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Synthesis of Azetidinium-Functionalized Polymers Using a Piperazine Based Coupler

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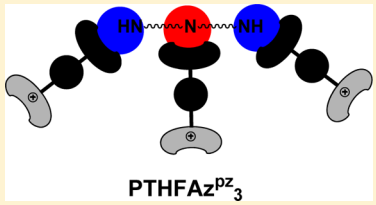
Supporting Information

ABSTRACT: A bifunctional coupler bearing an azetidinium and an aminochlorohydrin group was synthesized in water as solvent starting with piperazine and epichlorohydrin. Conversion of the bifunctional coupler in aqueous solution with primary and secondary amines (hexylamine and diethylamine) were studied as a model reaction. Using the established reaction conditions, azetidinium-functionalized polytetrahydrofurans were prepared in a controlled way by reacting the coupler in water as solvent with amine-functionalized polytetrahydrofurans.



INTRODUCTION

Polymers bearing reactive and charged functional groups are of increasing interest in today's research due to their potential application in various fields.[1−4] In this context, azetidinium-functionalized polymers are important because they fulfill these requirements; they have quaternary ammonium groups and are highly reactive.[5−7]

A few azetidinium-functionalized polymers are known in the literature and were found to improve various properties, like adhesion to surfaces,[8] and in addition showing antimicrobial activity[9] due to the presence of the cationic azetidinium groups. Azetidinium functional groups are reactive due to the angle strain and can react with a number of nucleophiles such as amines, phenolates, thiolates, etc. By choosing specific functional nucleophiles, the properties of polymers bearing azetidinium groups can be tuned for various applications. In a patent application of Devan Chemicals, the properties of textiles treated with polymers bearing reactive azetidinium groups were optimized for increasing substantivity and tenacity, durability or longevity of other compounds coapplied with the cationic polymers onto textiles.[10] Although this type of polymers is important, only few research articles are known on their synthesis. The main problem is the difficulty to prepare and stabilize the reactive azetidinium groups within these polymers.

First results regarding the selective synthesis of azetidinium-functionalized compounds were reported by Coscia et al. The reaction of a secondary amine (diethylamine) with epichlorohydrin yields the corresponding azetidinium compound in high yield and high purity.[11] Later, based on this concept, azetidinium-functionalized polymers were prepared by conversion of secondary amine groups within the polymer backbone with epichlorohydrin. For example, Hercosett 125 was synthesized via the reaction of a poly(amino-amide) with epichlorohydrin.[12] Azetidinium-functionalized guanidine based polymers were also prepared via the reaction of guanidine based prepolymers, such as polyhexamethylene guanidine hydrochloride, polyhexamethylene diethylene triamine guanidine hydrochloride, with epichlorohydrin.[13] In our previous work,[14] different azetidinium-functionalized polymers were prepared starting with an aminotelechelic polytetrahydrofuran, bearing primary and secondary amine groups. While the secondary amine group in the polymer leads solely to azetidinium groups the primary amine groups can be converted to aminochlorohydrin and aminoepoxy propane groups depending on the reaction conditions. Conversion of the aminochlorohydrin groups to azetidinium groups is rather difficult; the azetidinium groups being obtained with low (≈ 50%) conversion.

The main disadvantage for the synthesis of azetidinium-functionalized polymers from a starting material with primary and secondary amine groups is the occurrence of parallel or consecutive side reactions leading to a cross-linked polymer (Scheme 1).[15]

The side reactions occur due to interaction of the azetidinium group with aminochlorohydrin or not converted secondary amine groups. This reaction occurs upon storage of the solution or during evaporation of the solvent leading to branched polymers and finally to cross-linking.

To solve these problems, it is indispensable to find a more suitable method by which azetidinium-functionalized polymers can be prepared in a controlled way. Quantification of these groups in the polymer backbone and elimination of side reactions are also important.

