Hydrolytic Stabilities of Some Polyurethane Hydrogels

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SYNOPSIS

The hydrolytic stability of some polyurethane hydrogels derived from UV-curable urethane prepolymers and hydrophilic monomers was addressed. It was found that polyurethane hydrogels derived from prepolymers with hydrophilic polypropylene glycol soft segments were not stable when the films were cast from nonpolar solvent, whereas they are stable if the films were cast from neat monomer mix. The causes for this instability were analyzed. Spectroscopic and gel permeation chromatographic studies of the water extractables suggested that improper curing of hydrophilic monomers with the urethane prepolymers in nonpolar solvent was mainly responsible for the instability phenomenon.

INTRODUCTION

Polyurethanes have broad applicability because their properties can be tailored by variation of their components: the flexible polyol, short chain diol, and polyisocyanates. Urethane polymers are used extensively as foams, coatings, adhesives, elastomers, and fibers.[1] Polyurethanes are widely used as biomedical materials and rapid growth is expected as scientists and manufacturers are capable of tailoring the basic polyurethane products to suit their intended applications.[2]

Polyurethane hydrogels were claimed to have applications in the biomedical area. Blair and Hudgin disclosed the use of hydrophilic polyurethanes as a soft contact lens material.[3] Gould and Johnston reported the interpenetrating polymer networks of polyurethane and acrylates by polymerizing diacrylates in the presence of a hydrophilic polyurethane.[4-7] These systems formed hydrogels and were claimed to have applications as contact lenses,[5] surgical implants,[8] canulae,[9] and separation membranes.[10]

One of the most critical requirements for hydrogels to be useful as durable devices is their hydrolytic stability. Not all hydrogels are hydrolytically stable. Recently, in an evaluation of some polyurethane hydrogels for biomedical applications,[11] we found that some hydrogels were not hydrolytically stable. The causes for this phenomenon are described in this paper.

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EXPERIMENTAL

Preparations of Hydrogel Films

The synthesis of urethane prepolymer, INP4H, derived from isophorone diisocyanate, neopentyl glycol, poly(propylene glycol) of molecular weight 4000, and 2-hydroxyethyl methacrylate (HEMA) has been described elsewhere.[12] Homogeneous solutions containing INP4H, HEMA, or *N,N*-dimethyl acrylamide (DMA, from Aldrich), or glycerol methacrylate (GM, from Polysciences) neat, or in toluene, with 0.3% benzoin methyl ether were cast between two glass plates of 10 × 8 cm and cured under a long wave UV lamp (UVP Inc.) for 2 h. After being released, the films were extracted with methylene chloride (overnight), dried, extracted with boiling water for 4 h, and finally dried *in vacuo* overnight. In some cases, methacryloxypropyl tris(trimethysiloxy) silane (TRIS, from Silar) was included in the hydrogel composition for stability studies.

Hydrolytic Stability Testing

Twelve preweighed dry films were saturated with buffered saline (pH 7.4) and stored in sealed glass vials and then stored in an oven at 80°C. Three samples were removed after 3, 5, 7, and 14 days, respectively. They were washed with distilled water

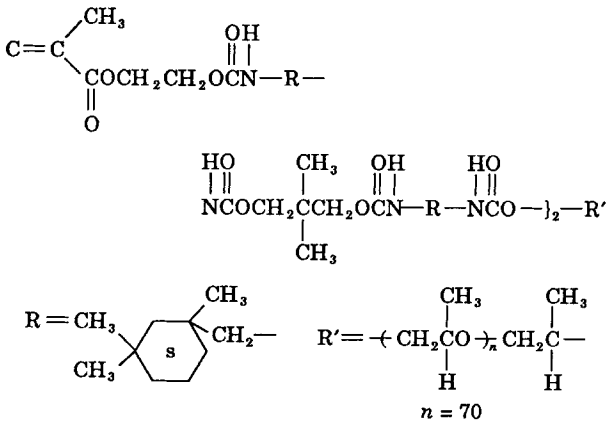
and dried at 80°C for 16 h. The percent weight losses of sample after different periods of testing were obtained by comparing the weight of dry sample before and after the testing.

