Water Structure in Poly(2-hydroxyethyl methacrylate): Effect of Molecular Weight of Poly(2-hydroxyethyl methacrylate) on Its Property Related to Water

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ABSTRACT: Low molecular weight poly(2-hydroxyethyl methacrylate) (polyHEMA) with a number average molecular weight (Mn) <22,600, were prepared by atom transfer radical polymerization. The molecular weight and end groups of the polyHEMA were varied, and the water content equilibrium moisture sorption and water structure were analyzed using differential scanning calorimetry (DSC) and X-ray diffractometry (XRD). Higher water content was observed for polyHEMA with Mn < 10,000. DSC revealed that the amounts of nonfreezing water are affected neither by the molecular weight nor by the end groups of the polyHEMA. On the other hand, the amount of freezing water was affected by both the molecular weight and end groups of polyHEMA, especially for polyHEMA with Mn < 20,000. The XRD-DSC measurements showed that water in polyHEMA form hexagonal ice and that the direction of crystal growth is dependent on the molecular weight. These findings indicate that the molecular weight of polyHEMA plays a significant role in the water structure in polyHEMA. © 2011 Wiley Periodicals, Inc. J Appl Polym Sci 125: 53–60, 2012

Key words: poly(2-hydroxyethyl methacrylate); atom transfer radical polymerization (ATRP); water structure; crystal structure; differential scanning calorimetry (DSC); X-ray diffraction (XRD)

INTRODUCTION

It is said that 2-hydroxyethyl methacrylate (HEMA)-based polymers have good biocompatibility. Indeed, there have been many attempts to apply these materials to various types of medical devices—soft contact lenses, intraocular lenses, matrix for controlled drug release, and so on. As for blood compatibility, there are many reports stating that HEMA-based block or graft copolymers show excellent performance, and that HEMA homopolymer (polyHEMA) does not show good compatibility with the complement and the coagulation systems.[1–5] As one of the mechanisms or reasons for excellent blood compatibility, the microphase separated surface structure was proposed, where the structure does not destroy the biomembrane structure of the blood cell. However, it was proved by Senshu et al.[6] that in such block copolymers the surface was covered with polyHEMA segments when the polymer was in a wet state. This fact raises a question: what is the difference between polyHEMA segments at the block-copolymer surface and polyHEMA at the homopolymer surface in terms of the blood compatibility? Recently, Fukuda et al.[7] attempted to explain this question on the basis of the results of surface-initiated polyHEMA, where they studied the relationship between the density and length of polyHEMA brush and protein adsorption. Their interpretation was that polyHEMA segments in block copolymers covered the surface like a polymer brush, resulting in the low adsorption of blood cells or proteins on the surface. There are several reports on the fouling of protein or the adhesion of cells onto surface-initiated polymer brushes including polyHEMA, and it is believed that the steric hindrance by the brush (higher density or molecular weight) plays an important role in determining the adhesion of proteins or cells onto the surface.[8,9] On the other hand, as a reason for the expression of blood compatibility, some researchers pointed out that water in the polymer plays an important role.[10–18] Thus, the mechanism for the blood compatibility of materials is still a controversial issue. From our previous studies on a wide range of polymers, we have proposed that the water structure in polymers plays an important role in determining the blood compatibility of the polymers, and there is no discrepancy when explaining the effects of the water structure on the blood compatibility.[19–22] If the differences in the

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earlier mentioned two polyHEMA surfaces can be explained by the differences in the water structure, then this will strongly support our hypothesis. To confirm this point, we have been investigating HEMA-based block copolymer. When HEMA-based block copolymers and homo-polyHEMAs used for evaluation as biomaterials are compared, the length of polyHEMA segment in the copolymers is small, less than 10,000 as molecular weight, whereas the molecular weight of the homopolymers is over several tens of thousands, up to several 100,000. Before further studies on the water structure of the HEMA-based block copolymer can be undertaken, the water structure in the low molecular weight polyHEMA should be clarified. PolyHEMA has been regarded as a water-swellable rather than water-soluble polymer.[23] However, recent research demonstrated that a low molecular weight polyHEMA prepared by atom transfer radical polymerization (ATRP) is water soluble or has a cloud point when the molecular weight is less than 8000.[24] This fact suggests that the intensity of the interaction between water molecules and polyHEMA molecules is affected by the molecular weight of polyHEMA. Thus, it will be interesting to investigate the effect of the molecular weight of polyHEMA on water structure and blood compatibility. In this work, we report the water structure in low molecular weight polyHEMA varied from 2500 to 22,500, and the effect of the end group introduced by the initiator on the water structure. PolyHEMA was prepared by ATRP and the water structure was analyzed by differential scanning calorimetry (DSC), and X-ray diffractometry (XRD)—DSC simultaneous measurement. As for the blood compatibility, we do not report because the polymer is water soluble or partially soluble resulting in a difficulty in measurement of blood compatibility.