In the current work, a bifunctional coupler was used to prepare azetidinium-functionalized polymers. Bifunctional couplers[16] are molecules containing two functional groups which due to their different reactivity can be addressed selectively. One of the active groups of these couplers reacts with a suitable group of the polymer. As a result, a new

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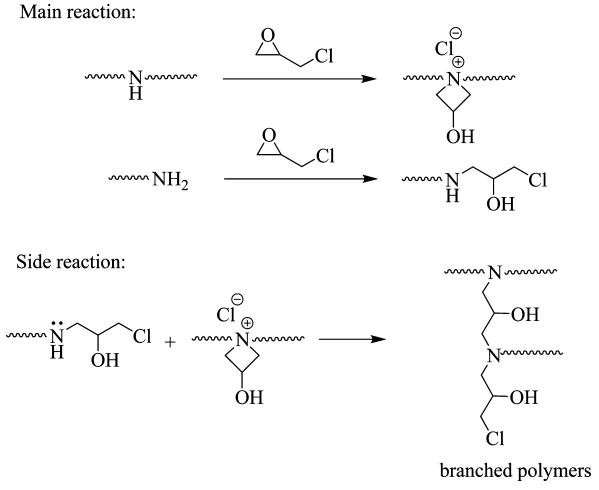
Scheme 1. Main Reaction and Side Reaction during Conversion of an Amino-Functional Substrate with Epichlorohydrin



functionalized polymer is obtained (Figure 1). Couplers were used to bring different functionalities in the polymer backbone or side chains which were otherwise difficult to introduce.[17,18]

The goal of the present study is to establish a novel procedure for synthesis of azetidinium-functionalized polymers using a bifunctional coupler. To achieve this, a suitable bifunctional coupler was designed, synthesized and treated with low molecular weight primary and secondary amines as model reaction to obtain azetidinium-functionalized compounds. Later using these reaction conditions, azetidinium-functionalized polytetrahydrofurans were prepared by reacting amine-functionalized polytetrahydrofurans with the coupler. Aminotelechelic polytetrahydrofurans [XTJ-548 (Huntsman Corporation)] was used as models for amine-functionalized polymers in general.

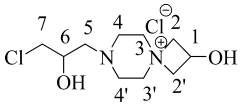
EXPERIMENTAL PART

Materials. Hexylamine (99%, Aldrich), diethylamine (99%, Aldrich), epichlorohydrin (99%, Merck), piperazine (99+%, Aldrich), aminotelechelic polytetrahydrofuran (PTHF) [XTJ-548 (Huntsman Corporation)], were used without further purification. XTJ-548 is a mixture of NH_2−PTHF−NH_2 and NH_2−PTHF−NH−PTHF−NH_2 in a ratio of 1:4 and a number-average molecular weight of 1700 g/mol. Distilled water was used as solvent for all the reactions.

Measurements. ^{1}H NMR and ^{13}C NMR spectra were recorded on a Bruker DPX-400 FT-NMR spectrometer at 400 and 100 MHz, respectively. Deuterium oxide (D_2O) and deuterated dimethyl sulfoxide (DMSO-d_6) were used as solvents. Tetramethylsilane (TMS) was used as an internal standard. All Raman spectra were recorded on a Buker RFS100/s Raman spectrometer, fitted with a Nd:YAG laser (1064 nm). The spectral resolution was 4 cm^{-1}. For one spectrum, 1000 scans were collected at a laser power of 200 mW.

Nomenclature of Polymers. For the functional polymers **PTHFAz$^{pz}_3$** and **PTHFAz$^{pz}_5$**, PTHF stands for the hydrophobic skeleton of polytetrahydrofuran, Az$^{pz}_n$ (n = 3, 5) stands for the azetidinium group (Az) attached to piparazine (pz) and n shows the number of azetidinium groups in a single polymer chain.

Synthesis. *Synthesis of the Bifunctional Coupler [7-(3-Chloro-2-hydroxypropyl)-2-hydroxy-7-aza-4-azoniaspiro[3.5]nonane Chloride] (**3**).* To a solution of piperazine (**1**) (1.65 g, 0.019 mol) in water (15 mL), was added epichlorohydrin (**2**) (3 mL, 0.038 mol). The mixture was stirred for 2 days at 25 °C. Then water was removed in vacuum. The bifunctional coupler **3** was obtained as a white solid (>95% purity). This compound was further purified via extracting the aqueous solution of the coupler with dichloromethane and removal of water in vacuum.