Characterization of Water Extracts

The water extracts from the above-mentioned procedure were collected, concentrated, and analyzed by gel permeation chromatography (GPC, Waters Model 510) and Fourier transfer infrared spectroscopy (Analect, Model fx 6160). These same analyses were also performed on INP4H, poly(propylene glycol), and poly(HEMA).

RESULTS AND DISCUSSION

The urethane prepolymer, INP4H, used in this study has the structure:



Hydrolytic Stability Problem of Hydrogel Films of INP4H/HEMA Cast in Nonpolar Solvent

The hydrogel films derived from INP4H/HEMA in toluene (60/40/40 in weight ratio), which have a water content of 15%, were subjected to the standard hydrolytic stability testing. Significant weight loss (34.5%) was found after 14 days at 80°C in buffered saline (see Table I). These results suggested that the hydrogels are not stable to these hydrolytic conditions. The same stability problems were also observed for hydrogel films derived from other mixes in toluene containing the prepolymer INP4H, TRIS, and hydrophilic monomers such as DMA and GM. They were also hydrolytically unstable when additional short chain crosslinkers such as ethylene glycol dimethacrylate and pentaerythritol triacrylate were added to the monomer mix.

These observations were contrary to the stability of polyether-based polyurethane materials and cured poly(HEMA). Because methylene chloride and boiling water extractions of films were conducted before the hydrolytic stability tests, any hydrophilic monomer/linear polymer molecules not properly bound to the cured networks were removed.

To understand the source of the hydrolytic stability problems, the GPC traces of 3-day, 5-day, 7-day, and 14-day extractables from INP4H/HEMA (60/40) hydrogels were examined and compared closely to that of the prepolymer INP4H [see Table II and Figs. 1(A) and 1(B)]. Also, the FTIR spectrum of the 14-day extractables was compared against to those of HEMA, poly(HEMA), PPG-4000, and the prepolymer INP4H (see Table III).

As illustrated in Table II and Figure 1, the high molecular weight fractions (MW 3500–4300) of the water extractables matched closely the high molecular weight (4500) fraction of the starting prepolymer, INP4H, indicating incomplete curing of the prepolymer molecules and/or incomplete end-capping of prepolymer molecules with HEMA. Furthermore, the extraction of the high molecular weight portion decreased during hydrolysis relative to the low molecular weight fraction as shown in Table II. The low molecular weight portions of the water extractables have molecular weights (400–500) too low to result from the prepolymer, INP4H. On the contrary, it is more probable that they comprised oligomers of HEMA not associated with the cured urethane materials. A study of the characteristic peaks (Table III) of the FTIR spectrum of the 14-day extractables indicated that the extractables were more likely oligomeric molecules of HEMA.

Both GPC and FTIR studies strongly suggested that the formation of oligomers of HEMA, with mo-

Table I Hydrolytic Stability Testing of Hydrogel Films Derived from INP4H/HEMA (60/40) Cast in Toluene

	Original	3 Days	5 Days	7 Days	14 Days
Wt loss	—	13.9	20.3	24.6	34.5
% water	15.0	20.8	22.3	19.5	20.4

Table II GPC Data of Water Extractables for Hydrogel Films Derived from INP4H/HEMA (60/40) Cast in Toluene

Water Extract	High MW (M_n)	Low MW (M_n)	Weight Loss (%)	High MW : Low MW
3-day	3758	516	13.9	30 : 70
5-day	3547	360	20.3	20 : 80
7-day	4315	403	24.6	15 : 85
14-day	—[a]	395	34.3	—[a]
INP4H	4487	1251	—	—

[a] Very weak peak for 4000–5000.

lecular weight in the range of 400–500 (a trimer), was occurring. We postulate that these oligomeric molecules associated strongly with the polar fraction (the PPG portion) of the prepolymer. They remained tightly bound to the cured prepolymer during short term solvent and boiling water extractions, but were extracted out gradually during the longer term hydrolytic stability testing.