By the way, in this study, the water structure was investigated in terms of the amounts of nonfreezing water, cold crystallizable water, and freezing water determined below 0°C. The properties of water thus studied do not correspond to those of the water involved in biological events or blood compatibility at 37°C. The water structure that we have claimed as the important factor involving in the blood compatibility is the state of water. The water structure is determined by the interactions between water molecules and the polymer and the mobility of water molecules. It is well-known that the strength of the interaction follows the order; nonfreezing water > bound water > free water, or when the mobility of water molecules is considered, the order is nonfreezing water < bound water < free water, where bound water and free water comprise freezing water. Thus, in this study, the state of water (interaction and mobility) is investigated by the property of water due to the phase transition.

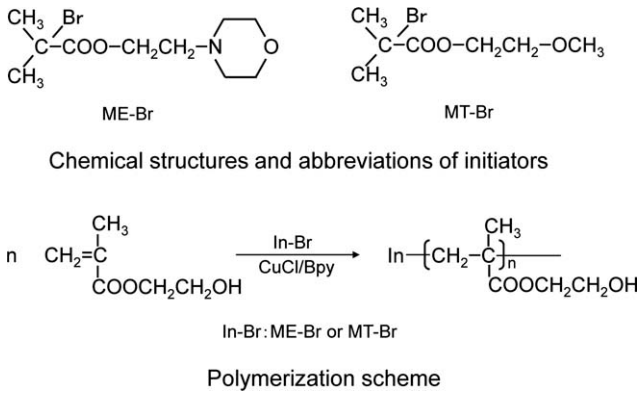

Figure 1 Chemical structure of ATRP initiators and preparation scheme of polyHEMA.

MATERIALS AND METHODS

Materials

HEMA was supplied by Cognis (Hythe, UK). Bipyridine, Cu(I)Br, triethylamine, and 2-methoxyethanol were purchased from Tokyo Kasei (Tokyo, Japan), and 4-(2-hydroxyethyl)morpholine and 2-bromoisobutyl bromide were obtained from Aldrich (St. Louis, MO). Methanol, diisopropylether, and tetrahydrofuran were supplied by Sigma-Aldrich Japan (Tokyo, Japan). Dry toluene was obtained from Wako Pure Chemicals (Tokyo, Japan). These reagents were used without further purification.

Synthesis of initiator and preparation of polyHEMA

The syntheses of the initiators for ATRP and the polymerization were carried out according to the method reported by Weaver et al.[24] Briefly, the methods are mentioned later. Two types of initiators shown in Figure 1 were synthesized by the stoichiometric reaction of 4-(2-hydroxyethyl)morpholine or 2-methoxyethanol with 2-bromoisobutyryl bromide in dry toluene in the presence of triethylamine as a scavenger. The reaction product (initiator) was purified by active carbon. The initiators thus obtained were abbreviated as ME-Br and MT-Br as shown in Figure 1, and were used for the ATRP of HEMA. The structures of the initiators were determined by NMR in $CDCl_3$ and their chemical shifts (δ) were as follows: ME-Br: $(CH_3)_2CBr$—: δ = 1.92 ppm (s), —$COOH_2$: δ = 4.31 ppm (t), —$COOCH_2CH_2N$—: 2.68 ppm (m), —$N(CH_2)_2$ (morpholine ring): 2.54 ppm(m), —CH_2OCH_2— (morpholine ring): 3.69 ppm (m). MT-Br: $(CH_3)_2CBr$—: 1.94 ppm (s), —$COOCH_2$—: 4.32 ppm (t), —$COOCH_2CH_2O$—: 3.62 ppm (t), and —OCH_3: 3.40 ppm (s). The polymerization of HEMA was carried out by adding a degassed methanol solution of the initiator and HEMA to a flask containing adequate amounts of bipyridine and Cu(I)Br under a nitrogen atmosphere at room temperature. After 16 h of the

reaction, the reaction solution was exposed to air. After the Cu catalyst in the reaction solution was removed by silica column, the colorless methanol solution thus obtained was evaporated, yielding a white crude polymer. The polymer was dissolved in a small amount of methanol and was precipitated in diisopropylether as a nonsolvent. The precipitations, repeated three times, gave pure polyHEMA. High molecular weight polyHEMA as a control was prepared in dimethylformamide (DMF) by using 2,2′-azobis(isobutyronitrile) (AIBN) as a radical initiator according to the reported method.[10] Thus, three types of polyHEMAs were prepared, and they were presented as the following abbreviations: ME-polyHEMA, MT-polyHEMA and AIBN-polyHEMA according to the abbreviations of the initiators used, ME-Br, MT-Br, and AIBN, respectively. In addition, polyHEMA prepared by ATRP was abbreviated as ATRP-polyHEMA.

