less. Form I would be able to filter out urea the most efficiently out of the three options. The mass transfer coefficient, $\boldsymbol{k_o}$, which represents the rate of transfer of the particles, was calculated with Equation 9 (12) below. $\boldsymbol{\varepsilon}$ represents the membrane porosity, $\boldsymbol{\tau}$ represents the

$$\textbf{Equation 9: } \boldsymbol{k_o = \frac{\varepsilon D_{eff}}{\tau \delta_m}}$$

membrane tortuosity (curvature of pores), $\boldsymbol{\delta_m}$ represents membrane thickness, and $\boldsymbol{D_{eff}}$ represents solute diffusivity. This value was calculated from Equation 10 (12). $\boldsymbol{\lambda}$ refers to the ratio between solute radius and pore radius, and $\boldsymbol{D_o}$ refers to the solute diffusion coefficient in

Equation 10: $\frac{D_{eff}}{D_o} = (1 - \lambda^2)[1 - 2.848\lambda + 3.269\lambda^2 - 1.361\lambda^3]$

free solution. It was determined using Equation 11 (12), where k_B is the Boltzmann constant, T is the absolute temperature, and μ is the solution viscosity. All values calculated can be found in

Equation 11: $D_o = \frac{k_B T}{6\pi\mu R_s}$

Table 2. Once the ratio of porosity to tortuosity **(ε/τ)** was known, a theoretical model of the mass transfer coefficient was developed to show the relationship between the mass transfer coefficient and the molecular weights of urea, lysozyme, and BSA, which can be found in Figure 5. Based on the values calculated, both Form I and 50/50 have a higher rate of transfer of particles. Form II also showed improvement but not to the same extent.

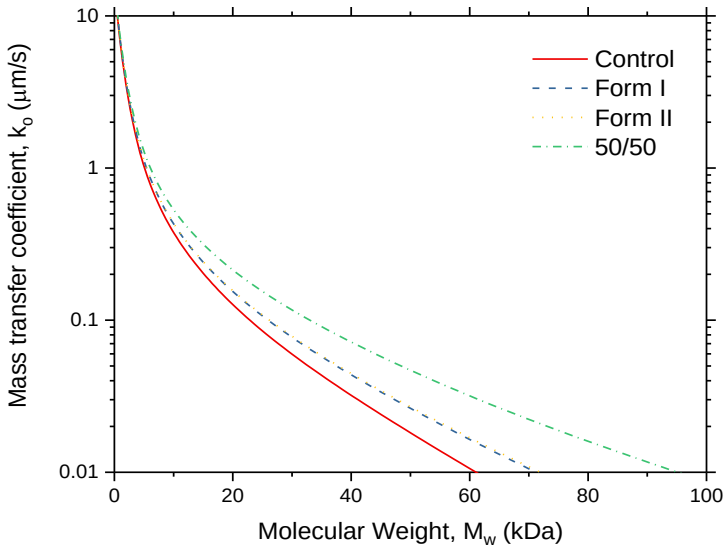

Figure 5: Theoretically determined mass transfer coefficient (k_o) plotted on the y-axis and protein molecular weight plotted on the x-axis.

