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Influence of Monosodium Glutamate Additive on the Morphology and Permeability Characteristics of Polyamide Dialysis Membranes

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ABSTRACT: Membranes were prepared with dope solutions of various concentrations of polyamide and monosodium glutamate (MSG) additive for dialysis applications. The results show that the membranes with higher MSG concentrations had higher water uptakes and porosities. The membranes were characterized with scanning electron microscopy (SEM) and atomic force microscopy techniques and evaluated in terms of the permeability of solutes, such as urea and creatinine. The cross-sectional structure of the membranes prepared without MSG additive or with a low MSG concentration were dense, and their surfaces consisted of large-sized nodule aggregates. The permeation of solutes was less through these membranes. When the amount of additive in the membrane solution was sufficient, macrovoids were seen in the SEM images, and the sizes of nodules were small, which caused an increase in the diffusive permeability of solutes. The surfaces of the membranes with higher MSG concentrations were found to be smooth; this could be useful for the dialysis process. The contact angles of these membranes were also lower; this indicated that this additive improved the hydrophilicity of the membranes. © 2012 Wiley Periodicals, Inc. J. Appl. Polym. Sci. 000: 000–000, 2012

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INTRODUCTION

Hemodialysis is a membrane process that includes the removal of contaminants from blood for patients suffering from kidney disease. In this process, blood containing impurities, such as urea, uric acid, and creatinine, flows on one side of the membrane. A portion of these impurities diffuse through the membrane because of the concentration gradient and mix with the dialysate stream flowing on the other side. Particles of larger size, however, are unable to pass through the membrane and remain in the blood. The membranes are usually prepared through a dry–wet phase-inversion process in which a sufficient quantity of polymer is mixed with an appropriate solvent to obtain a dope solution. The dope is then given either a thin-film or a hollow-fiber form and then passed through a coagulant liquid to obtain a membrane. The dialysis performance is influenced by the type of polymeric material, solvent, and additive added to the solution.

Numerous researchers have examined the effect of polymers and additives on dialysis membrane performance. Barzin and coworkers[1–3] studied the influence of poly(vinyl pyrrolidone) additive and the coagulant bath temperature. The rejection of urea and creatinine and ultrafiltration performance of dextran solutions were determined to indicate suitable poly(vinyl pyrrolidone) concentrations and coagulant bath temperatures. In another study, Barzin et al.[4] found that poly(ethylene glycol) (PEG) and acetic acid in the membrane solution improved the removal of uremic toxins. Saljoughi et al.[5] tested the performance of cellulose acetate membrane along with PEG additive. Membranes with a PEG amount of 10% had higher sieve coefficients of insulin and pure water permeation rates. Idris and Yet[6] showed that higher molecular weights PEG restricted the formation of macrovoids within the membrane structure. Idris and coworkers[7,8] studied the effect of the additives monosodium glutamate (MSG) and D-glucose monohydrate on cellulose acetate dialysis membranes.[9] The effects of cellulose and the additive material on blood was not investigated in these studies. Abe and Mochizuki[10,11] prepared hemodialysis membranes from a cellulose/*N*-methyl morpholine-*N*-oxide solution. Increases in the cellulose concentration and a decrease in the coagulant temperature increased the sieving coefficients of dextran. Seita et al.[12] compared the permeability characteristics of poly(propylene oxide) segmented nylon and poly(tetramethylene oxide) segmented nylon. The poly(propylene oxide) segmented nylon

had a better diffusion of urea and vitamin B_{12}. Several patents also discuss the effect of different polymers and additives for the dialysis process.[13–16]

A review of the existing literature shows that numerous attempts have been made to obtain dialysis membranes to remove toxic materials in blood. Despite much advancement in the field of hemodialysis membranes and instruments in the recent years, there is still a need for membranes with better rejection characteristics. The issue of the interaction of blood with membrane materials, which causes the adhesion of blood cells and the activation of platelets, is also a limitation of dialysis membranes.[17,18] Cellulosic membranes, even though they have been used for dialysis for some time, still raise concerns because of their ability to enhance the blood-clotting process.[19,20] The motivation of this study, therefore, was to find a membrane that had less influence on and interaction with the blood and also resulted in higher permeation rates of urea and creatinine. For membrane preparation, polyamide (nylon 66) was selected as the polymer. Polyamide has good mechanical and thermal properties and is one of the few polymers that is used for medical devices because of its biocompatibility.[13,21,22] Previous studies have indicated that a polymer solution without a suitable additive leads to low permeation rates. The additive in the solution has specific interactions with the solvent, polymer, and coagulant fluid and is, therefore, used to control the membrane morphology and performance.[23,24] In addition to organic types, inorganic additives have also been found to be appropriate for increasing membrane performance.[25,26] In previous studies, we tested the effect of MSG, an easily available and inexpensive item as an additive on the polyamide solution properties (density, viscosity, and refractive index), membrane tensile strength, and thermal characteristics.[27,28] It was shown that MSG in the dope solution increased the membrane tensile strength and glass-transition temperature. However, the permeation, hydrophilic, and topographical characteristics of the MSG membranes were not discussed in these earlier articles. In this study, we examined in detail the influence of MSG on the membrane structure and separation characteristics.