Characterization of polymer

The polymerization degree or the number average molecular weight (Mn) of polyHEMA was determined by ^{1}H-NMR (Unity-Inova 400, Varian, Palo Alto, CA) in d_4-methanol. The degree was estimated from the ratio of the peak intensity of six azamethylene protons derived from ME-Br (at 2.5–2.7 ppm) or three methoxy protons derived from MT-Br (at 3.4 ppm) to two oxymethylene protons of a HEMA unit (at 4.3 ppm). The molecular weight of polyHEMA was also determined by gel permeation chromatography (GPC) after benzoylation of the polymer according to the method reported by Nakahama et al.[25] The GPC system used was composed of a pump (LC-6AD, Shimazu, Kyoto, Japan), a differential refractometer (IR-203a, JASCO, Tokyo, Japan) and two columns (Shodex LF-804, Showa Denko, Tokyo, Japan). The elution of the polymer sample by tetrahydrofuran was carried out under the following conditions: column temperature = 40°C and flow rate = 1.0 mL/min. The standard for molecular weight was polystyrene.

Hydrated polymer sample for DSC

Hydrated polyHEMA, which was in an equilibrium moisture sorption (EMS) state, was prepared as follows. The dry polymer, whose weight was W_d, was kept under saturated water vapor pressure at 25 ± 0.2°C, until the increase in the sample weight stopped, and then the weight was measured (W_h). It took 3 or 4 weeks to reach the equilibrium state. Thus, the water content of the sample under EMS (WCEMS) was determined by the following equation:

$$\text{WCEMS (wt \%)} = (W_h - W_d)/W_d \times 100. \quad (1)$$

Determination of water structure by DSC

Comparison of water structure in the polymers was carried out by using DSC (DSC Rigaku, Tokyo Japan), according to a previous report.[11] Briefly, the sample was first cooled to −80°C and then heated to 30°C at a rate of 2.5°C/min. The heating process was monitored. From the enthalpy change (ΔHm) in the melting of ice and WCEMS, the amounts of water in the polymer were determined according to the following equations:

$$\text{WCEMS (wt \%)} = W_{nf}(\text{wt \%}) + W_{fz}(\text{wt\%}) \quad (2)$$

$$W_{fz}\ (\text{wt \%}) = (\Delta Hm/334)/(W_d/W_h) \times 100 \quad (3)$$

$$W_{nf}\ (\text{wt \%}) = \text{WCEMS} - W_{fz} \quad (4)$$

where the weight percentages of these waters were based on the weight of dry polymer, and the subscripts, *nf* and *fz* stand for nonfreezing and freezing waters, respectively. In determining the water structure, the heat capacity in phase-transitions from ice to water assumed to be 334 J/g.[26] Freezing water was defined as water that freezes and forms ice crystal in the heating or cooling process in the range from −80 to 0°C. Nonfreezing water is water that does not crystallize even at −80°C.

Simultaneous XRD-DSC measurement

Simultaneous X-ray diffractometry (XRD)-DSC was carried out using an XRD-DSC II instrument (Rigaku, Tokyo, Japan). This instrument combines a heat-flux type DSC with an X-ray diffractometer based on the Rigaku RINT-ULTIMA+. A hydrated polymer was placed on an aluminum square-shaped container (8 mm × 8 mm) and was covered with 6-μm thick aluminum foil to prevent water evaporation. XRD and DSC were measured simultaneously during the heating process from −80 to 30°C at a heating rate of 2.5°C/min, where the XRD operating condition was as follows: X-ray source = Cu Kα, X-ray generation = voltage at 40kV, current 50 mA, 2θ range = 18–40°, and scanning rate of 2θ = 7.5°/min. During the heating process, the XRD measurements were carried out. Thus, the temperature rose by ca.7.5°C during one scan of XRD.[27] The intensities of crystalline peaks at 2θ = 23.0°, 24.4°, and 26.1° were compared as follows. The peak areas observed at each XRD scan in a temperature range from −60 to −20°C were summed and the total peak areas at 24.4° and 26.1° were normalized by the total peak area at the 23° peak.

RESULTS AND DISCUSSION

Characterization of polyHEMA

The characterization results of ATRP-polyHEMA are listed in Table I together with the results of

TABLE I
Characterization of PolyHEMA Prepared by ATRP

Polymer	NMR		GPC[a]		Solubility[b]
	Mn	Pn	Mn	Mw/Mn	
ME-polyHEMA	2500	19	3500	1.08	Soluble
	3300	25	5100	1.09	Soluble
	4200	32	5800	1.22	Soluble
	6100	47	8300	1.14	Partially soluble
	8200	63	10,000	1.23	Partially soluble
	9800	75	12,300	1.18	Partially soluble
	19,200	148	19,300	1.12	Partially soluble
	22,500	173	22,500	1.11	Partially soluble
MT-polyHEMA	2300	18	3600	1.09	Soluble
	5300	41	6200	1.18	Soluble
AIBN-polyHEMA	–	–	189,000	2.51	Nonsoluble

Pn, polymerization degree.
[a] GPC after benzoylation.
[b] Solubility to water at 4°C.

