Polycondensation of hydroxyl-group containing aliphatic diamines and dibromides yielding highly branched poly(2-hydroxypropylene imines)

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Highly branched poly(2-hydroxypropylene imines) (PHPI) were synthesized by polycondensation of 1,3-diamino-2-propanol and 1,3-dibromo-2-propanol in several polar protic and aprotic solvents.

Kinetics of polycondensation was studied using solution calorimetry and conductometric titration, and PHPI were characterized by SEC, ^{1}H and ^{13}C NMR spectroscopy, and DSC. PHPI with the highest degree of branching were synthesized in DMF, while those with the lowest degree in methanol. Independent of the degree of branching, PHPI were not crosslinked and well soluble in aqueous solutions. Presumptive mechanism of branching during polycondensation of aliphatic diamines and dibromides in polar protic and aprotic solvents is presented.

Key words: poly(2-hydroxypropylene imine), polycondensation, aliphatic diamines, aliphatic dibromides, branching

INTRODUCTION

Polycondensation is one of the most widespread techniques used for the synthesis of polymers. Large potential of this method is predetermined by both impressive variety of the suitable monomers and a wide range of the chemical reactions leading to the formation of macromolecules. The method seems to be very simple and allows obtaining various polymeric structures through the reactions of functional groups present in monomers and oligomers. During polycondensation, the main reaction of the chain propagation implies the interaction of two functional groups which belong to the same or different molecules, monomeric or oligomeric [1–5]. Usually, linear polymers are obtained from bifunctional monomers, and branched or crosslinked polymers are obtained when at least one of the monomers has functionality higher than two [6, 7]. Furthermore, topological structure of the polycondensation polymers is predetermined not only by functionality of the initial monomers but also by molar ratio of the reactive groups and extent of the reaction [8–10].

Polycondensation of alkylene (arylene) diamines with dihaloalkanes gained much less attention than polycondensation of diamines with dicarboxylic acids or their anhydrides [11, 12]. To be more specific, polycondensation of tertiary diamines and dihaloalkanes yielding polymers containing quaternary ammonium groups in the backbone (so-called ionenes) was studied thoroughly, including kinetics, mechanism and structure [13]. In contrast, publications devoted to polycondensation of primary diamines with dihaloalkanes are scarce. Nevertheless, this field deserves attention since the products of such polycondensation polyimines possess some specific attractive properties.

Usually, when one of the monomers is di- or polyamine, several reactions compete during polycondensation, which results in a relatively low reaction extent and branched or even crosslinked products. Moreover, in some cases cyclic and macrocyclic products are obtained instead of linear high-molecular polymers [3, 6]. Nevertheless, an interest in polycondensation of diamines with dihaloalkanes is increased during the last years, mostly because of high interest in linear and branched polyimines [14].

Linear high-molecular polyamines have been synthesized by polycondensation of 1,2-dihaloethanes and ammonia [15]. It was shown that polycondensation of 1,2-diiodoethane with ammonia was much faster and gave polyamines with higher molecular weight compared to polycondensation of 1,2-dibromoethane under the same conditions [16]. The reaction products contained not only high-molecular polyamines but also low-molecular compounds like diethylene triamine, triethylene tetramine, etc. [16]. Polycondensation of 1,2-diaminoethane with p-dichloromethyl benzene at various molar ratios of the monomers at room temperature gave insoluble

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(crosslinked) polymer [17]. Polycondensation of dihaloalkanes (of 1 to 4 C atoms) with diamines (of 4 to 15 C atoms) at some excess of the latter resulted in linear or branched polymers with little or no cyclic compounds. Unfortunately, structure and molecular characteristics of such polymers were not studied thoroughly [18].

In some cases, interaction of low-molecular aliphatic diamines with dihaloalkanes tends to formation of cyclic low-molecular products rather than polymers. For instance, condensation of 1,2-diaminoethane with 1,2-dichloroethane or 2,2'-dichloroethyl ether in acetonitrile resulted in low-molecular cyclic products like piperazine and 2-ethylamino morpholine only [17, 19]. It was determined that diamines containing less than 4 C atoms between the amine groups produce cyclic compounds [18]. The tendency to cyclization was explained by the entropic factor [17]. Direct coupling between diamines and bis(bromomethyl) compounds containing benzene, pyridine or aliphatic moieties under especial conditions gave macrocyclic insoluble products [20]. Contrarily, formation of cyclic products during polycondensation of aryl dihalides and diamines is negligible [17] which is associated with the steric effect of the aryl groups.