EXPERIMENTAL

Materials

Membranes were prepared from polyamide (nylon 66, Behn Meyer, Subang Jaya, Malaysia) with a melt flow index of 54.7 g/10 min. MSG (Ajinomoto, Kuala Lumpur, Malaysia) was an additive, and formic acid (Merck, Petaling Jaya, Malaysia, purity > 98%, analytical grade) was used as a solvent. Creatinine (molecular weight = 113 Da) and urea (molecular weight = 60 Da) were purchased from Kanto Chemical Co., Inc., Pinang, Malaysia and HmbG Chemicals (Gombak, Malaysia), respectively. Sodium bicarbonate was purchased from Fisher Scientific (Shah Alam, Malaysia). The reagents used for testing urea and creatinine were obtained from Randox Laboratories, Antrim, United Kingdom.

Membrane Preparation

The setup for preparing the polymer solutions consisted of a round flask with a digital stirrer. The polymer (polyamide 66), solvent (formic acid), and additive (MSG) were stirred for about 6 h at room temperature in the flask so that the polymer and the additive completely dissolved in the solvent, and the solution became homogeneous. Membranes were prepared from the solutions with a dry–wet phase-inversion technique at a room temperature of 28°C. For membrane synthesis, the solution was poured onto a clean glass plate and then spread by a casting setup to yield a solution film of 0.3 mm. The solution film, along with the glass plate, was immersed in a water (nonsolvent) bath for phase change. Within few seconds, the solvent exchanged with the nonsolvent, and a flat membrane was obtained. Before testing, the membranes were posttreated in an ultrasonic bath containing distilled water for about 30 min to completely remove the solvent or additive trapped in the membrane pores.

Water Uptake and Porosity Measurements

The water uptake and porosity were determined from eqs. (1)–(3). For these measurements, the weight of a dry piece of membrane 1 × 1 cm^2 in size was initially determined with a weighing balance (A&D Tokyo, Japan, GR-200). The membrane piece was then dipped in a flask containing water. After excess water was wiped from the membrane surface, the weight of the wet membrane was determined. The water uptake (W_{up}) and porosity (P; as defined in Takai[13] and Arthanareeswaran and Kumar[29]) were then calculated as follows:

$$W_{\mathrm{up}} = \frac{W_{\mathrm{w}} - W_{\mathrm{d}}}{W_{\mathrm{d}}} \tag{1}$$

$$P = \frac{W_{\mathrm{w}} - W_{\mathrm{d}}}{\rho_{\mathrm{w}} V_{\mathrm{a}}} \tag{2}$$

$$V_{\mathrm{a}} = \frac{W_{\mathrm{w}} - W_{\mathrm{d}}}{\rho_{\mathrm{w}}} + \frac{W_{\mathrm{d}}}{\rho_{\mathrm{p}}} \tag{3}$$

where W_d is weight of the dry membrane, W_w is weight of wet membrane, V_a is the apparent volume, ρ_w is the density of water, and ρ_p is the density of polyamide.

Cross-Sectional and Surface Morphologies of the Membranes

Cross-sectional and surface images were obtained with a scanning electron microscopy (SEM) instrument (model Zeiss EVO 50, Oberkochen, Germany). The membranes were dipped and snapped in liquid nitrogen and mounted on sample stubs. The membrane samples were then gold-treated in a sputter-coating system and finally shifted to the SEM machine to examine the morphology. The roughnesses of the membrane surfaces were determined with an atomic force microscopy (AFM) instrument (model Shimadzu, Kyoto, Japan, SPM-9500J2) in the contact-type scan mode. The contact angles of the membranes were measured through a contact angle meter (KSV Instruments, Ltd., Helsinki, Finland, model CAM 101).

Membrane Testing

The apparatus used for testing the membranes is shown in Figure 1. It consisted of two 250-mL flasks: one included the feed aqueous solution containing creatinine and urea, whereas the other included deionized water. Creatinine and urea measurements are regarded as important tests in the assessment of kidney diseases and the performance of any dialysis system. The feed solution in the system was circulated at 140 mL/min, whereas the dialysate (deionized water) was circulated at 240 mL/min in the opposite direction. The temperature in the two

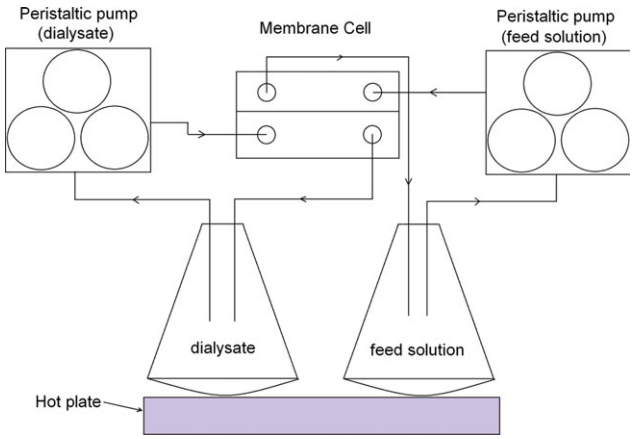

Figure 1. Apparatus for dialysis membrane testing. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

flasks was maintained at 37°C. The two fluids were passed through the membrane for 3.5 h, during which time the solutes (urea and creatinine) diffused from the feed solution to the dialysate (deionized water). The osmotic flow of the deionized water to the feed side, on the other hand, was observed to be less than 10 mL for all of the membranes. The effective area of the membranes in the dialysis cell was 40 cm^2. The diffusive permeability (P_D) values of urea and creatinine were determined from the following relation:

$$P_D = \frac{\ln(\Delta C_1/\Delta C_2)}{A\left(\frac{1}{V_f}+\frac{1}{V_d}\right)(t_2 - t_1)} \quad (4)$$

where ΔC_1 is the difference between the concentrations of the feed and dialysate at time t_1; ΔC_2 is the difference between the concentrations at time t_2; V_f and V_d are the volumes of the flasks/reservoirs of the feed and dialysate, respectively; and A is the effective area of the membrane. The creatinine and urea concentrations were determined by a spectrophotometer (U-1800, Hitachi, Tokyo, Japan). Each membrane was tested twice, and a mean value of P_D was determined to compare the membranes (the difference between two P_D values was less than 5%). The permeability of sodium bicarbonate through the membranes was also calculated from eq. (4). The sodium bicarbonate concentration was measured by a conductivity meter (Cyberscan Con 410, Eutech Instruments, Singapore).

The pure water flux was determined in a different apparatus (an ultrafiltration cell) with an effective membrane area of 7.06 cm^2. In this case, only pure water was circulated across the membrane. The fraction of water that permeated the membrane in 30 min was collected to calculate the pure water flux.

The membrane performance was also examined with blood obtained from the Kuantan slaughterhouse. Before the tests were performed on the dialysis cell, the blood was kept at a temperature of 2–8°C. The blood analysis was carried out at the Gambang Health Center. We studied the effect of sterilization on the membrane performance by heating the membrane in an autoclave machine (HVE-50, Hiramaya, Saitama, Japan).

RESULTS AND DISCUSSION

Solutions with various polyamide and MSG concentrations used for the preparation of the membranes are given in Table I. The membranes were prepared with the help of a casting setup that yielded a solution film of 0.3 mm, as mentioned in Experimental section. The actual membrane thicknesses, however, were smaller and varied between 0.1 and 0.2 mm because of polymer densification or solvent removal during the phase change. In addition to polymer densification, the membranes also swelled during coagulation, as known from previous studies. The calculated water uptake/porosity parameters are, therefore, shown in Table I. Swelling characteristics or higher water uptakes are desirable for dialysis membranes because this results in an increased permeability of small-sized impurities and ultrafiltration water flux.[30,31] The water uptakes (W_{up}) in the table show that all of the membranes with or without the additive absorbed water. The membranes with higher MSG contents, however, had higher uptakes compared with the membranes with lower MSG concentrations. We noticed that membrane M1610 with 10 wt % MSG (or polyamide, 16%) had W_{up} and porosity values approximately 5 and 2 times higher, respectively, than membrane M2600 (without any additive). The W_{up} and porosity data in Table I reveal that the MSG additive did not get trapped too much in the polymer network and did not become part of the polymeric structure. The reason was the hydrophilic nature and affinity of MSG for the nonsolvent (water), because of which it rapidly mixed in the coagulant bath and, thereby, created voids. The substantial increase in porosity showed that the MSG additive acted as a pore-creating material in the polyamide membrane.

Other factors related to the pore structure or porosity in dry–wet phase-inversion process are the kinetic hindrance and the thermodynamic force, which depends on the composition of the dope solution[32] and the coagulation conditions, such as the temperature and composition of the coagulant medium.[2,21] Because the coagulation conditions were the same and the total amounts of polymer and additive were equal, we expected that the pore structure and porosity depended on the kinetic hindrance (viscosity) of the dope solutions. The solutions with

Table I. Compositions of the Solutions for Membrane Preparation, Water Uptake, and Porosity Values

Membrane name	Polyamide (%)	MSG (%)	Water uptake	Porosity
M2600	26	0	0.592	0.416
M2501	25	1	0.837	0.501
M2402	24	2	0.836	0.501
M2303	23	3	1.183	0.587
M2204	22	4	1.304	0.610
M2105	21	5	1.527	0.647
M2006	20	6	1.728	0.675
M1907	19	7	1.884	0.693
M1808	18	8	2.178	0.723
M1709	17	9	2.476	0.748
M1610	16	10	3.000	0.783