AIBN-polyHEMA. The relationship between the Mn determined by NMR and that by GPC is shown in Figure 2, where the Mn estimated by GPC is in reality the one for the benzoylated-polyHEMA. This figure shows that the Mn determined by GPC is close to that determined by NMR in the range of molecular weight investigated, from 2500 to 25,500. Weaver et al.[24] compared the Mn for unmodified polyHEMA by GPC (an elution solvent: DMF) with the Mn by NMR, and showed that the one by GPC was much higher (2–3 times) than that by NMR. These facts indicate that the benzoylation of polyHEMA is a good method in GPC analysis to estimate the real Mn of untreated polyHEMA. The polydispersities (Mw/Mn) of these benzoylated polyHEMAs are low (<1.2) (Table I). Thus, these characterization results indicate that the living polymerization of HEMA by ATR succeeded.

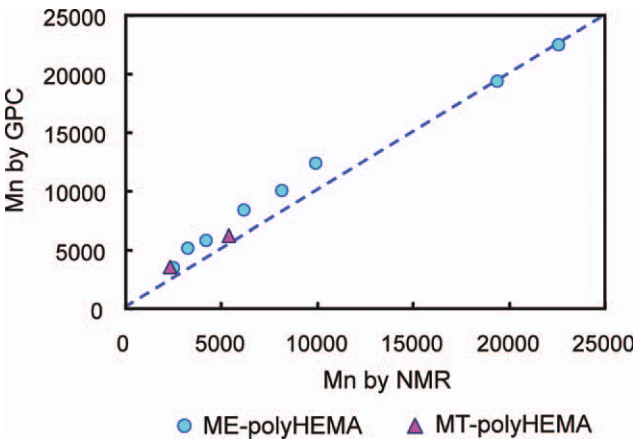

Figure 2 Comparison of molecular weights determined by NMR and GPC. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

Water content of polyHEMA

The determination of the capacity of polyHEMA to contain water molecules is important to investigate the effect of the molecular weight of polyHEMA on the water structure in it. However, it is difficult to determine an equilibrium water content (EWC) obtained by soaking the polyHEMA sample in water because the sample is water soluble or partially soluble, as mentioned earlier. Thus, the dependence of the moisture sorption capacity of polyHEMA presented by WCEM on the molecular weight was investigated. In the case of polyHEMA with Mn <10,000, the appearance of the polymer in EMS was that of a viscous liquid at 25°C. On the other hand, polymers with Mn ≥ 19,200 were in a solid, soft gel state. The results of WCEMS are shown in Figure 3. This figure shows that WCEMS sharply decreases from 100 wt % to 45 wt % with an increase in Mn from 2500 to 22,500. This value, 45 wt %, is close to the WCEMS for AIBN-polyHEMA (Mn = 189,000).

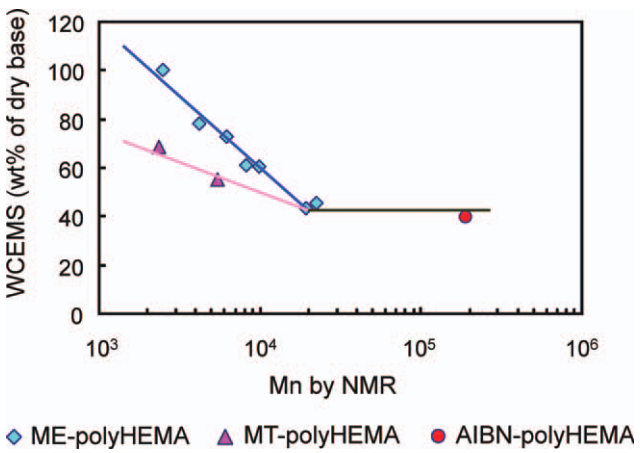

Figure 3 Dependence of WCEMS on molecular weight of polyHEMA. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

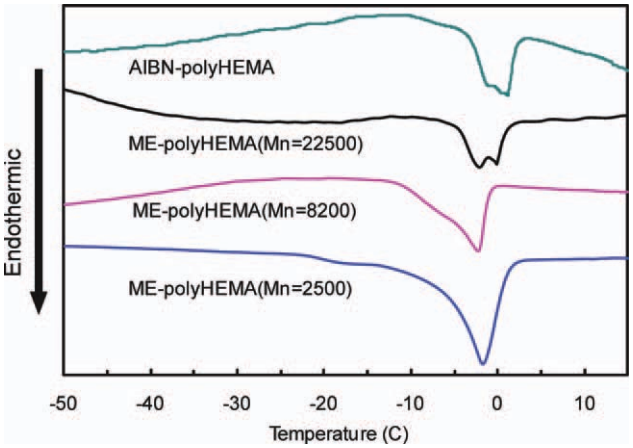

Figure 4 Representative DSC curves of polyHEMA with WCEMS ME-polyHEMA: Mn = 2500, 8200, and 22,500 (by NMR) ATRP-polyHEMA: Mn = 189,000 (by GPC), heating rate = 2.5°C/min. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