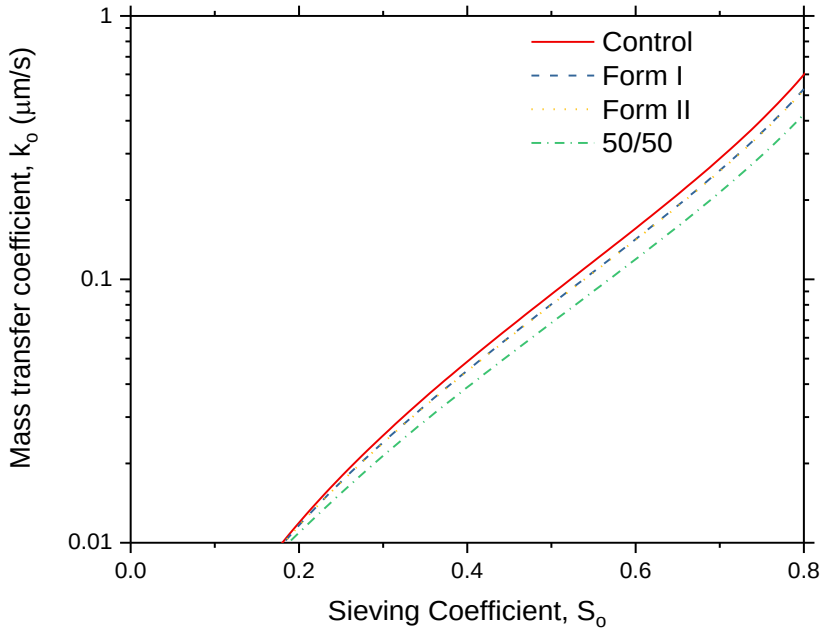

Figure 6: Experimentally determined mass transfer coefficient (k_o) curve plotted on the y-axis and sieving coefficient (S_o) plotted on the x-axis.

Additionally, mass transfer coefficients were plotted against the sieving coefficients to create a theoretical model to determine pore structure. This can be found in Figure 6 above. Based on the shape of the curve, the membranes have a symmetric pore structure. Additionally, a porosity/tortuosity ratio was obtained. The pores were all uniform and did not curve or twist throughout the membrane. All three membranes with the TOOCNs showed an increase in the ratio.

3.3 Theoretical Urea Clearance and Treatment Time

Theoretical urea clearance can be compared to the actual values to determine theorical model validity. The theoretical urea clearance was calculated by simultaneously solving Fick's law, the log mean concentration difference, and a mass balance to express the ratio $\frac{K}{Q_f}$ as a function of two dimensionless parameters, neither of which involves solute concentration, Equation 12**. Z** is the ratio of the blood flow rate to the dialysate flow rate and $\boldsymbol{R = \frac{K_{OA}A}{Q_b}}$.

Equation 12: $\frac{K}{Q_f} = \frac{1-exp(R(1-Z))}{1-exp(R(1-Z))}$

The theoretically determined values can be found in Table 3. When compared to the experimental values in Table 2, it can be determined that the theoretical values are nearly

Table 3: Theoretical urea clearance and treatment times for dialysis using the different membrane variations.

	$K_{Theoretical}$ (mL/min)	% error	$K_{Theoretical}$ (mL/min) For 1 m^2 membrane	Theoretical Treatment Time (hrs)
Control	9.184794	2.7	210.888	3.98
Form I	20.62068	1.0	284.4885	2.95
Form II	12.19495	18.9	253.8926	3.31
50/50	15.90278	2.0	257.8775	3.26

identical to experimental values. Additionally, percent error can be found for each of the theoretical calculations. These all show low values with the exception of Form II. This can be attributed to the existence of separation facilitating attributes not explored in this investigation, such as charge. From the theoretical clearance values, the theoretical treatment time was calculated in accordance with the US National Kidney Foundation Kt/V target. In this equation, a 70 kg person, at 60% water weight, must reach a Kt/V of 1.2. It was found that Form I decreased treatment time the most drastically. 50/50 and Form II also showed a decrease in treatment time, while the control showed the typical treatment time average. However, it must be noted again that the goal is not to reduce treatment time, but to simply show the ability of the membranes to perform filtration more quickly and with efficacy maintained.

3.4 ESEM Images

Traditional cellulose triacetate membranes form a single support pore layer. ESEM images were taken to determine the pore structure of the membranes with the nanoparticles. The images obtained from ESEM can be found in Figure 7. Each membrane formed a unique pore structure. It can be observed that the control (a) formed a single layer of uniform support pores. All three of the other membranes formed a double layer of support pores. Form I (b) had the