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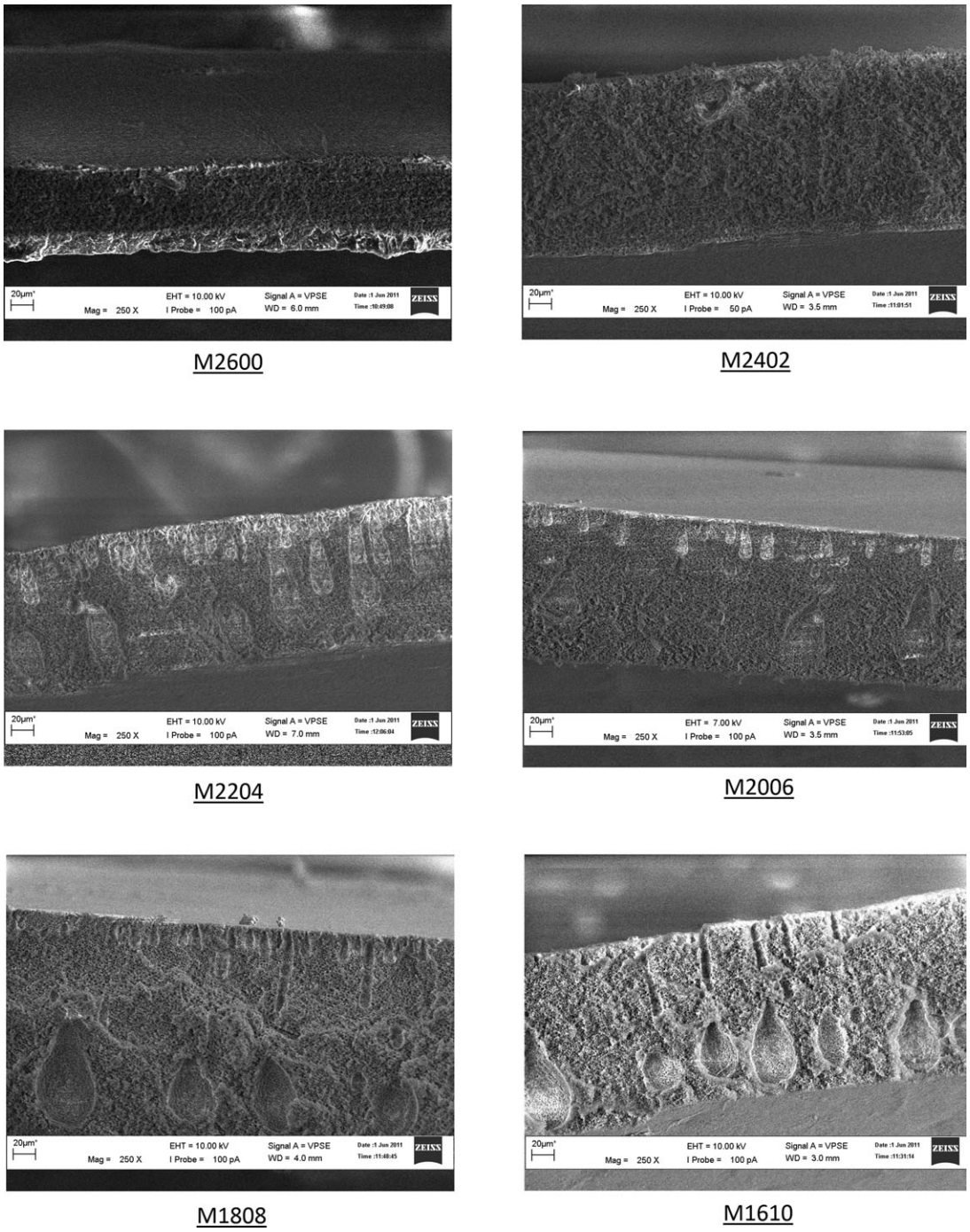

Figure 2. Cross-sectional images of membranes obtained by SEM.

higher polymer concentrations (for M2600) were more viscous, as shown by the visual/qualitative examination of the prepared dopes in this study. The higher viscosity increased the kinetic resistance, because of which the phase-change process was slow. This, in turn, facilitated the aggregation of polymer nodules, and less porous membranes were produced. The solutions containing less polymer were less viscous, because of which demixing and change of phase took place quickly in the nonsolvent. The instantaneous demixing or separation of solvent and additive from the polymer created more porous membranes.

The images of the developed membranes obtained from SEM analysis are shown in Figure 2. The image of the membrane without MSG (M2600) showed a dense and sponged structure, which included a few small-sized (ca. 1–3 μm), irregularly shaped voids. The cross section of M2600 did not show any obvious asymmetric structure. The SEM image of M2402, which contained 24% polyamide and 2% MSG, showed a similar structure to that of M2600. The minor difference between the structures of M2600 and M2402 implied that MSG additive in case of a higher polymer concentration was unable to create a

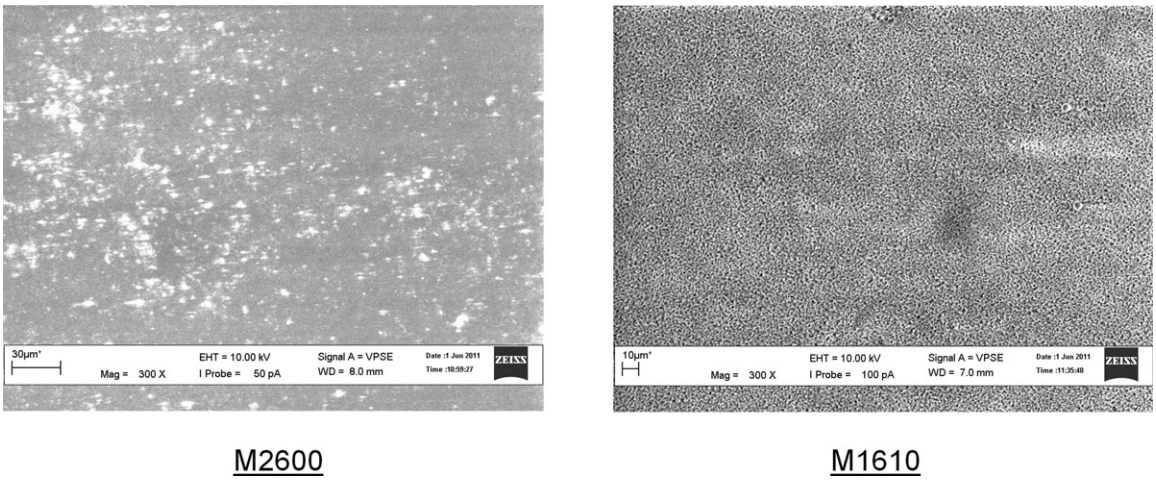

Figure 3. Surface SEM images of M2600 and M1610.

large number of pores/voids. The explanation, in terms of viscosity or fluidity, was that the removal of the additive and the solvent from the viscous solution film (due to the higher polymer concentration) was at a slower rate. This impeded the phase-inversion process and enhanced the densification of the polymer network or the suppression of pores in the membranes.

