

Polyurethane–Poly(methyl methacrylate) Interpenetrating Polymer Networks. I. Synthesis, Characterization, and Preliminary Blood Compatibility Studies

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SYNOPSIS

Simultaneous polyurethane–poly(methyl methacrylate) (PU–PMMA) interpenetrating polymer networks (IPNs) were synthesized with the PMMA polymerization initiated at room temperature. Transparent IPNs with better miscibility and synergism of mechanical properties were obtained. Dynamic mechanical analysis data indicated that up to 30% PMMA can be incorporated into PU networks without substantial phase separation. The PU–PMMA 90/10 IPNs elicit less than 2% hemolysis, suggesting that these materials could be used as blood contacting materials. © 1996 John Wiley & Sons, Inc.

INTRODUCTION

Polyurethane (PU) materials are extensively used in blood contacting applications and organ reconstruction. Although PUs are relatively biocompatible materials,¹ they are also known to be prone to surface cracking,² stress induced degradation,³ biodegradation,⁴ and calcification.⁵ Surface modification of PU by hydrophilic monomers was carried out to enhance blood compatibility of the PUs.⁶ However, modifications can produce alterations in the physicochemical characteristics of the PUs making them more susceptible to degradation. Better compatibility, enhancement of mechanical properties, and resistance to degradation may be achieved by interpenetrating polymer network (IPN) synthesis.

Although the concept of IPN synthesis is now extensively used in the new generation of plastics, a parallel use of such material is not seen in the medical field. Further, even though the hydrophobic polymer poly(methyl methacrylate) (PMMA) has a long history of good biocompatibility,^{7,8} modification of the PU by the hydrophobic polymer PMMA for medical uses seems unexplored. This article reports

on the synthesis, characterization, and preliminary blood compatibility studies of the PU–PMMA IPNs.

EXPERIMENTAL

Materials

All chemicals and reagents used were of analytical grade purity. Toluene 2,4 diisocyanate (TDI), dibutyltindilaurate (DBTL), methylmethacrylate monomer (MMA), and ethylene glycol dimethacrylate (EGDMA) were supplied by Fluka A.G. 4,4-Diphenylmethane diisocyanate (MDI) was from Polysciences. Polytetramethylene glycol (PTMG 1010) was from Quaker Oats U.S.A. Benzoylperoxide (BPO), trimethylpropane (TMP), *N,N* dimethyl *p*-toluidene, and dimethylacetamide solvent (DMA) were from Sisco, India.

Solvent was dried and distilled before use. BPO was recrystallized from chloroform–methanol. All other chemicals were used as such.

Synthesis

PU

The synthesis of the PU was as reported elsewhere.⁹ Biurets of the isocyanates (TDI and MDI) were pre-

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Table I IPN Composition

Polymer Code	NCO/OH	Content (Wt %)	
		PU	PMMA
PU 1A (TDI based)	1.09	100	—
PU1A-PMMA			
90/10	1.09	90	10
80/20	1.09	80	20
50/50	1.09	50	50
PU 4A (MDI based)	1.09	100	—
PU 4A-PMMA			
90/10	1.09	90	10
80/20	1.09	80	20
70/30	1.09	70	30
50/50	1.09	50	50

pared by reacting 3 mol of the isocyanate with 1 mol of water at 80°C in a nitrogen atmosphere. DBTL, 0.01 wt %, was used as catalyst. The biuret was solution polymerized in DMA with an equivalent amount of the polyol (PTMG) at 80°C for 1 h for the TDI and 1.5 h for the MDI. After cooling the prepolymer, TMP dissolved in DMA was added with high torque mixing to maintain a NCO/OH ratio of 1.09. The mixture was degassed by applying a vacuum at room temperature for 10 min. Curing was carried out at 60°C for 3 h followed by 80°C for 24 h. Postcuring was at 60°C for 24 h. The PU was extracted with hexane and distilled water-ethanol 80 : 20 to remove the unreacted nonpolar and polar constituents.