Recently, poly(hydroxyalkyleneimines) were synthesised reacting aliphatic bis(2-hydroxy-3-chloropropyl)alkylamines with 1,2-ethylenediamine, *N,N'*-dimethylethylenediamine or *N,N,N',N'*-tetramethylethylenediamine [21]. When the reaction took place in alcohol / water, it afforded a mixture that contained the desired linear product, some oligomers, and unreacted monomers. The weight-average molecular weight of the products was about 2 kDa, and the polydispersity index 1.31–1.69. When the reaction was carried out without a solvent and at higher temperature, the molecular weight of the products was higher (4.3–7.2 kDa) [22]. The polymers of a similar structure were synthesized by L. Zaliauskiene, U. Bernadisiute and co-workers [14, 23]. The poly(hydroxyalkylene imines) were obtained by polycondensation of 1,3-diamino-2-propanol and various dihaloalkanes such as 1,2-dibromoethane, 1,3-dibromoethane or 1,3-dibromo-2-propanol. Unfortunately, polycondensation was done in methanol only which likely restricted possibilities to get a larger fraction of poly(hydroxyalkylene imines) with higher molecular weight. Moreover, the structure of such polymers was not studied thoroughly which led to the conclusion that poly(hydroxyalkylene imines) were linear polymers. Besides, this was in contradiction with a very compact structure of macromolecular coils.

In the present study, we examined polycondensation of 1,3-diamine-2-propanol with 1,3-dibromo-2-propanol in various polar solvents with the aim to synthesize poly(2-hydroxypropylene imines) with medium to high molecular weight. Simultaneously, an attempt was made to elucidate the mechanism of polycondensation of aliphatic diamines and dibromides, and ascertain possibilities to control branching of the desired poly(2-hydroxypropylene imines).

EXPERIMENTAL

Materials
1,3-Diamino-2-propanol (DAP, 98%), 1,3-dibromo-2-propanol (DBP, 95%) and *N,N*-dimethylacetamide (DMAC, 99%) were purchased from Sigma-Aldrich. *N,N*-dimethylformamide (DMF, 99.8%), methanol (MeOH, 99.5%) and 2-propanol (IPOH, 99.7%) were obtained from Reachem Slovakia. Prior to use, all solvents were purified according to standard procedures and stored over molecular sieves (3Å). Other reagents used were of analytical grade.

Synthesis of poly(2-hydroxypropylene imine) (PHPI)
DAP 1.49 g (16.6 mmol) and DMAC 8.1 mL were placed in a 25 ml capacity round-bottom reaction flask submerged in an oil bath. Under moderate stirring, the reaction mixture was slowly preheated to 80 °C. Then, under vigorous stirring, DBP (3.62 g, 16.6 mmol) was added dropwise to the reaction mixture, and the polycondensation was carried out for 168 hours. The resulting solution was diluted with 0.15 M NaCl solution (100 mL) and ultrafiltrated through a Pellicon membrane (Millipore) with nominal cut-off 10 kDa against water. PHPI as a solid polymer was isolated by freeze-drying. Yield 0.99 g (19.5%).

The same procedures were employed when carrying out the synthesis of PHPI in DMF, MeOH, ISP and H_2O (total concentration of the monomers 40%) except that the reaction in methanol was conducted at 60 °C.

Spectroscopic measurements
FT-IR spectra were recorded with a PERKIN-ELMER Frontier spectrometer using Universal ATR Sampling Accessory. ^1H and ^{13}C-NMR spectra were recorded on a Brucker 400 Ascend™ 400 MHz spectrometer in D_2O at 29 °C. In order to record NMR spectra of fully deprotonated samples, pH of the sample solutions in D_2O was adjusted to 12–13 by adding few drops of 40% NaOD in D_2O. Chemical shifts were referenced to the signal of water (4.68 ppm for neutral and 4.74 ppm for alkaline solutions, respectively). To avoid any influence of the Nuclear Overhauser Effect (NOE), ^{13}C NMR spectra used for quantitative analysis were recorded using inverse gated decoupling pulse sequences [24]. In this case, the weight of a polymer sample was approx. 100 mg, and the number of scans approx. 6 000. Ratio of different amino groups present in the polymer was calculated from the intensities of the signals at 42 ppm (A_1), 52 ppm (A_2), and 59 ppm (A_3) attributed to the carbons next to primary, secondary and tertiary amino groups, respectively. Amount of primary, secondary and tertiary amino groups (N_1, N_2 and N_3, respectively, mol%) was calculated using the following equation:

$$A_1 + \frac{A_3}{2} + \frac{A_2}{3} = Z \qquad N_1 = \frac{A_1}{Z} \cdot 100$$

$$N_2 = \frac{A_2}{2 \cdot Z} \cdot 100 \qquad N_3 = \frac{A_3}{3 \cdot Z} \cdot 100$$

$$ER = \frac{Br^-}{51.88} \cdot 100,$$

Size exclusion chromatography

Molecular weight and molecular weight distribution (MWD) of PHPI were determined by size exclusion chromatography (SEC) using a Viscotek TDAmax system equipped with a triple-detection array (TDA305) and a column A6000M, 300 × 8.0 mm, General mixed for aqueous solutions. The polymers were dissolved in aqueous 250 mM CH_3COONa, pH 4 (5 mg/mL), and eluted with the same buffer at a flow rate of 0.5 mL/min. SEC measurements were performed at 35 °C. The refractive index increment dn/dc of PHPI was determined using a Differential refractometer Waters 410, and was equal to 0.1858 mg/mL. OmniSEC software from Viscotek was used to collect and analyse the data.