In the membranes with relatively higher MSG concentrations, voids of several sizes existed, as was clear from the images of M2204 and M2006. The structures of these membranes were of asymmetric type with a number of voids present on one side (top) and with few of them extending and reaching up to the middle. This showed that MSG had the ability to create macrovoids when it was included in the dope solution in sufficient amounts. The SEM results of membranes M1808 and M1610 showed more obvious effects of MSG and polymer amount. Not only was the number of voids higher, but their sizes were also greater. The voids, therefore, could not only be initiated, but its dimensions could be adjusted through the modification of the amounts of additive and polymer.

Top surface images of membranes M2600 and M1610 were also obtained. Figure 3 indicates that the membrane surface was nonporous and dense for M2600. The nonporous surface ultimately resulted in negligible or very low permeation of solutes from the dialysis feed solutions, as is described in the discussions related to urea and creatinine P_D. In the membrane with a higher additive concentration, M1610, the surface was less dense, and voids were observed (in Figure 3). These voids were the same that were observed earlier near the top membrane surface in the cross-sectional image shown in Figure 2.

The topographical characteristics of the membranes obtained with the AFM method on a scan area of 5×5 μm^2 are shown in Figure 4. For all the cases, we observed that the membrane surfaces were not perfectly smooth, and multiple nodule aggregates were formed. The nodules were arranged in rows, which were separated by depressed cavity channels (or valleys). The peaks of the nodule appeared bright and yellowish, whereas the valleys appeared brown in these figures. The nodule patterns of different membranes indicated that in the membranes containing no MSG or lower amounts, the nodule aggregates were organized in a relatively random manner. The sizes of the nodules were also nonuniform. The nodule alignment was regular, and the size was relatively uniform in the membranes with higher MSG. Furthermore, it was obvious that the nodule sizes decreased with increasing MSG amount. The approximate nodule aggregate size in membranes M2600 and M2501 was about 0.5–1 μm, whereas it was approximately 0.2 μm for the membranes containing higher MSG amounts, such as M1610. The large size of the nodule aggregates in M2600 was probably due to the fact that the solution of this membrane precipitated gradually, because of which the nodule aggregates united and grew in size. When the solution consisted of a lower amount of polymer, the nodule aggregates were unable to merge in large size. This was inconsistent with the work of Ruaan et al.,[33] which showed that a faster coagulation rate of the membrane led to a small nodule size and vice versa. Small nodule sizes are expected to be beneficial as the permeation of solutes can be higher from the interstitial spaces surrounding the nodules.

The roughness parameters of the various membranes were also determined through AFM analysis. The parameters found and given in Table II are the mean roughness (R_a), maximum difference between peak and valley (R_y), and root mean square roughness (R_{rms}). The values in Table II for most of the cases indicate that the roughness increased initially with the addition of MSG. It was thus observed that the R_a and R_{rms} values of membranes M2501, M2303, M2204, and M2105 were higher than those of M2600. These roughness parameters with further increases of MSG started to decrease. The R_y value was at a maximum for M2600; this showed that the difference between the top (peak) and the bottom (valley) was greatest for this membrane. The R_y roughness for M2006–M1610 was lower; this indicated that the difference between the nodule top and the valley depression was lower and the membrane surface is smooth. Other roughness-related information could be obtained from the distribution of the nodule heights in the color map bar in Figure 4. The distribution in these bars was skewed (either toward top or bottom) for membranes M2600–M2105,