That is, when Mn exceeds ~20,000, WCEMS is predicted to be constant, regardless of Mn. The higher WCEMS observed for polymers with Mn of less than 22,500 can be explained by two points: one is an increase in the hydrophilicity of polyHEMA according to the decrease in molecular weight, and the other is the effect of the end group of ME-polyHEMA. Since ME-polyHEMA has a strong hydrophilic end group due to a morpholyl group, the contribution of this group to EWCMS may relatively increase according to the decrease in the Mn of polyHEMA. To clarify the dominant factor, we investigated MT-polyHEMA, having a methoxy group as an end group instead of a morpholyl group. As a methoxy group is less hydrophilic than a hydroxyl group, it will not additionally contribute to an increase in the WCEMS of MT-polyHEMA. The result of MT-polyHEMA is also shown in Figure 3, which shows that the WCEMS of MT-polyHEMA increases with a decrease in Mn and is smaller than that of ME-polyHEMA. When WCEMSs of ME- and MT-polyHEMAs with close Mn are compared, the values for the former are ~1.4 times larger than those for the latter. (e.g., the WCEMSs of ME- and MT-polyHEMA with Mn = 2500 and 2300, respectively, are 100.0 and 68.6 wt %, respectively.) Consequently, it is concluded that the molecular weight and end group of polyHEMA affect the WCEMS or hydrophilicity of polyHEMA when Mn is less than 22,500.

Water structure analyzed by DSC

As described earlier, the water content in polyHEMA is strongly affected by the molecular weight and the end group. To discuss it more quantitatively, the water structure in polyHEMAs in the state of EMS was analyzed by DSC. Representative DSC curves of ME-polyHEMA are shown in Figure 4 together with that of AIBN-polyHEMA, where Mn of ME-polyHEMA is 2500, 8200, and 22,500. From these curves it was found that there was no exothermic peak during the heating process, and there was only an endothermic peak with a significantly asymmetric shape. The former result indicates that the polyHEMAs investigated do not have cold-crystallizable water. Cold-crystallizable water is observed in poly(2-methooxyethyl acrylate) and is believed to play an important role in determining blood compatibility.[20] The latter result, the asymmetric shape of the fusion peak, suggests that freezing water is composed of at least two types of water. The peak areas at the lower temperature side and at the higher temperature side can be attributed to bound water and free water, respectively. Bound water means water molecules that are restricted by the interaction with the polymer. In relation to the asymmetric shape, the onset temperature of the fusion of ice gives important information on the strength of the interaction. Thus, the temperature is plotted against Mn together with the peak top temperature. (Fig. 5) The onset temperature rises from −18 to −9°C with an increase in Mn from 2500 to 22,500, though the temperature of the peak top does not change. The temperature for AIBN-polyHEMA is −8°C (datum not shown in Fig. 5). In addition, this figure shows that the onset temperatures of ME-polyHEMA and MT-polyHEMA are on the same line. These facts indicate that the change of the onset temperature is not caused by the end group but by the molecular weight of polyHEMA. Thus, it is concluded that the interaction of water molecules (bound water) with polyHEMA strengthens or the amount of bound water in polyHEMA increases with a decrease in Mn.

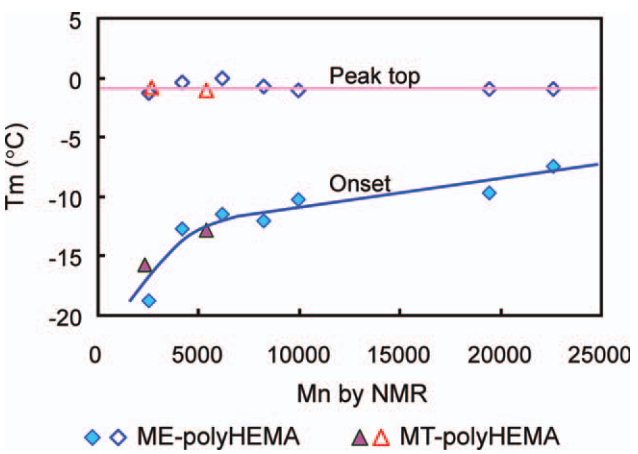

Figure 5 Dependence of fusion temperature of ice on molecular weight of polyHEMA with WCEMS. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