Differential scanning calorimetry

Glass transition temperature (T_g) of the polymers was determined using a differential scanning calorimeter DSC 8000 (Perkin Elmer). Before analysis, the samples were dried at room temperature in 8 mbar vacuum for 2 hours. DSC analyses were done under nitrogen gas (flow rate 40 mL min^{-1}). During the DSC measurements, a sample in a closed aluminium DSC pan was heated from room temperature to 120 °C at a heating rate 10 °C/min, then cooled to –50 °C at a cooling rate 30 °C/min, and then heated again to 120 °C at a heating rate 10 °C/min. T_g values were determined from the second heating scan curves.

Determination of bromide content and calculation of the extent of reaction

Bromide content was determined by conductometric titration using a conductometer FiveEasy™FE30 (Mettler Toledo). A small amount of the reaction mixture was withdrawn from the reaction flask and vacuum-dried. 0.02 g of a dry (solvent-free) sample was dissolved in 40 ml of water, and, after correction of pH, the solution was titrated with 0.1 M $AgNO_3$. Titration end point was determined graphically from the plot "conductance versus volume of the titrant".

The content of Br^- (%) in the dried reaction mixture was calculated as follows:

$$Br^- = \frac{79.9 \cdot c \cdot v}{m} \cdot 100,$$

where 79.9 is the molecular weight of bromine (g/mol), c is the molar concentration of $AgNO_3$, V is the volume (ml) of $AgNO_3$ solution, and m is the weight of the sample (g). The extent of the reaction (ER, mol%) was calculated as follows:

where 51.88 is the theoretical (maximal) content (%) of bromide in PHPI at the extent of the reaction 100 mol%.

Calorimetric measurements

The reaction between aliphatic DAP and DBP was monitored by the use of a reaction calorimeter SuperCRC 208–110 under isothermal mixing. The sample vessel containing 0.15 g of DAP, dissolved in an appropriate amount of a solvent, and the reference vessel containing the same amount of the solvent were placed into the calorimeter. A syringe containing 0.17 mL DBP was placed in the sample injection port and kept until thermal equilibrium at 80 °C was reached. The reaction was initiated injecting DBP. The total concentration of the monomers was 40%. The heat flow data were accumulated during 24 hours. Polycondensation reaction was stopped by addition of few drops of 5% HNO_3 into the sample vessel. In order to convert calorimetric data to the extent of the reaction, the reaction mixture dried under vacuum for 24 hours at room temperature was dissolved in water and, after correction, titrated with 0.1 M $AgNO_3$.

The same calorimetric measurements were employed when carrying out the synthesis of PHPI in all the solvents (DMAC, DMF, MeOH, ISP and H_2O) except that the reaction in methanol was conducted at 60 °C.

RESULTS AND DISCUSSIONS

Polycondensation of 1,3-diamino-2-propanol and 1,3-dibromo-2-propanol in various solvents

Polycondensation is classified as a step-growth polymerization, in which molecular weight of the polymer is depending on the reaction extent, and the polydispersity index M_w/M_n theoretically approaches 2 at high extent of the reaction [6–8]. Several conditions should be fulfilled trying to obtain high-molecular polymers by polycondensation, the main being equimolar ratio of the reacting groups, proper reaction temperature, and suitable solvents [9, 25].

Polycondensation of 1,3-diamino-2-propanol (DAP) and 1,3-dibromo-2-propanol (DBP) was studied in five different solvents, namely, methanol (MeOH), 2-propanol (IPOH), water (H_2O), N,N-dimethylacetamide (DMAC) and N,N-dimethylformamide (DMF) (Scheme 1). Preliminary study has revealed that polycondensation of DAP and DBP in these solvents at 25–60 °C resulted in PHPI whose yields after ultrafiltration were less than 10%. Obviously, low yield of PHPI
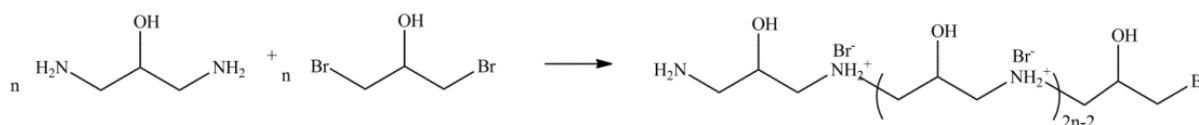
Scheme 1. Simplified scheme of polycondensation between DAP and DBP

was predetermined by removal of low-molecular fractions of the product during ultrafiltration. This indicates that the extent of the reaction irrespective of the temperature was rather low giving mainly oligomers and polymers with a molecular weight of several thousands. At temperatures over 60 °C, the yield of ultrafiltrated PHPI was substantially higher. Unfortunately, too high temperature was unfavourable, since the reaction mixture turned to yellow-brown indicating an increasing role of side reactions. Thus, in the present study, the reaction temperature was set to 80 °C except methanol which is rather volatile; polycondensation in methanol was carried out at 60 °C.