PU-PMMA IPN

Prepolymer of the PU was prepared as mentioned above. After cooling the prepolymer to 0°C, cal-

culated weight percentages of MMA monomer were added. A mixture of 0.5 wt % of BPO and 0.5 wt % *N,N'* dimethyl *p*-toluidene was added to initiate the MMA polymerization at room temperature. EGDMA, 2 wt %, which is the crosslinker for MMA, was added to the prepolymer-monomer mixture with high torque mixing. A stoichiometric amount of the TMP with respect to the corresponding PU was also added simultaneously and the mixture was cast on a silicone oil coated glass mold. Curing was carried out at room temperature for 3 h, followed by 80°C for 24 h. Postcuring was at 60°C for 24 h. Extraction of the IPNs was carried out under similar conditions to that of the PU. Composition of the IPNs prepared is given in Table I.

Characterization

Physicochemical

The IPNs were characterized by the following properties and ASTM specifications¹⁰: chemical resistance, D 543 (1978) and mechanical properties, D 882 (1981).

Infrared (IR) spectra were recorded on a Perkin Elmer 597 IR spectrophotometer. Dynamic mechanical properties were evaluated using a Rheovibron Dynamic mechanical analyzer.

Preliminary Blood Compatibility Studies: Hemolysis

Red cell lysis in the presence of the IPN materials were tested by treating 20 mg of the materials with 2 mL of ACD anticoagulated calf blood at 37°C for 1 h. Blood was centrifuged twice at 150 × *g* for 15 min for the complete removal of red blood cells

Table II Solvent Resistance of PU-MMA IPNs

Solvents	% Weight Loss			
	PU 1A	PU 1A-PMMA 90/10	PU 4A	PU 4A-PMMA 90/10
Hexane	4.05	0.93	3.06	0.85
Toluene	7.25	3.09	6.35	2.57
Dioxan	13.56	4.78	11.0	3.64
Methanol	8.89	4.41	5.78	3.20
CCl ₄	4.52	2.57	3.24	1.95
10% HCl	2.53	—	1.98	0.67
3% H ₂ O ₂	2.58	0.73	1.86	—
10% NaOH	1.26	—	1.05	—
H ₂ O	1.33	—	0.78	—
25% CH ₃ COOH	2.51	0.54	1.46	0.20

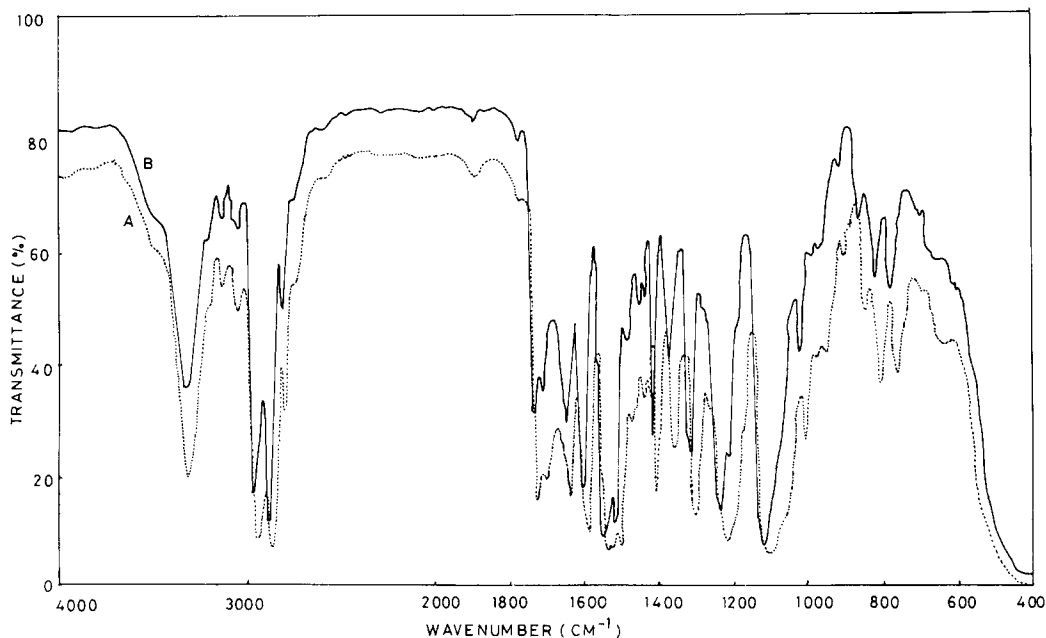


Figure 1 Infrared spectra of MDI based PU 4A and PU 4A-PMMA 50/50 IPN.