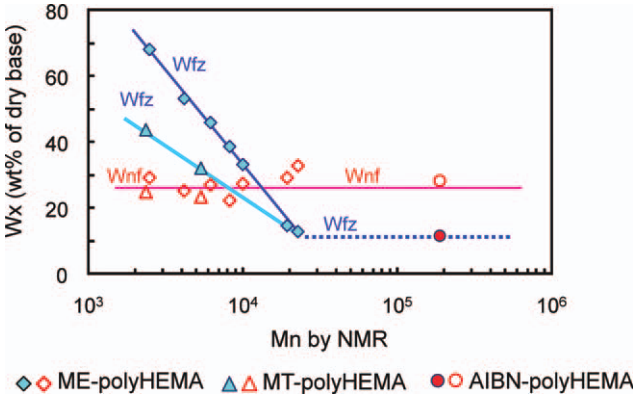

Figure 6 Relationship between water structure and molecular weight of polyHEMA with WCEMS ME-polyHEMA; Mn by NMR, AIBN-polyHEMA: Mn determined by GPC. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

On the basis of the enthalpy change in the endothermic peak in the DSC curve, we can determine the amounts of nonfreezing water and freezing water in the polymer according to equations (3) and (4). The amounts of these waters in ATRP-polyHEMA are shown in Figure 6 together with the result of AIBN-polyHEMA. As for nonfreezing water in ME-polyHEMA, Figure 6 shows that W_{nf} is in the range of 26.3 ± 3.1 wt %, and is very close to the value for AIBN-polyHEMA, 28.1 wt %, indicating that W_{nf} in polyHEMA is not affected by Mn in a wide range. Figure 6 also shows that W_{nf} in MT-polyHEMAs is on the same line as that of ME-polyHEMA. This fact suggests that the end group does not affect W_{nf}. The reason is explained as follows. W_{nf} corresponds to the number of water molecules strongly bound to HEMA units and end group in polyHEMA. The amount of the former is determined by multiplying the polymerization degree (Pn) of polyHEMA and the hydration number per HEMA unit. Thus, the number of water molecules in polyHEMA is very large compared to the number based on the end group, resulting in the fact that the effect of the end group on W_{nf} is negligible. On the basis of W_{nf}, 26.3%, the hydration number of HEMA unit is calculated to be 1.89. These values seem to be reasonable for nonfreezing water. As for freezing water, Figure 6 shows that the W_{fz} in ME-polyHEMA decreases from 68 to 12.3 wt % simply by an increase in Mn from 2500 to 22,500, and that the value will get to be close to the one for AIBN-polyHEMA, 11.3 wt %. In the case of MT-polyHEMA, the W_{fz} is smaller than that in ME-polyHEMA, and also decreases from 43.7 wt %, tending to converge to 11 wt %. These facts indicate that W_{fz} is affected by the Mn of polyHEMA and the end group when Mn is less than 22,500.

Consequently, these findings reveal that the increase in the WCEMS of polyHEMA due to the decrease in Mn is caused by the increase in W_{fz}, not in W_{nf}, and that polyHEMAs with Mn of more than ~20,000 have the same water structure in terms of freezing and nonfreezing waters regardless of molecular weight or type of end group.

Water structure analyzed by DSC-XRD simultaneous measurement

In the DSC study, the available information about water structure is based on the enthalpy change from ice to water. In analyzing water structure, we sometimes come across cases where an endothermic peak or an exothermic peak in a DSC curve is very broad, and may misunderstand it as the drift of a base line. To avoid such misunderstanding, crystallographic analysis together with DSC is very worthwhile. Recently, we reported the water structure in AIBN-polyHEMA (Mn = 189,000) with the EWC observed by XRD-DSC simultaneous measurement.[27] In the article, it was shown that three clear peaks due to the hexagonal ice were almost unchanged during the heating process from −80 to 0°C and disappeared with the appearance of the DSC endothermic peak. Thus, DSC-XRD simultaneous measurement has the potential to give additional information to analyze the water structure in a polymer, and was applied to ME-polyHEMA with WCEMS. The representative figure obtained by the simultaneous measurement is shown in Figure 7, where the Mn of ME-polyHEMA were 3300 and 6100. The ME-polyHEMA investigated had Mn of 3300, 6100, 8200, and 9800. The XRD spectra for the polymers with Mn = 6100, 8200, and 9800 show similar crystalline peak patterns; three peaks are observed at 2θ = 23.0, 24.4, and 26.1°. The one with Mn 3300 shows only two peaks at 23.0 and 26.1°. In the XRD-DSC simultaneous measurement, these XRD peaks disappeared with the appearance of an endothermic peak in the DSC curve at the temperature range from −15 to 3°C. (DSC data are not shown) These results indicate that freezing water in polyHEMA forms hexagonal ice. In addition, XRD spectra show that the intensity of each crystalline peak in each sample is almost unchanged during heating. Thus, it is concluded that the polyHEMAs investigated have no cold crystallizable water. In other words, the water in these polyHEMA is composed of nonfreezing water and freezing water. When the XRD spectra are compared, it is found that the intensity of the (002) peak increases with an increase in Mn, while that of the (011) peak was almost constant, as shown in Figure 8. The (002) peak is related to the growth of crystals in the longitudinal direction. Thus, it is suggested that in lower-molecular-weight polyHEMA the crystal growth in the direction of the z-axis is