3

^{1}H NMR (DMSO-d_6, 400 MHz): δ = 6.70 and 5.36 (d, OH), 4.65 (m, H^1), 4.49 and 4.17 (m, H^2, H$^{2\prime}$), 3.84 (m, H^6), 3.7−3.4 (m, H^3, H$^{3\prime}$, H^7), 2.8−2.4 (m, H^4, H$^{4\prime}$, H^5) ppm. ^{13}C NMR (DMSO-d_6, 100 MHz): δ = 70.25 (C^2, C$^{2\prime}$), 67.83 (C^6), 60.58 (C^3), 59.59 (C$^{3\prime}$), 58.84 (C^5), 57.72 (C^1), 48.33 (C^7), 47.88 (C^4), 47.54 (C$^{4\prime}$) ppm.

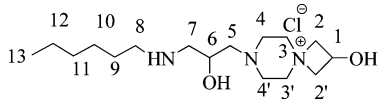
Figure SI 1, Supporting Information: CH HSQC of the coupler **3**.

Figure SI 2, Supporting Information: Raman spectrum of coupler **3** showing the characteristic band of the alkyl chloride bond.

For the results of the MALDI analysis, see Table SI 2, Supporting Information.

Anal. ($C_{10}H_{20}Cl_2N_2O_2$) Calcd: C, 44.29; H, 7.43; N, 10.33. Found: C: 44.15; H, 7.82; N, 10.35.

*Reaction of the Coupler **3** with Hexylamine (1:1 Mol Ratio). Synthesis of the Functional Coupler **4**.* To a solution of coupler **3** (1.42 g, 5.25 mmol) in distilled water (5 mL) was added hexylamine (0.53 g, 5.25 mmol). The solution was allowed to stir for 5 h at 90 °C and then cooled down to room temperature. Removal of water yielded the pure functional coupler **4**.



4

^{1}H NMR (DMSO-d_6, 400 MHz): δ = 6.70 and 5.6 (d, OH), 4.64 (m, H^1), 4.52 and 4.17 (m, H^2, H$^{2\prime}$), 3.7−3.3 (m, H^3, H$^{3\prime}$, H^6), 2.8−2.4 (m, H^4, H$^{4\prime}$, H^5), 1.8−1.2 (m, H^9, H^{10}, H^{11}, H^{12}), 0.87 (m, H^{13}) ppm. ^{13}C NMR (DMSO-d_6, 100 MHz): δ = 70.25 (C^2, C$^{2\prime}$), 63.78 (C^6), 60.52 and 60.047 (C^3, C$^{3\prime}$), 58.76 (C^5), 57.65 (C^1), 51.04 (C^7),

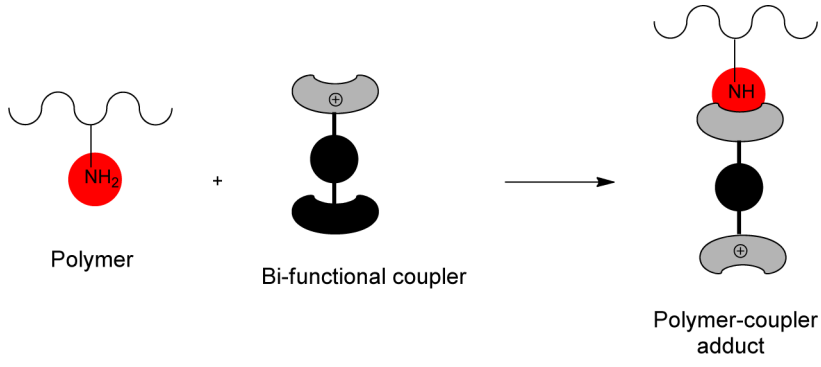


Figure 1. Synthesis of functionalized polymers using a bifunctional coupler.

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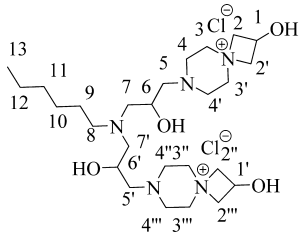
47.85–47.35 (C^4, $C^{4\prime}$), 47.03 (C^8), 30.67 (C^9), 26.72 (C^{10}), 25.48 (C^{11}), 21.80 (C^{12}), 13.77 (C^{13}) ppm.

For the result of the MALDI analysis see Table SI 2, Supporting Infomation.

Anal. ($C_{16}H_{34}ClN_3O_2$, HCl, 1/2 H_2O) Calcd: C, 50.39; H, 9.51; N, 11.02. Found: C: 50.81; H, 9.85; N, 10.81.