(RBC). The control was untreated blood. Distilled water, 3.6 mL, and 0.4 mL of plasma, were mixed and the absorbance measured at 429 and 398 nm. The hemoglobin released was assayed according to the method of Raphael¹¹ as

$$\frac{\text{mg plasma hemoglobin released}}{100 \text{ mL plasma}} = \frac{\{A_{414} - (A_{429} + A_{398})\} \times 266}{2}$$

Table III Mechanical Properties of PU-PMMA IPNs

Samples	Ultimate Tensile Stress (MPa)	% Elongation at Break	Modulus at 100% Elongation
PU 1A	14.12	746	5.69
PU 4A	30.78	563	10.90
PU 1A-PMMA			
90/10	35.78	1188	5.10
80/20	17.16	784	2.45
70/30	23.53	693	2.75
50/50	38.14	866	4.90
PU 4A-PMMA			
90/10	40.59	593	13.14
80/20	47.84	682	13.16
70/30	36.87	603	15.29
50/50	42.55	448	14.51

RESULTS AND DISCUSSION

Synthesis

The prepolymer of the PU, network I, was formed first by condensation polymerization. After partial synthesis of the PU network took place, the polymerization of the second network of PMMA was initiated and this reaction was by addition polymerization. The polymerization of MMA was initiated at room temperature to avoid monomer loss at the higher temperature of curing. Because solubility parameters of PMMA (9.4 cal/mol K) is close to the solubility parameter of PU (10 cal/mol K), partial miscibility was expected. The synthesis of IPNs enhances mutual miscibility and very transparent IPNs were obtained by the above method of synthesis.

Solvent Resistance

The IPNs examined for changes in physical appearance did not show any discoloration, loss of gloss, or surface cracking. The percent weight loss obtained on contacting the IPNs with different solvents is given in Table II. The PU-PMMA IPNs are more solvent resistant, as less than 5 wt % loss was observed for these IPNs. The homopolymer PU, however, lost more weight in some of the solvents such as dioxan.