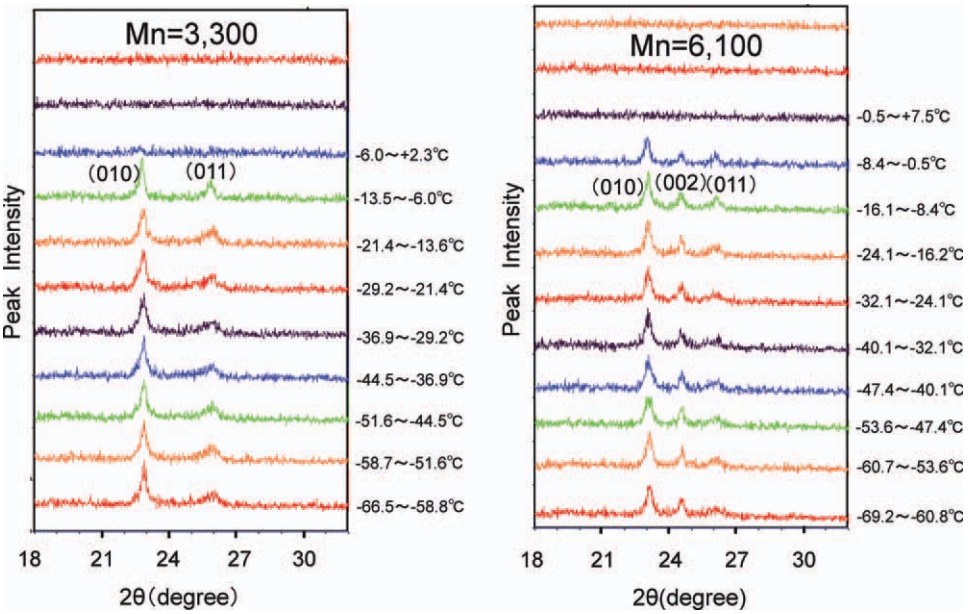

Figure 7 Representative XRD spectra obtained by XRD-DSC simultaneous measurement. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

depressed when compared with growth in the planar direction. The reason is not clear.

CONCLUSIONS

Low molecular weight polyHEMAs were prepared by ATRP, the molecular weight (Mn) of which varied from 2500 to 22,500. The effects of Mn and the end group of polyHEMA on its property were investigated in terms of the water content and water structure. PolyHEMA with larger Mn had lower water content and the onset temperature of the fusion of ice decreased with an increase in Mn. These facts indicated that the interaction between water and polyHEMA was strengthened with a decrease in Mn. As for nonfreezing water, the amount was independent of Mn and the end group, and kept a constant value (26.3 wt %). The amount of freezing water in polyHEMA decreased simply to 12.3 wt % with an increase in Mn from 2500 to 22,500, and the value was close to the one for AIBN-polyHEMA, 11.3 wt %. In addition, the amount was affected by the end group. These results showed that the increase in the water content of polyHEMA due to the decrease in Mn was caused by the increase in the amount of freezing water, and that polyHEMAs with Mn of more than ~20,000 had the same water structure in terms of freezing and nonfreezing water. XRD-DSC simultaneous measurement showed that freezing water formed hexagonal ice and that the direction of crystal growth was affected by Mn. These findings lead to the conclusion that the molecular weight of polyHEMA affects the formation of water structure significantly, and that the end group also does.

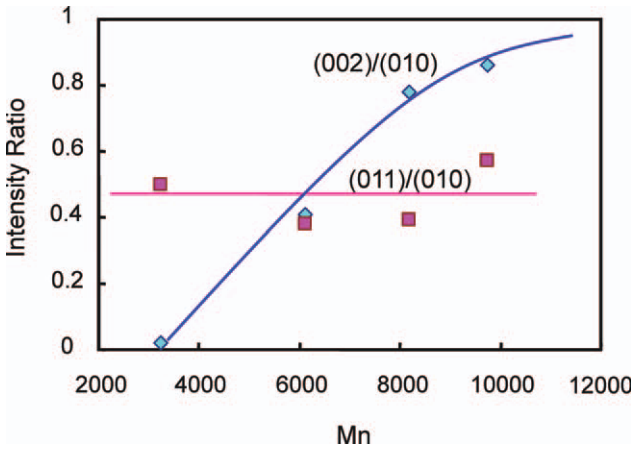

Figure 8 Relationship between XRD peak intensity and Mn of polyHEMA with WCEMS intensity of peaks (002) and (011) based on hexagonal ice was normalized by (010) peak ($2\theta = 23.0°$). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