*Reaction of the Coupler **3** with Hexylamine (2:1 Mol Ratio). Synthesis of Compound **5**.* To a solution of coupler **3** (1.42 g, 5.25 mmol) in distilled water (5 mL) was added hexylamine (0.27 g, 2.65 mmol). The solution was allowed to stir for 9 h at 90 °C and then cooled down to room temperature. Removal of water yielded the pure compound **5**.



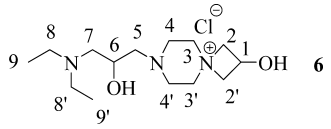
5

^{1}H NMR (DMSO-d_6, 400 MHz): δ = 6.70 and 5.6 (d, OH), 4.65 (m, H^1), 4.49 and 4.16 (m, H^2, $H^{2\prime}$), 3.7–3.3 (m,), 3.8–2.4 (m, H^3, $H^{3\prime}$, $H^{3\prime\prime}$, $H^{3\prime\prime\prime}$, H^4, $H^{4\prime}$, $H^{4\prime\prime}$, $H^{4\prime\prime\prime}$, H^5, $H^{5\prime}$, H^6, $H^{6\prime}$, H^7, $H^{7\prime}$, H^8), 1.8–1.2 (m, H^9, H^{10}, H^{11}, H^{12}), 0.87 (m, H^{13}) ppm. ^{13}C NMR (DMSO-d_6, 100 MHz): δ = 70.44 (C^2, $C^{2\prime}$, $C^{2\prime\prime}$, $C^{2\prime\prime\prime}$), 64.27 and 63.83 (C^6, $C^{6\prime}$), 60.58- 59.85 (C^3, $C^{3\prime}$, $C^{3\prime\prime}$, $C^{3\prime\prime\prime}$), 58.81 (C^5, $C^{5\prime}$), 57.72 (C^1, $C^{1\prime}$), 51.06 (C^7, $C^{7\prime}$), 47.92- 47.39 (C^4, $C^{4\prime}$, $C^{4\prime\prime}$, $C^{4\prime\prime\prime}$), 47.08 (C^8), 30.69 (C^9), 26.77 (C^{10}), 25.52 (C^{11}), 21.84 (C^{12}), 13.82 (C^{13}) ppm.

For the result of the MALDI analysis, see Table SI 2, Supporting Information.

Anal. ($C_{26}H_{53}Cl_2N_5O_4$·2HCl) Calcd: C, 47.17; H, 8.22; N, 10.58. Found: C: 47.6; H, 8.22; N, 10.30.

*Reaction of the Coupler with Diethylamine (1:1 Mol Ratio). Synthesis of the Functional Coupler **6**.* To a solution of coupler **3** (0.363 g, 1.34 mmol) in distilled water (2 mL) was added diethylamine (0.098 g, 1.34 mmol). The solution was allowed to stir for 7 h at 90 °C and then cooled down to room temperature. Removal of water yielded the pure functional coupler **6**.



6

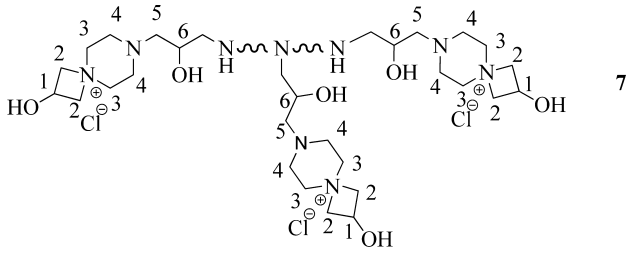
^{1}H NMR (DMSO-d_6, 400 MHz): δ = 6.70 and 5.6 (d, OH), 4.64 (m, H^1), 4.50 and 4.15 (m, H^2, $H^{2\prime}$), 3.8–3.3 (m, H^3, $H^{3\prime}$, H^6), 3.15 (m, H^8, $H^{8\prime}$), 3.00–2.3 (m, H^4, $H^{4\prime}$, H^5, H^7), 1.21 (m, H^9, $H^{9\prime}$) ppm. ^{13}C NMR (DMSO-d_6, 100 MHz): δ = 70.39 (C^2, $C^{2\prime}$), 62.99 (C^6), 60.34 and 60.26 (C^3, $C^{3\prime}$), 58.88 (C^5), 57.70 (C^1), 55.03 (C^7), 47.36 and 47.21 (C^4, $C^{4\prime}$), 47.05 and 41.16 (C^8, $C^{8\prime}$), 10.86 and 8.51 (C^9, $C^{9\prime}$) ppm.