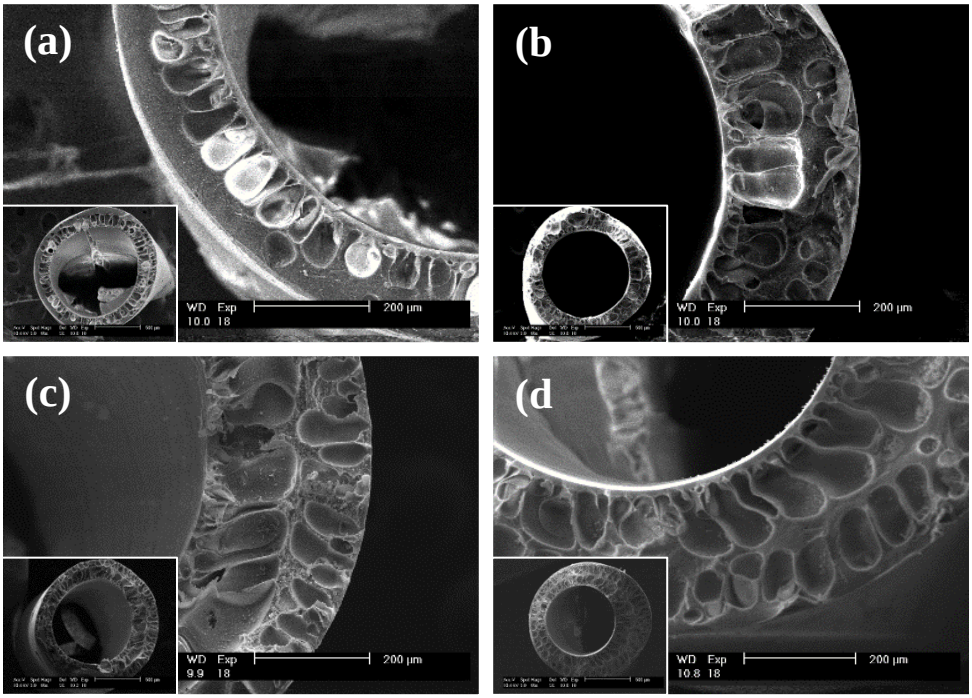

Figure 7: ESEM images of (a) the control, (b) Form I, (c) 50/50, and (d) Form II to show pore structure and membrane size at a 200 µm scale.

smallest outer layer of support pores. 50/50 (c) had a double layer of support pores that had some irregularity. Form II had a double layer of support pores with the most uniformity. The addition of a double layer of support pores could explain the increase in flux and urea clearance, as well as suggest that the nanocellulose material may also act as a pore former. The more porosity available, the more easily things can pass through. Additionally, it can be noted that the support pores in the 50/50 membrane appear to be slightly bigger than the control. This matches the same

relationship seen in the theoretically defined pore radius showing that the membrane has the capacity to filter larger molecules with more ease than the control and current dialysis filters.

4. Conclusion

Each of the three membrane derivatives showed marked improvements when compared to the control, the cellulose triacetate membrane. All showed an increase in flux, mass transfer area coefficient, and urea clearance. Additionally, all three showed a decrease in the theoretical treatment time. The 50/50 membrane had been hypothesized to show the greatest increase in all aspects of dialysis treatment. However, while it did show a relatively significant improvement to the control, Form I was the filter that showed the greatest improvement. The only data where the 50/50 was improved from Form I was pore size. 50/50 would allow for larger particle filtration with minimized fouling. However, that caused a decrease in sieving coefficient, so valuable proteins may be lost. Form II also showed a notable improvement in many aspects, but it was very similar to the control. The properties of each membrane also suggests that any of the three would foul less during dialysis. Each membrane showed unique improvements, but Form I appeared to be the ideal filter out of the three derivatives.

5. Future Work

In the future, the membranes need to be tested using real blood to determine how they perform under real dialysis conditions. Animal blood, most likely pig blood, would be used to determine this. Additionally, exploration of different ratios of nanoparticles may be pursued to obtain a mix of the different properties of each membrane to find the ideal filter for a dialysis setting. A potential direction to pursue would be the creation of an implantable filter. Most filters foul so quickly that they would not be ideal for an implant; however, the low-fouling properties

of these membranes suggest they would withstand filtration in vivo for an extended period of time without losing functionality. Perhaps a filter could be designed using these nanoparticles that could act as an artificial kidney.

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