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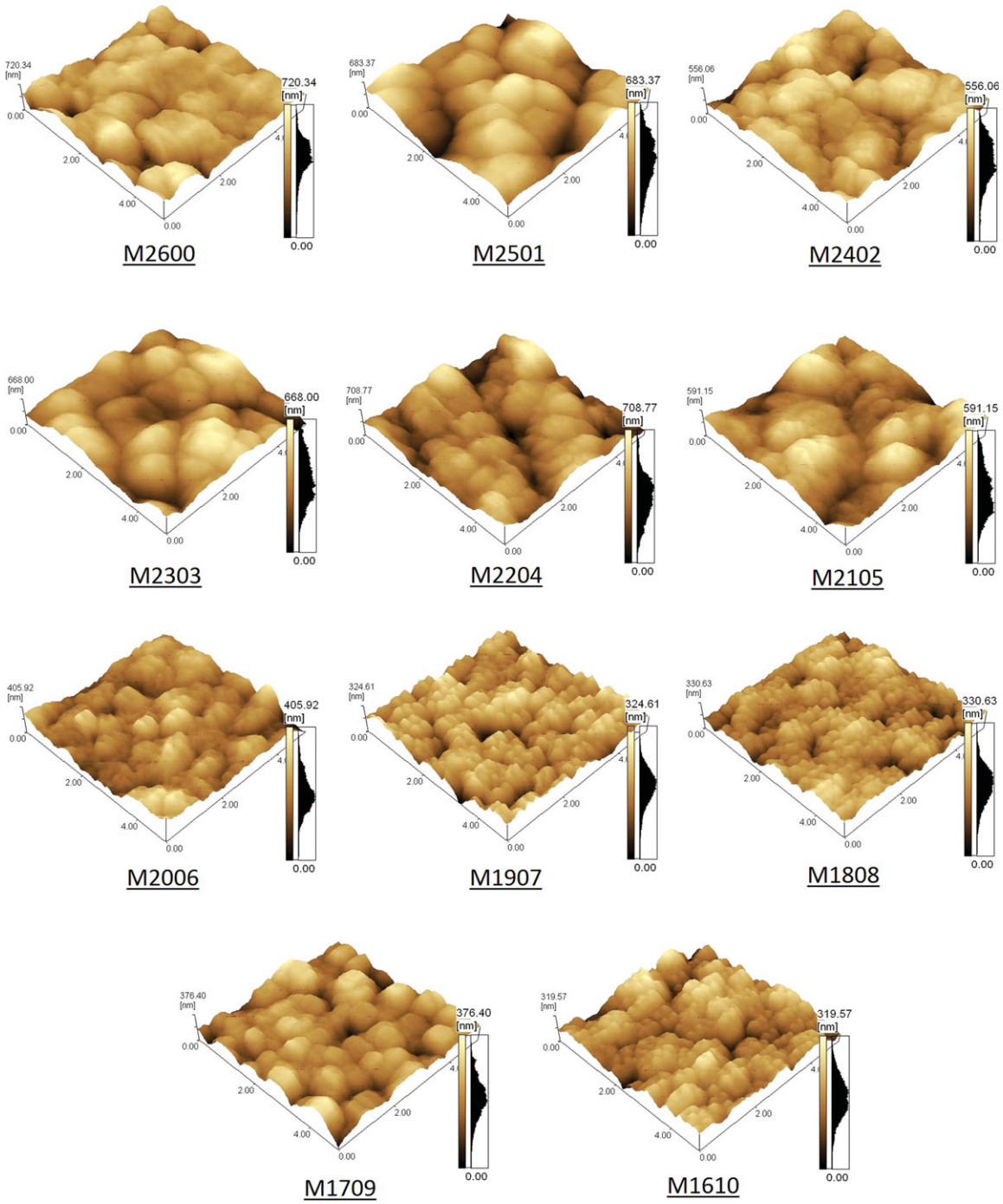

Figure 4. AFM characterization of the membrane surfaces. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

which meant that the nodule heights were not equally distributed about the mean height. The distribution for the membranes with higher MSG was more uniform about the mean. The smoother membrane surface was anticipated to be advantageous because there was a lower possibility for the useful proteins, platelets, and cells in blood to adhere and stick to a smooth surface. The smoother surface hence made the membrane hemocompatible.[34,35]

The contact angles of the different membranes were found to predict the hydrophilic characteristics of the membranes. To measure the contact angle, dry membrane samples about 1 × 2 cm^2 were placed on the sample stage. The position of the syringe and the camera of the contact angle meter were adjusted so that the syringe needle appeared in the middle of the computer screen. A droplet from the syringe was then injected on the membrane surface, and the contact angle was autocalculated

Table II. Roughness Parameters of the Membrane Surfaces

Membrane	R_a (nm)	R_y (nm)	R_{rms} (nm)
M2600	72.71	700.12	95.03
M2501	102.23	676.58	125.60
M2402	70.13	541.35	86.34
M2303	96.33	653.92	116.81
M2204	94.04	696.17	117.10
M2105	83.09	578.28	100.97
M2006	42.15	385.18	53.35
M1907	34.41	316.62	43.80
M1808	35.53	317.96	44.50
M1709	43.53	359.79	55.24
M1610	38.48	312.74	47.79

by the software (CAM 100, Helsinki, Finland). The results in Figure 5 show that the contact angle values were more or less the same up to M2006. The contact angles were significantly lower for higher concentrations (>7%) of MSG. The lower contact angles indicated that the membrane hydrophilicity improved with the addition of MSG. We noticed further during the contact angle measurement that in the membranes with higher polymer (or lower additive) concentration, the droplet introduced on the surface either did not penetrate the membrane surface at all or took considerable time to permeate the membrane. The drops on the membranes with higher MSG permeated the membrane film in relatively less time. For example, the profile of a drop injected on membrane M2006 is shown at different time steps. In Figure 6, $t_{ref} = 0$, where t_{ref} is the reference time in minutes, which shows the initial condition that is the profile of the injected droplet when it reached the membrane surface. After 1 min, we noticed that the size/height of the drop was approximately two-thirds of the initial size. Similarly, the sizes were one-half and one-quarter of the original size at $t_{ref} = 2$ and 3 min, respectively. At $t_{ref} = 4$ min, the drop height had negligible meaning in that it was completely inside the membrane pores.

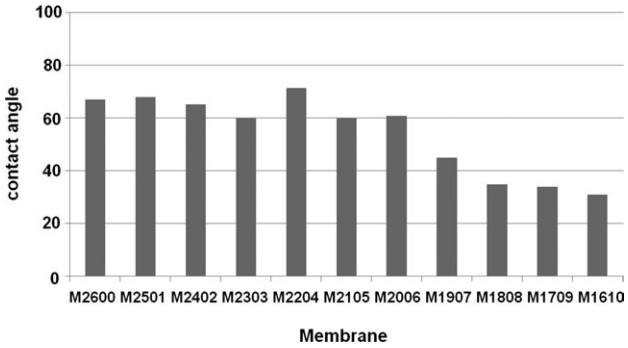

Figure 5. Contact angles of various membranes.