Kinetics of this reaction was followed measuring bromide concentration in the reaction mixture. The course of the reaction was similar in all the solvents except IPOH: the extent of the reaction, which shows the part of the functional groups that are reacted, increased rapidly during several first hours, then raised slowly, and finally after approximately 100 hours nearly stopped (Fig. 1). Evidently, the highest reaction rate and the highest *ER* were characteristic of polycondensation in DMAC, which is the most polar amongst the tested solvents. These results are in accordance with the solvent effect on S_N2 type reactions [26, 27]. Polar solvents favour formation and stabilization (via solvation) of a transition state and, in some cases, charge separation. Polar protic solvents like alcohols, however, could act also as hydrogen donors, decreasing activity of the nucleophile DAP in the reaction with DBP. This speculation is in accordance with the experimental data evidencing lower rate of polycondensation in alcohols compared to that in polar aprotic solvents DMAC and DMF. Higher rate of nucleophilic substitution in MeOH compared to that in IPOH, possibly, is predetermined by high relative dielectric permittivity of MeOH (32.7) which almost twice exceeds relative dielectric permittivity of IPOH (17.9). Usually, water is not a proper solvent for S_N2 reactions [28]. Nevertheless, polycondensation in water proceeded with the similar rate as in MeOH evidencing high nucleophilicity of DAP, even higher than that of water.
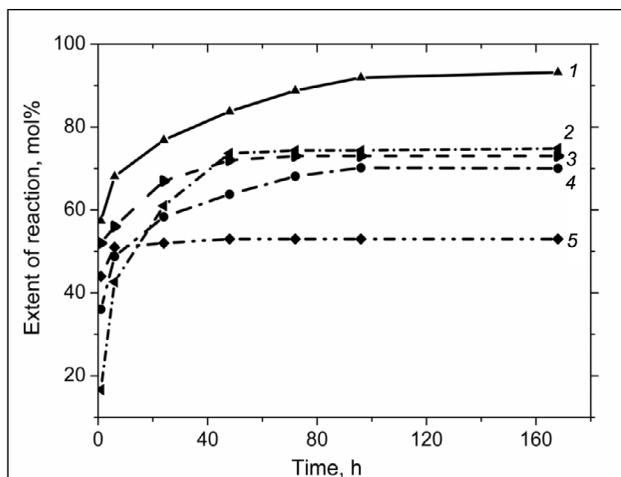
Independent of the solvent, the extent of the reaction after a certain period approaches some limiting value which, possibly, is predetermined by heterogeneity of the reaction mixture. Solubility of protonated PHPI in all the solvents (except water) is low which leads to phase separation at a certain *ER* and limits mobility of the reacting species. Protonated PHPI is well soluble in water but total protonation of unreacted amino groups at high *ER* makes S_N2 reaction impossible.

In parallel, kinetics of polycondensation between DAP and DBP in various solvents was studied using a reaction calorimeter. Calorimetry is a powerful tool studying kinetics of exothermal reactions, including step-growth polymerization. Figure 2 shows typical reaction heat flow profiles for polycondensation started by addition of DBP to the reaction vial. The heat flow profiles confirm that the reaction starts immediately independent of the solvent. The rate of the reaction differs, however, being the highest in aprotic solvents. The lowest reaction rate is characteristic of polycondensation in IPOH. These results are in good consistency with the titration data (Fig. 1).
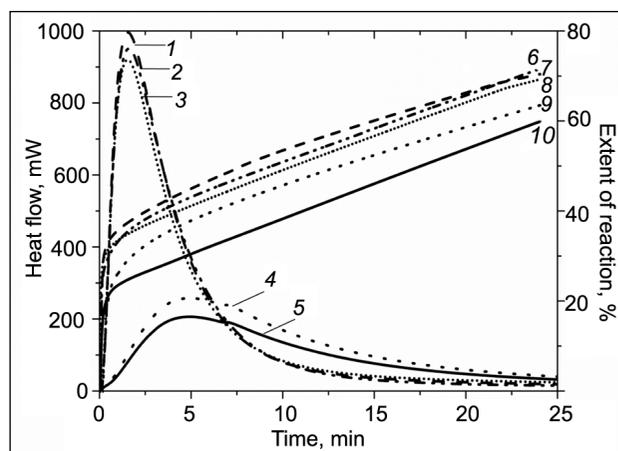

Fig. 2. Reaction heat flow profiles (*1–5*) and extent of the reaction (*6–10*) during polycondensation of DAP and DBP in DMF (*1, 6*), DMAC (*2, 7*), H_2O (*3, 8*), MeOH (*4, 9*), and IPOH (*5, 10*)

From the reaction heat flow profiles, the extent of the reaction after a certain period of the polycondensation was calculated (Fig. 2). Obviously, 20–30 mol% of functional groups are reacted during 5 minutes. Later on, polycondensation proceeds smoothly and relatively slowly allowing to reach the extent of the reaction 55–70 mol% during 24 hours. It should be noted that the data of calorimetric measurements are in good agreement with the results obtained by a chemical method (Fig. 2). Interestingly, the differences in the reaction extent in various solvents are predetermined by the course of the reaction during the first minutes. Later on, the rate of the reaction is almost the same irrespective of the solvent.