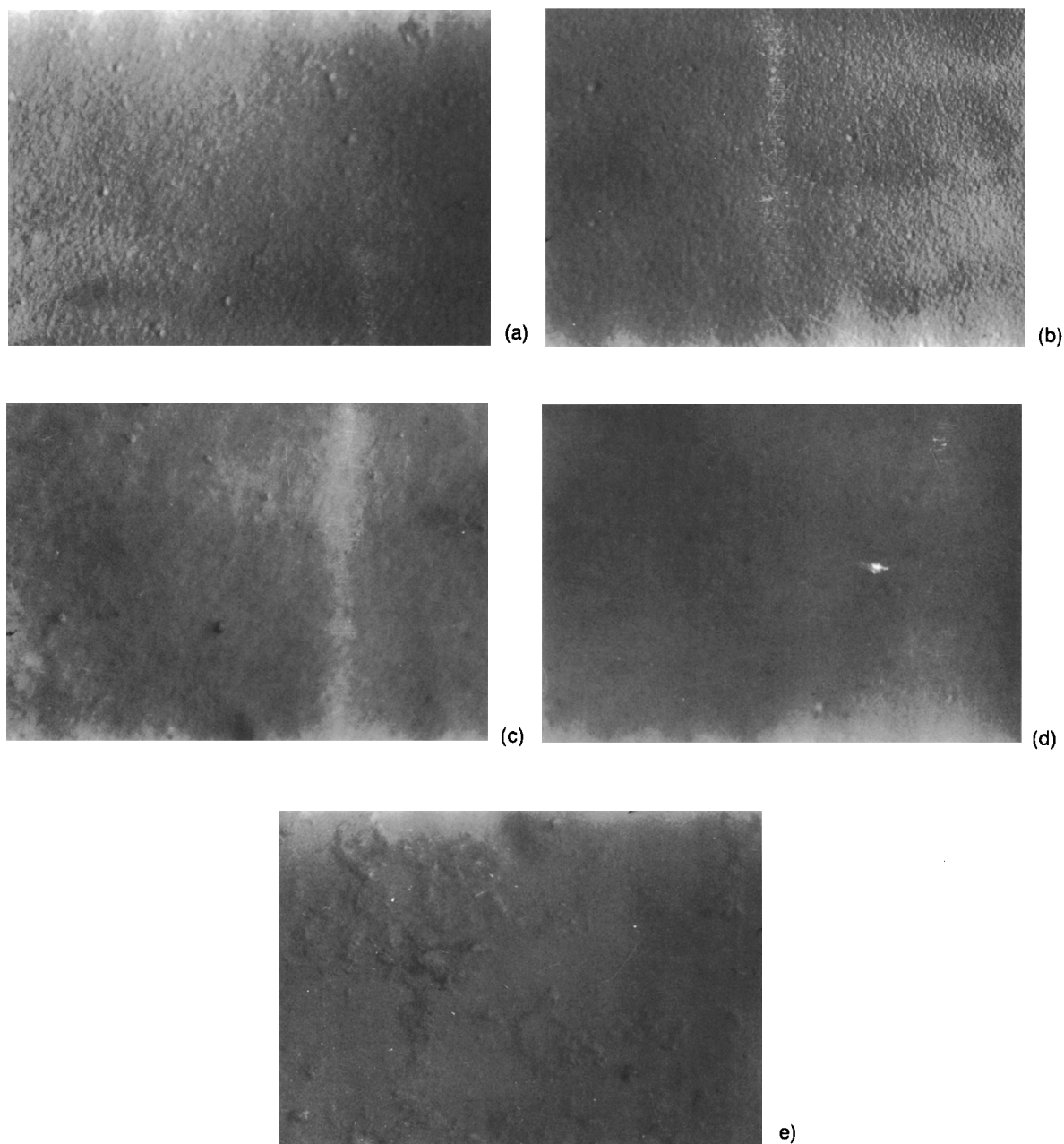


Figure 2 Optical micrographs of polyurethane and IPNs. (a) PU 4A, (b) PU 4A-PMMA 90/10, (c) PU 4A-PMMA 80/20, (d) PU 4A-PMMA 70/30, and (e) PU 4A-PMMA 50/50.

IR Spectra

The characteristic peaks of the PU namely 3300, 1724, 1538, 1600, 1227, and 1150–1160 cm^{-1} were observed in the spectra of the PUs PU 1A and PU 4A. The IPNs also showed the characteristic polyacrylate peaks such as 1730, 1260, 1234, 1190, 1149, and 746 cm^{-1} . The absence of any major spectral

differences in the PU and the IPN spectra (Fig. 1) indicated the absence of any interaction between the constituent networks.

Mechanical Properties

Table III summarizes the mechanical properties of PU 1A and PU 4A. As MDI is more symmetric than

Table IV Dynamic Mechanical Properties of PU-PMMA IPNs

Sample	Tan δ max		Storage Modulus
	$^{\circ}\text{C}$	Value	
PU 1A	-22	0.253	2.1
PU 4A	-24	0.24	1.75
PU 1A-PMMA			
90/10	0, 32	0.315, 0.294	2.9
70/30	7	0.49	4.7
50/50	4, 14	0.351, 0.37	3.2
PU 4A-PMMA			
90/10	15, 15	0.24	1.95

TDI, increased ordering of chains and increased tensile stress for the PU 4A was expected. Cross-linking reaction during biuret formation was also expected to be more efficient for the MDI structure due to its more symmetric nature. The increased tensile stress and modulus observed for the PU 4A and IPNs as well as the reduced elongation of PU 4A and IPNs in comparison to that of PU 1A and IPNs, can be attributed to the more efficient cross-linking of the MDI structure. When the composition of the PMMA was varied from 10 to 50 wt %, the individual IPNs showed maximum and minimum tensile stress. Addition of 10 wt % of vinyl monomer can produce IPNs with optimum mechanical properties. The increased tensile stress on IPN formation may be attributed to the enhanced interlocking of polymeric chains on IPN formation. Presence of heterogenous interfacial regions on IPN formation were reported by Lipatov¹² for PU IPNs. The random increase of tensile stress observed for the present PU-PMMA IPNs could be a contribution of such an interfacial region. Synergism of the tensile