The P_D values of the solutes urea and creatinine for the membranes considered are shown in Figure 7. The figure shows that in the membranes without MSG or with lower MSG additive concentrations, the solutes were less permeable and were mostly rejected by the membrane. The compact structure of these membranes resisted diffusive transport through the membrane. The membranes with 6% or greater amounts of additive allowed significant permeation of urea and creatinine. This was due to the porous structure of the membranes with a number of elongated voids and small nodule aggregates, as shown previously in the SEM and AFM images. The presence of the voids and relatively small-sized nodule aggregates in the membrane thus augmented the permeation of the unwanted solutes and could be considered suitable for the dialysis process.

The permeabilities of the membranes in this study were compared with the ones in the previous studies. Several of the

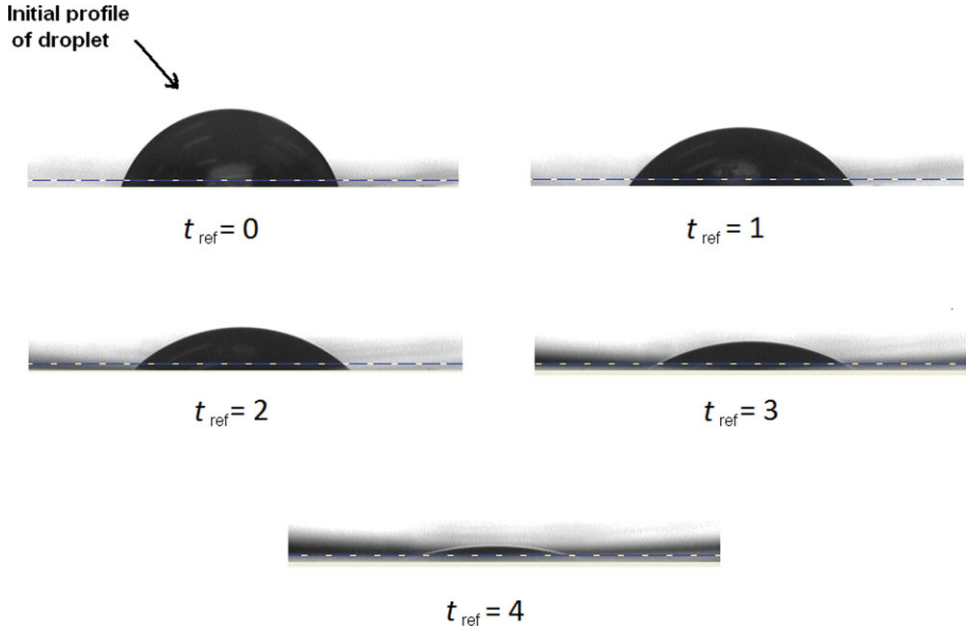

Figure 6. Profile of the water droplet at different times (in minutes) on membrane M2006.

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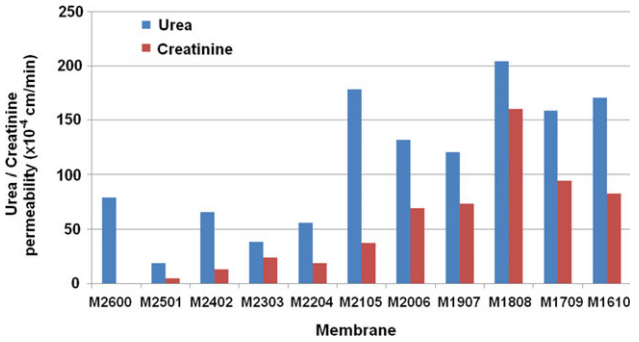

Figure 7. Effect of the MSG additive on the permeability of urea and creatinine. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

previous studies compared membranes in terms of sieving coefficients through ultrafiltration experiments. Likewise, some studies compared the membranes on the basis of urea reduction, which depends on the volumes of the feed and the dialysate solutions circulated, the surface area of the membrane, and the processing time set during the experiments. It is, however, appropriate to compare the membranes in terms of $P_{D,}$ which indicates the reduction of solutes such as urea and creatinine normalized by the volume processed, membrane area, and circulation time for the dialysis process. A comparison with the studies that used P_D as the parameter showed that Kee and Idris[8] reported values of up to 160×10^{-4} and 80×10^{-4} cm/min for urea and creatinine, respectively. Similarly, the membranes of Seita et al.[12] showed permeabilities below 150×10^{-4} cm/min. The urea permeabilities of membranes M1808, M1709, and M1610 were between 160×10^{-4} and 200×10^{-4}, whereas the creatinine permeabilities were 80×10^{-4} to 160×10^{-4} cm/min. This indicated that the membranes in this study had higher or comparable diffusivities and were able to eliminate the undesirable materials in blood.

The dialysate solution used for hemodialysis most often includes useful minerals that in higher amounts than are in a patient's blood. Because of the higher concentration of these minerals in the dialysate, diffusion occurs through the membrane, and the minerals are mixed with the blood. The diffusion rates of sodium bicarbonate were thus determined from the dialysate to the feed stream for the membranes and are shown in Figure 8. Similar to the case of the unwanted materials urea and creatinine, the permeability of sodium bicarbonate was higher in the membrane with higher MSG concentrations. The permeation rate values were nearly in the same range as those of urea and creatinine. In membranes M1907–M1610, hence, not only were the undesirable solutes cleared from impure blood, but also useful materials were added to the blood through the dialysate.