The products of polycondensation between DAP and DBP were characterized by size exclusion chromatography (SEC). MWD curves of PHPI are multimodal containing peaks attributed to monomers and oligomers (Fig. 3). During
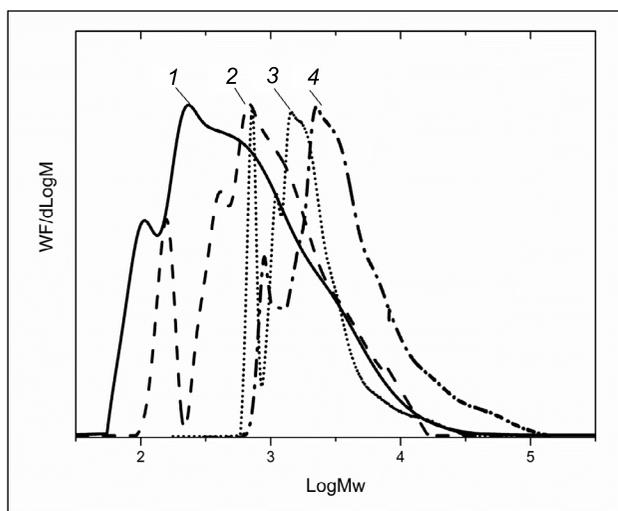

Fig. 1. Extent of the reaction between DAP and DBP in various solvents versus time. Polycondensation was carried out in DMAC (*1*), DMF (*2*), H_2O (*3*), MeOH (*4*) and IPOH (*5*)

Fig. 3. MWD curves of PHPI synthesized in DMAC. Reaction time 1 h (*1*), 24 h (*2*); 48 h (*3*) and 168 h (*4*)

polycondensation, average molecular weight of the products shifts towards higher values. Nevertheless, even after 7 days of polycondensation, PHPI contain a small oligomeric fraction with a molecular weight about 1 kDa. MWD curves evidently confirm that polycondensation does not stop after 24 or 48 hours, it continues, but at a very low rate. Unfortunately, even after 168 hours (7 days) of polycondensation, the fraction of PHPI with a molecular weight exceeding 10 kDa is rather small.

Characteristics of high-molecular fraction of poly(2-hydroxypropylene imines)

Poly(2-hydroxypropylene imines) are efficient gene transfection reagents [14, 23]. Molecular weight and structure of the transfection reagents are the key factors affecting transfection efficiency and cytotoxicity of the polymer / DNA polyplexes. It is well established [29] that poly(ethylene imine) (PEI) with the molecular weight M_n 25 kDa is highly effective in gene transfection but also induces rather high cytotoxicity. When the molecular weight is low (M_n 1.8 kDa), PEI is less cytotoxic, but its gene transfection efficiency, unfortunately, is low [30–36]. Efficiency in the gene transfection of linear PEI is considerably higher compared to that of branched PEI. Thus, PHPI used for gene transfection should possess a proper molecular weight and a certain structure. As it was shown before (Fig. 3), the fraction of PHPI with a molecular weight above 10 kDa is small, even after 7 days of polycondensation. One possibility to obtain high-molecular PHPI is fractionation of the final product of polycondensation. Fractionation of PHPI synthesized in lower alcohols, water and aprotic solvents was done by ultrafiltration using membrane with the nominal cut-off 10 kDa. Obviously, the yield of the purified PHPI was low (15–20%), but the weight average molecular weight M_w raised during ultrafiltration up to 8–17 kDa (Table 1). The polydispersity index M_w/M_n of the ultrafiltrated PHPI remained large, about 2, for

the samples synthesized in methanol and water, and nearly 5 for those synthesized in aprotic solvents. High polydispersity of PHPI synthesized in DMAC and DMF are predetermined by a high-molecular fraction present in these samples (MW approaching and even exceeding 100 kDa) (Fig. 4).

Table 1. **Molecular characteristics of PHPI synthesized in various solvents and purified by ultrafiltration**

Solvent	Yield, %[a]	M_w, kDa	M_w/M_n	IV, dL/g	R_h, nm	α[b]	T_g[c]
MeOH	14.2	12.7	2.04	0.118	3.08	0.50	−21.8
IPOH	5.7	9.70	2.71	0.091	2.51	0.52	−20.9
H_2O	17.4	8.06	1.94	0.082	1.93	0.50	−26.0
DMF	15.7	16.4	4.72	0.166	4.27	0.44	35.7
DMAC	19.5	17.6	4.84	0.172	4.53	0.43	32.0

[a] Determined by gravimetric method.

[b] Slope of Mark-Houwink plot.

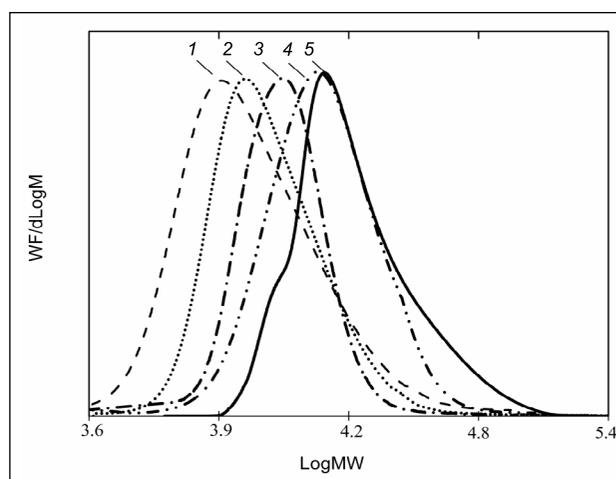[c] Glass transition temperature determined by DSC.