These results suggest that the hydrogel films do not effectively crosslink in nonpolar solvent such as toluene. Significant association of HEMA molecules occurred with the polar fractions of the urethane prepolymer, such as the hard segment and PPG fraction (75% of the total weight) of the urethane prepolymer, as well as to the less polar end-capping methacrylate fractions of the prepolymer. The use of nonpolar solvent, such as toluene, forced an even stronger association of HEMA with polar fraction of the prepolymer, possible through hydrogen bonding. Therefore, it can be envisioned that a portion of HEMA oligomerized around the polar fraction of the prepolymer molecules during the curing process,

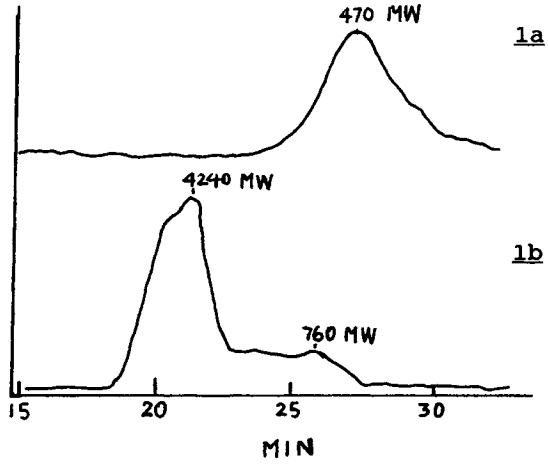


Figure 1 GPC traces of 14-day extractables (1a) from INP4H/HEMA (60/40) and INP4H (1b).

rather than randomly copolymerizing with the end-capping methacrylate groups. These arguments were further supported by the finding that comparable hydrogels were hydrolytically stable when they were prepared from urethane prepolymers with a nonpolar siloxane soft segment.[13] Separately a polyurethane specimen, cut from a commercially available polyether-based unfilled polyurethane rubber material, was subjected to the same test. It was found that the polyurethane rubber was hydrolytically stable, with weight loss less than 2%.

Hydrolytic Stabilities of Polyurethane Hydrogel Films Cast Neat

Similar hydrolytic stability testings were performed on hydrogel films derived from INP4H/HEMA, INP4H/TRIS/HEMA, INP4H/TRIS/HEMA with the addition of poly(ethylene glycol)-200 dimethacrylate, INP4H/DMA, INP4H/TRIS/DMA, and prepared without the presence of solvent. Because the weight loss during the 14-day tests was less than 2% in every case, these hydrogel films were hydrolytically stable. It was surmized that, without nonpolar solvents, the medium was sufficiently polar to allow for good mixing of all components such that true random copolymerization occurred during the curing process.

CONCLUSION

Polyurethane hydrogels derived from polyether-based urethane prepolymers and hydrophilic monomers have questionable hydrolytic stability if they are prepared in nonpolar solvent. This may be due to the strong association of the hydrophilic monomer with the polar portion of the urethane prepolymer in nonpolar solvent. The polyurethane hydrogels are hydrolytically stable if they are prepared in the absence of solvent.

Table III Characteristic Peaks of FTIR Spectra of INP4H, 14-Day Extract, Poly(HEMA), HEMA, and PPG-4000

IR Peak (cm^{-1})	Functional Group	INP4H	14-Day Extr.	Poly(HEMA)	HEMA	PPG-4000
3450	OH		x	x	x	x
3330	NH	x				
2990	CH_3	x	x	x	x	
2900	CH_3, CH_2	x	x			x
1720	C=O	x	x		x	
1640	C=C	x			x	
1530	Amide II	x				
1100	C—O—C	x	x	x	x	x

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