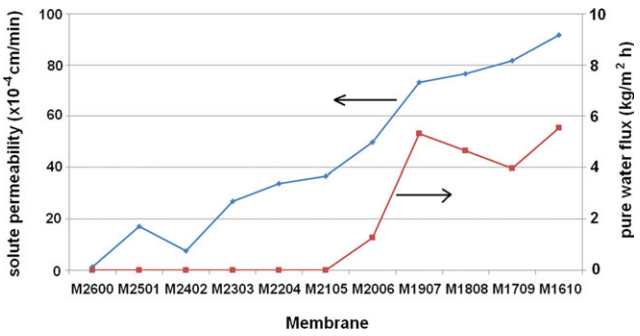

Figure 8. Permeability of sodium bicarbonate and pure water flux. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Table III. Effect of the Dialysis Treatment on Different Parameters of Blood

Parameter	Before dialysis	After dialysis
White blood cells (1/μL)	5.8×10^3	6.7×10^3
Red blood cells (1/μL)	7.6×10^3	7.4×10^3
Hemoglobin (g/dL)	13.2	13.0
Hematocrit (%)	41.2	39.3
Mean corpuscular volume (fL)	54.0	53.3
Mean corpuscular hemoglobin (pg)	17.3	17.6
Mean corpuscular hemoglobin (g/dL)	32.0	33.1 concentration
Platelet count (1/μL)	180×10^3	131×10^3
Lymphocytes (1/μL)	2.0×10^3	1.9×10^3
Neutrophils (1/μL)	3.4×10^3	4.5×10^3
Mixed cells (1/μL)	0.4×10^3	0.3×10^3
Red cell distribution width (%)	16.5	16.4
Platelet differential width (fL)	8.9	10.1
Mean platelet volume (fL)	6.8	6.7
Large platelet ratio (%)	7.3	8.6

In addition to the permeability of sodium bicarbonate, Figure 8 depicts the pure water flux through the membranes obtained in an ultrafiltration cell. The operation feed pressure for these tests were kept low (100 mmHg), which is typical of a dialysis process. A sufficient amount of ultrafiltration flux through the dialysis membrane is important for removing excess fluid from the patient's body.[10,11] A comparison of various membranes showed that the flux was negligible in membranes M2600–M2105. Membrane M2006 had a lower water flux of approximately 1.3 kg/m^2·h, whereas membranes M1907–M1610 had higher fluxes, between 4 and 6 kg/m^2·h.

The plots in Figures 7 and 8 show rather a scattered behavior of the permeability/flux values versus MSG, and these did not simply increase with increasing MSG. The trend and the overall behavior, however, confirmed that a higher MSG quantity in the dope solution led to membranes that were able to reject the impurities and the excess fluid. Membranes M1907–M1610, therefore, were considered superior to the rest of the membranes.

A characteristic of any dialysis membrane is that it allows diffusion of small-sized contaminants in the blood but does not

Table IV. Effect of the Autoclave Sterilization on the Membrane (M1808) Performance

Solute type	Before sterilization	After sterilization
Urea permeability (cm/min)	0.0204	0.0224
Creatinine permeability (cm/min)	0.0160	0.0147

permit the leakage of relatively large sized particles, such as albumin, red blood cells, and white blood cells. In a similar manner, the membrane should not allow adsorption of particles that can cause diseases such as anemia, leukopenia, and thrombopenia. To verify this feature, the membrane that performed better in terms of urea, creatinine, and pure water permeability (M1808) was tested on blood. Similar to the tests on the aqueous urea and creatinine solutions, blood and the dialysate were circulated for 3.5 h. The various blood parameters determined before and after the dialysis process are given in Table III. A comparison showed that the parameters of the red blood cells, white blood cells, and platelets and their subtypes did not vary or drop too much after the process. This showed that the developed polyamide–MSG membranes were satisfactory in terms of biocompatibility and could be used for the dialysis application. Few of the parameter values, however (Table III) were seen to be higher after the treatment; this was unexpected. A possible reason was the experimental uncertainty/accuracy of the blood cell analyzer because the fluid flow due to osmosis was very low in the dialysis experiments, as mentioned in the Membrane Testing section.

Membranes for medical use are frequently subjected to sterilization. Most common is the autoclave method, in which the treatment is done with hot water for better effectiveness.[13] Membrane M1808 was, therefore, autoclave-treated to check its stability against this treatment. The sterilization was carried out by the placement of membrane in an autoclave filled with water at a higher temperature of 121°C for duration of 20 min. After sterilization, the physical appearance of the membrane did not show any apparent deterioration; this indicated that the membrane could sustain such treatments. The quantitative analysis after sterilization was done by the testing of the membrane again for urea and creatinine permeability. The comparison in Table IV shows that after treatment, the membrane was still able to permeate urea and creatinine, as the difference between the results before and after treatment was less than 10%.

CONCLUSIONS

A study of membranes developed for the dialysis process revealed that MSG additive in the dope solutions increased the porosity of the membranes. The SEM results of the membranes that contained higher MSG concentrations showed the presence of elongated voids in the membrane structure. The AFM analysis showed nodule aggregates of relatively smaller size and lower surface roughness in these membranes. The permeation of unwanted solutes and ultrafiltration fluxes were also found to be higher when the membrane dope solution contained higher amounts of MSG. A membrane with improved dialysis performance was also tested on blood to predict its biocompatibility. The test indicated that the developed membrane did not affect the important blood parameters. Also, autoclave sterilization did not have any detrimental effects on the membrane performance.

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