Fig. 4. MWD curves of fractionated PHPI synthesized in IPOH (*1*), H_2O (*2*), MeOH (*3*), DMF (*4*), and DMAC (*5*)

PHPI is a polymer which properties depend on the degree of protonation (neutralization) like for other cationic polymers [37, 38]. It is known that the NMR spectra of protonated and deprotonated samples of poly(hydroxyalkylene imines) differ [13]. In ¹H-NMR spectrum of PHPI recorded in D_2O, the imine groups of PHPI are partially protonated which broadens the signals of methylene and methyne protons (not shown). In the spectrum recorded in an aqueous alkaline solution (deprotonated form), the corresponding signals are narrower and shifted towards higher field (Fig. 5). Obviously, this spectrum is more suitable for quantitative analysis. The ¹H NMR spectrum of the deprotonated PHPI contains a broad signal at 2.36 ppm attributed to -NH-C$\underline{H}_2$-NH-C$\underline{H}_2$-CH(OH)-C$\underline{H}_2$-, and two signals at 3.45 ppm and 3.62 ppm
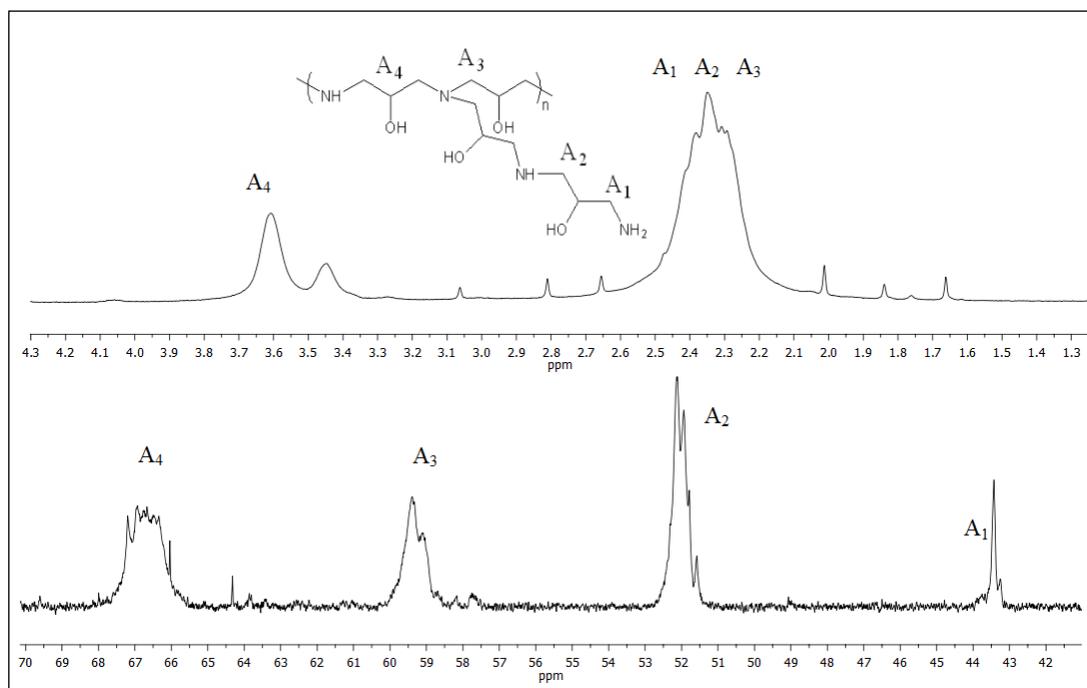
Fig. 5. ^{1}H-NMR (top) and ^{13}C-NMR (bottom) spectra of fractionated PHPI synthesized in DMAC. The spectra were recorded in D$_2$O containing several drops of NaOD, pH 13–14 (deprotonated form)

attributed to -CH$_2$-C$\underline{H}$(OH)-CH$_2$-. Similarly, as in the previous work [13], the signal of methyne protons was splitting into two well-resolved components in alkaline media. Unfortunately, the ^{1}H-NMR spectra of PHPI did not reveal any valuable information about the presence of primary, secondary and tertiary amino groups in the polymer.