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References

1. Okano, T.; Nishiyama, S.; Shinohara, I.; Akaike, T.; Sakurai, Y.; Kataoka, K.; Tsuruta, T.; Kuwana, K.; Miyata, S. Artif Organs 1979, 3(Suppl), 253.
2. Okano, T.; Nishiyama, S.; Shinohara, I.; Akaike, T.; Sakurai, Y.; Kataoka, K.; Tsuruta, T. Biomed J Mater Res 1981, 15, 393.
3. Okano, T.; Uruno, M.; Sugiyama, N.; Shimoda, M.; Shinohara, I.; Kataoka, K.; Sakurai, Y. J Biomed Mater Res 1986, 20, 1035.
4. Kataoka, K.; Ito, H.; Amano, H.;; Nagasaki, Y.; Kato, M; Tsuruta, T; Suzuki, K; Okano, T; Sakurai, Y. J Biomater Sci Polym Ed 1998, 9, 111.

5. Nakashima, T.; Takakura, K. J Biomed Mater Res 1977, 11, 787.
6. Senshu, K.; Yamashita, S.; Ito, M.; Hirano, A.; Nakahama, S. Langmuir 1995, 11, 2293.
7. Yoshikawa, C.; Goto, A.; Tsujii, Y.; Fukuda, T.; Kimura, T.; Yamamoto, K.; Koshida, A. Macromolecules 2006, 39, 2284.
8. Mei, Y.; Wu, T.; Xu, C.; Langenbach, K. J.;; Elliot, J T; Vogt, B D; Beers, K L; Amis, E J; Washburn, N. R. Langumuir 2005, 21, 12309.
9. Tsukagoshi, T.; Kondo, Y.; Yoshino, N. Colloids Surf B 2007, 54, 101.
10. Morra, M. Water in Biomaterial Surface Science; Wiley: New York, 2001.
11. Vogler, E. A. J Biomater Sci Polym Ed 1999, 10, 1015.
12. Kitano, H.; Ichikawa, K.; Fukuda, M.; Mochizuki, A.; Tanaka, M. J Colloid Surface Sci 2001, 242, 133.
13. Ichikawa, K.; Mori, T.; Kitano, H.; Fukuda, M.; Mochizuki, A.; Tanaka, M. J Polym Sci B Polym Phys 2001, 39, 2175.
14. Ide, M.; Mori, T.; Ichikawa, K.; Kitano, H.; Tanaka, M.; Mochizuki, A.; Oshiyama, H.; Mizuno, W. Langmuir 2003, 19, 429.
15. Bajpai, A. K.; Shrivastava, M. J Biomater Sci Polym Ed 2002, 13, 237.
16. Andrade, J. D.; Lee, H. B.; Jhon, M. S. W. Kim, S. Hibbs, J. B. Trans Am Soc Intern Organs 1973, 19, 1.
17. Gracia, C.; Anderson, J. M.; Bareneberg, S. A. Trans Am Soc Intern Organs 1980, 26, 294.
18. Volger, E. A. In An Introduction to Materials in Medicine—Biomaterials Science, 2nd ed.; Ratner, B. D.; Hoffman, A. S.; Schoen, F. J.; Lemons, J. E., Eds.; Academic Press: New York, 2004; Chapter 1.
19. Tanaka, M.; Motomura, T.; Kawada, M.; Anzai, T.; Kasori, Y.; Shiroya, T.; Shimura, K.; Onishi, M.; Mochizuki, A. Biomaterials 2000, 21, 1471.
20. Tanaka, M.; Mochizuki, A. J Biomed Mater Res A 2004, 68A, 684.
21. Hirota, E.; Ute, K.; Uehara, M.; Kitayama, T.; Tanaka, M.; Mochizuki, A. J Biomed Mater Res A 2006, 76A, 540.
22. Hirota, E.; Tanaka, M.; Mochizuki, A. J Biomed Mater Res A 2007, 81A, 710.
23. Montheard, J. P.; Kahovec, J.; Chappard, D. Desk Reference of Functional Polymer: Synthesis and Application, Arshady, R., Ed.; American Chemical Society: Washington DC, 1997; Chapter 5.3.
24. Weaver, J. V.; Bannister, I., Robinson, K. L.; Bories-Azeau, A.; Armes, S. P.; Smallridge, M.; McKenna, P. Macromolecules 2004, 37, 2395.
25. Hirao, A.; Kato, H.; Yamaguchi, K.; Nakahama, S.; Macromolecules 1986, 19, 1294.
26. Wolfgang, G. G.; Hatakeyama, T.; Viscoelasticity of Biomaterials, ACS Symposium Series 489, American Chemical Society, Washington DC, 1992.
27. Kishi, A.; Tanaka, M.; Mochizuki, A. J Appl Polym Sci 2008, 111, 476.