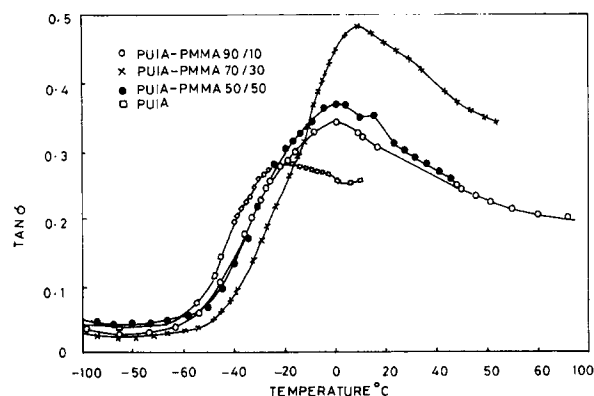


Figure 3 Effect of composition on $\tan \delta$ of TDI based PU 1A and PU 1A-PMMA IPNs.

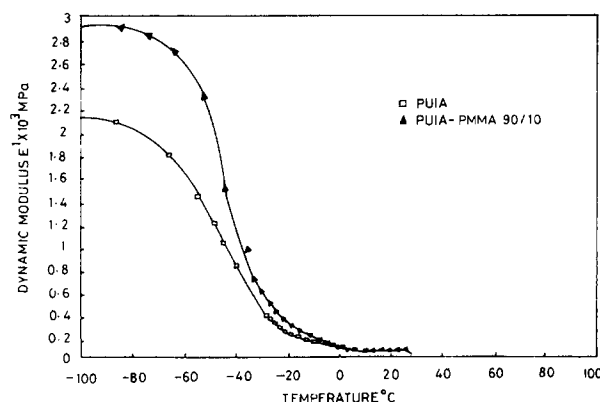


Figure 4 Dynamic modulus temperature plot of TDI based PU 1A and PU 1A-PMMA 90/10 IPN.

stress values occurred at all compositions of the PU-PMMA IPNs. The initial substantial increase in tensile stress was obtained on incorporating just 10 wt % of MMA. The increased tensile stress of the 50/50 composition could be influenced by phase inversion of the IPN with the PMMA becoming the cocontinuous phase. The optical micrographs [Fig. 2(a-d)] indicate the phase mixing for IPNs up to 70/30 composition. The phase inversion for the 50/50 composition with the PMMA becoming cocontinuous is also seen in Figure 2(e).

Dynamic Mechanical Properties

The dependence of the loss tangent on the temperature for the different IPN systems based on TDI, PU 1A, and IPNs is given in Table IV and Figure 3. In case of PU 1A, the loss factor exhibits a maximum at -22°C corresponding to the glass transition. In the PU 1A-PMMA IPNs, the location of

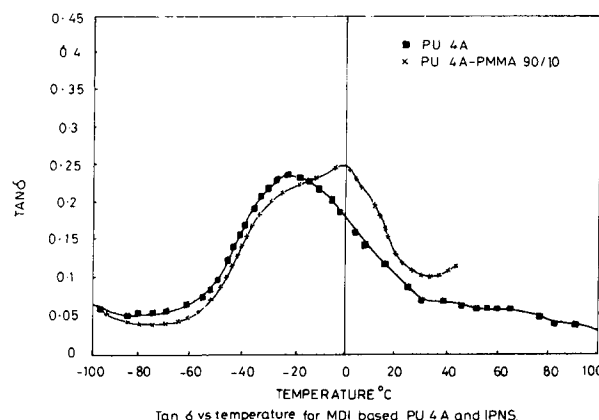


Figure 5 $\tan \delta$ temperature plot for MDI based PU 4A and PU 4A-PMMA 90/10 IPN.

this transition peak is shifted to higher temperatures indicating enhanced compatibility between the components of the IPNs. The glass transition temperatures (T_g) obtained do not strictly follow the random copolymer or Fox equation.¹³ The shift in T_g of the IPNs to higher temperature than the calculated T_g from the equation could be due to the increased hydrogen bonding in the IPN system. Such behavior of T_g departure was reported earlier¹⁴ for weakly phase segregated PUs. In the PU 1A-PMMA IPNs, the $\tan \delta$ max values of PU 1A increased on the IPN formation. However, increase of above 30 wt % PMMA resulted in a decrease of $\tan \delta$ max, confirming the earlier observed phase inversion.