More information about the structure of PHPI gives the deprotonated ^{13}C spectrum of this compound (Fig. 5). The chemical shift at 43.28 ppm belongs to the carbon associated with the primary amino group (NH$_2$-C$\underline{H}_2$-), while the shift at 52.80 ppm is related to the carbon attached to the secondary amine (-C$\underline{H}_2$-NH-C$\underline{H}_2$-CH(OH)-CH$_2$-). The shift at 59.10 ppm is related to the carbon next to tertiary amino group (N(C$\underline{H}_2$-CH(OH)-CH$_2$-)$_3$), and that at 64.20–63.80 ppm belongs to the carbon associated with the hydroxyl group -CH$_2$-C$\underline{H}$(OH)-CH$_2$-. Since the tertiary amino group represents the branching point on PHPI, the degree of branching can be calculated by the molar ratio of secondary to tertiary amino groups [24]. This ratio shows how many repeating units of PHPI are between two branched points. In order to avoid influence of the Nuclear Overhauser Effect on the signal intensities, an inversely gated decoupling pulse sequence was used in ^{13}C-NMR experiments intended for a quantitative analysis. It is known [23, 38] that this technique allows a quantitative analysis of ^{13}C-NMR spectra of PEI. The results of the analysis of PHPI by the use of ^{13}C-NMR spectroscopy are summarized in Table 2.

The data presented in Table 2 show that PHPI irrespective of the solvent used for the synthesis are branched polymers. Nevertheless, the degree of branching depends on the solvent. PHPI with the highest degree of branching were synthesized

in the aprotic solvents DMF and DMAC. For the polymers synthesized in these solvents, every second or third repeating unit has a branching point. Synthesis in the alcohols MeOH and IPOH leads to less branched products, the branching points being separated by approx. 3 repeating units.

Complementary information about chain conformation and branching of PHPI was abstracted from the data obtained using SEC with triple detection. The data from viscosity and light scattering detectors are presented as double-logarithmic plots of intrinsic viscosity against MW in the coordinates of the Mark-Houwink equation (Fig. 6). The Mark-Houwink plot reflects structural changes in a polymer, such as flexibility of polymer chain or branching [39–41]. Linear polymers in good solvents result in linear Mark-Houwink plots with the slope exceeding 0.5. For branched polymers, the slope is below 0.5, and a downward curvature can be observed. For PHPI synthesized in various solvents, the downward curvature is not evident, possibly, due to

Table 2. **Relative ratio of different amino groups present in PHPI calculated from ^{13}C-NMR spectra**

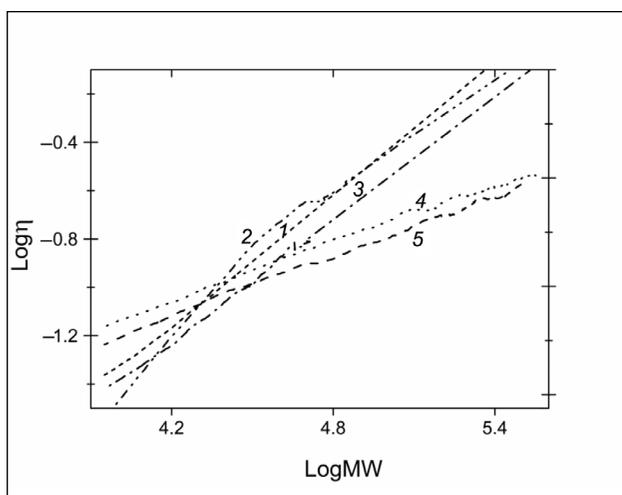| Solvent	Amino group, %			
	Primary, N$_1$	Secondary, N$_2$	Tertiary, N$_3$	N$_2$/N$_3$
MeOH	23.7	57.6	18.7	3.08
IPOH	22.5	55.1	22.4	2.45
H$_2$O	24.8	54.9	19.3	2.84
DMF	29.1	39.7	31.2	1.27
DMAC	16.9	52.8	30.3	1.74

Fig. 6. Data of SEC analysis of ultrafiltrated PHPI presented in the coordinates of Mark-Houvink equation. PHPI were synthesized in IPOH (*1*), MeOH (*2*), H_2O (*3*), DMF (*4*), and DMAC (*5*)

a relatively low molecular weight but the slope value is around 0.5 (synthesis in alcohols and water) or considerably less (0.43–0.44, synthesis in aprotic solvents). These data confirm formation of highly branched PHPI under polycondensation of DAP and DBP in the aprotic solvents DMF and DMAC.

Subject to the degree of branching, the glass transition temperature (T_g) of PHPI differs (Table 1). The DSC analysis revealed that PHPI are amorphous polymers possessing T_g at negative temperatures (–20 – –26 °C, synthesis in alcohols and water) or positive temperatures (32–36 °C, synthesis in aprotic solvents). Although T_g increases with

the molecular weight up to some critical value [40, 43], such large differences in T_g of the samples synthesized in different solvents cannot be explained by the molecular weight differing by 1.5–2 times. Presumably, T_g values are predetermined by different degree of branching of PHPI. It is known [44–47] that T_g of dendritic polymers increases with generation number to the limit, above which it remains nearly constant. The increase in T_g with generation number is assumed to reflect a decrease in chain mobility due to branching. Thus, a choice of a solvent for polycondensation of DAP and DBP enables to vary degree of branching and glass transition temperature of the product PHPI.

Mechanism of branching during polycondensation of DAP and DBP in polar solvents

The presumptive mechanism of branching during polycondensation of DAP and DBP is presented in Scheme 2. Branching, possibly, proceeds because of deprotonation of secondary amino groups which is related to proton migration from the protonated secondary amino groups of the polymer to non-protonated amino groups of DAP or terminal amino groups of the polymer (oligomer). Such type of reactions is known [48] and reported for polycondensation of some diamines and dihalogenides [17].

Likely, the effect of solvents on the degree of branching of PHPI is predetermined by the H-bonding which changes nucleophilicity of amino groups. In protic solvents, H-bonded amino groups partly lose their nucleophilicity and capability to deprotonate secondary amino groups, which lower possibility to branching. Contrarily, aprotic polar solvents act
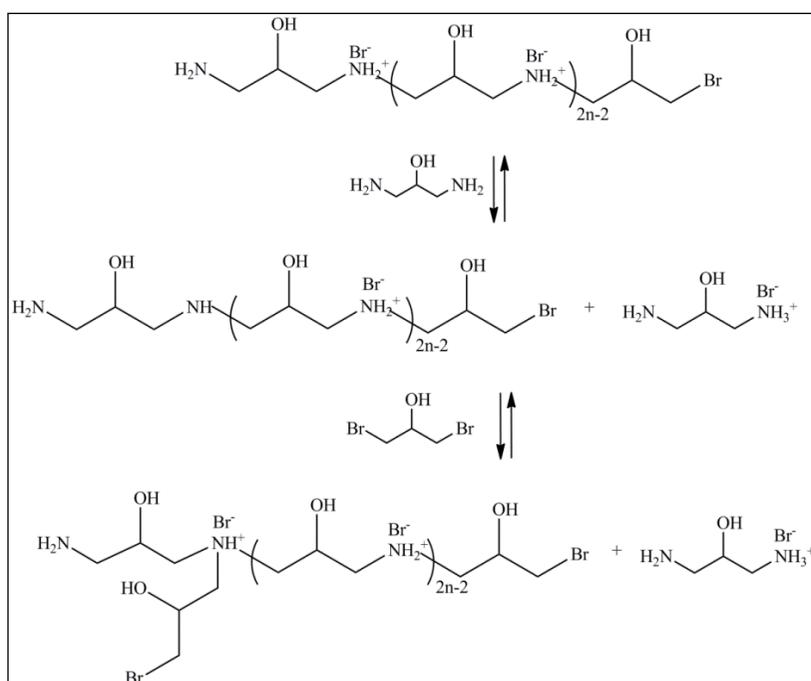
Scheme 2. Presumptive mechanism of branching during polycondensation of DAP and DBP

as proton acceptors increasing nucleophilicity (basicity) of amino groups and, the same, tendency to branching. Moreover, polar aprotic solvents (e. g. DMSO, acetone, acetonitrile, DMF) are very efficient in solvating cations [49–51]. This facilitates ion-exchange reactions between protonated secondary amino groups and non-protonated primary or even secondary amino groups leading to higher degree of branching.

CONCLUSIONS

Highly branched poly(2-hydroxypropylene imines) (PHPI) were synthesised by polycondensation of 1,3-diamino-2-propanol and 1,3-dibromo-2-propanol in several polar protic and aprotic solvents. The highest rate of polycondensation and the highest extent of the reaction were obtained using aprotic solvents DMAC and DMF. Even after 7 days of polycondensation in aprotic solvents, the number average molecular weight M_n of PHPI was relatively low, 2 to 3 kDa. Analysis of high-molecular fractions of PHPI by ^{13}C NMR spectroscopy revealed that these polyimines were highly branched polymers, with branching points being separated by approx. 1 to 3 repeating units. PHPI with the highest degree of branching were synthesized in DMF, while those with the lowest degree in methanol. Irrespective of the degree of branching, PHPI were not crosslinked and well soluble in aqueous solutions. T_g of PHPI was strongly dependent on the degree of branching being the highest for the polymers synthesized in DMF and DMAC.

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HIDROKSIGRUPIŲ, TURINČIŲ ALIFATINIŲ DIAMINŲ IR DIBROMIDŲ, POLIKONDENSACIJA SUSIDARANT LABAI ŠAKOTIEMS POLI(2-HIDROKSIPROPILENIMINAMS)

S a n t r a u k a

Vykdant 1,3-diamino-2-propanolio ir 1,3-dibrom-2-propanolio polikondensaciją įvairiuose poliniuose protoniniuose ir aprotoniniuose tirpikliuose, susintetinti labai šakoti poli(2-hidroksipropilenimi-nai) (PHPI). Polikondensacijos reakcijos kinetika ištirta naudojant skysčių kalorimetrijos ir konduktometrinio titravimo metodus. Susintetinti PHPI ištirti molekulinių sietų chromatografijos, FT-IR, ^{1}H ir ^{13}C BMR spektroskopijos bei DSK metodais. Labai šakoti PHPI susidaro sintezuojant dimetilacetamide, mažiau šakoti – metanoly-je. Nepriklausomai nuo šakotumo laipsnio, PHPI labai gerai tirpsta vandeniniuose tirpaluose. Pasiūlytas galimas šakojimosi mechaniz-mas, kai alifatinių diaminų ir dibromidų polikondensacija vykdoma įvairaus poliškumo tirpikliuose.