Values of dynamic storage modulus E' fall in the temperature range of -70 to -20°C characteristic of glass to rubber transition. Figure 4 shows the broad temperature range over which the dynamic storage modulus decreases and that was attributed to increased degree of intermixing by Lee and Kim.¹⁵ The value of the dynamic modulus (Table IV) for the IPNs was higher than that of the PU. This trend could be due to an increase of packing density caused by enhancement of permanent chain entanglements. Such synergism of modulus was also evident in the polypropylene oxide-polystyrene IPNs.¹⁶ The drop in modulus value for the 50/50 composition could be a consequence of the phase inversion of PU-PMMA IPN.

The MDI based PU, PU 4A, has a $\tan \delta$ max at -24°C . Figure 5 shows that the $\tan \delta$ transition is shifted to the higher temperature in the PU 4A-PMMA IPNs, indicating enhanced compatibility between the components of the IPNs. Appreciable changes in $\tan \delta$ max are not observable in the PU 4A-PMMA IPN, probably due to structures with less interfacial material. The dynamic storage modulus E' values falling over a broader region of -80

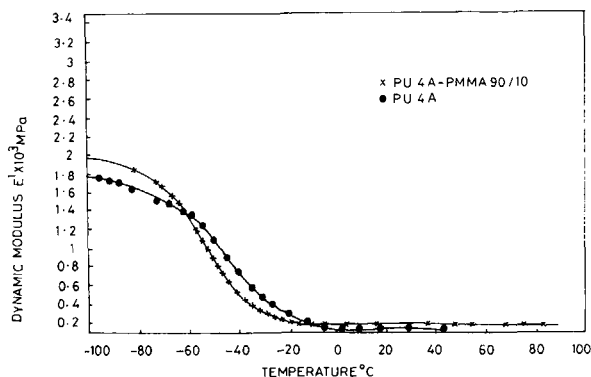


Figure 6 Dynamic modulus temperature plot of MDI based PU 4A and PU 4A-PMMA 90/10 IPN.

Table V Percent Hemolysis of Plasma in Contact with Polymers

Sample	% Hemolysis
PU 1A	2.0
PU 1A-PMMA 90/10	1.8
PU 4A	2.3
PU 4A-PMMA 90/10	2.0

to 10°C (Fig. 6), also indicate greater interpenetration in the PU 4A-PMMA IPNs. Greater interpenetration of MDI based IPNs is also borne out by the fact that in all cases the dynamic modulus values before the transition are higher than that for pure PU, PU 4A. The dynamic mechanical analysis studies therefore indicate that up to 30% PMMA can be interpenetrated with PU without substantial phase separation.

Hemolysis

This test was conducted mainly to see the effect of the materials on the RBCs. Damage to red cells as a result of exposure to foreign surfaces and rheological stresses were reported by Indeglia and Bernstein.¹⁷ Canine erythrocytes are reported¹⁸ to release several lipids from the cell membrane when a flowing suspension of cells is exposed to a foreign surface. The position of red cells in thrombosis is rather unclear. However, they can adhere to a surface and if hemolysis (or breaking up the red cells with the release of hemoglobin) occurs, erythrocyte ghosts are formed. Red cells also contain clot promoting factor (erythrocytin) and platelet aggregating substance (ADP) that becomes available by hemolysis. Attempted phagocytosis of the ghost by the platelet triggers the platelet release reaction¹⁹ leading into platelet adhesion and aggregation. The complex mechanisms of the red cell interaction with surfaces is poorly understood. However, Autian²⁰ reported that up to 5% hemolysis is permissible for a biomaterial. Table V gives the percent hemolysis values of plasma exposed to the TDI and MDI PUs and 90/10 IPNs. The values are nearly 2%, making the 90/10 IPNs suitable candidate materials for blood contacting applications.

CONCLUSIONS

IPNs of PU-PMMA can be synthesized with more compatibility. These IPNs are candidate biomaterials for blood contacting applications.

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