*Synthesis of PTHFAz$^{pz}_3$ (**7**).* To a solution of aminotelechelic PTHF (XTJ-548) (2.25 g) in water (5 mL), was added at 60 °C a solution of the coupler **3** (1.003 g, 0.0037 mol) in water (5.5 mL). (The ratio of primary and secondary amine groups in XTJ-548 and coupler is [NH_2: NH: coupler =3:1:4.4]). The reaction mixture was stirred at 90 °C for 5 h and then cooled down to room temperature. Removal of water in vacuum yielded polymer **7** as a white solid.

^{1}H NMR (DMSO-d_6, 400 MHz): δ = 4.64 (m, H^1), 4.48 and 4.15 (m, H^2), 3.6 (m, H^3, H^6), 2.8–2.2 (m, H^4, H^5, H^7) ppm. ^{13}C NMR (DMSO-d_6, 100 MHz): δ = 70.25 (C^2), 64.30 (C^6), 60.71 and 59.93 (C^3), 58.94 (C^5), 57.74 (C^1), 47.97 and 47.62 (C^4) ppm.

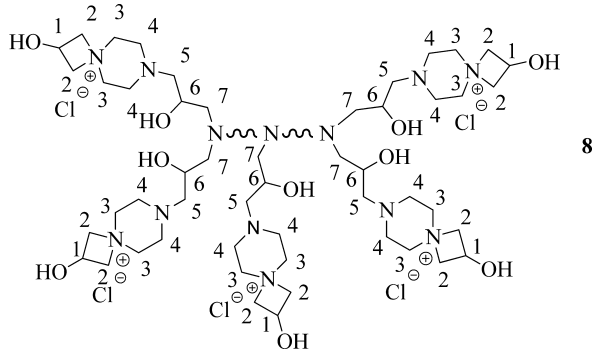
Table SI 1, Supporting Information: GPC data for PTHFAz$^{pz}_3$.

*Synthesis of PTHFAz$^{pz}_5$ (**8**).* To a solution of aminotelechelic PTHF XTJ-548 (2.25 g) in water (5 mL), was added at 60 °C a solution of the coupler **3** (1.708 g, 0.0063 mol) in water (8 mL). (The ratio of primary and secondary amine groups in XTJ-548 and coupler is [NH_2: NH: coupler =3:1:7.4]). The reaction mixture was stirred at 90 °C for



7

8 h and then cooled down to room temperature. Removal of water in vacuum yielded polymer **8** as a white solid.



8

^{1}H NMR (DMSO-d_6, 400 MHz): δ = 4.65 (m, H^1), 4.49 and 4.15 (m, H^2), 3.6–3.4 (m, H^3, H^6), 2.85–2.2 (m, H^4, H^5, H^7) ppm. ^{13}C NMR (DMSO-d_6, 100 MHz): δ = 70.25 (C^2), 64.30 (C^6), 60.65 and 59.91 (C^3), 58.89 (C^5), 57.73 (C^1), 48.30–47.55 (C^4) ppm.

Table SI 1, Supporting Information: GPC data for PTHFAz$^{pz}_5$.

RESULTS AND DISCUSSION

Multifunctional polymers are prepared either by copolymerization of functional monomers (Figure 2, route 1), mainly used in controlled vinyl- and ring-opening polymerization reactions or by post polymerization modification reaction (Figure 2, route 2 and 3). The preparation of functional monomers is often a multistep process associated with laborious purification procedures; in addition due to their high reactivity precaution measures must be taken for the storage of these monomers.

In post polymerization modification two approaches have to be considered: generation of the desired functionality by direct conversion of functional groups in the polymer with a suitable reagent (Figure 2, route 2) and by using a coupler (Figure 2, route 3). In the second approach, first functional couplers are prepared with the desired functionalities, and then these functional couplers are attached to the polymer.

In the previous paper, we have shown that polymers bearing primary or secondary amine groups can be converted under suitable conditions to polymers with azetidinium groups by reaction of these polymers with epichlorohydrin. In the current work a new synthetic strategy was developed to prepare azetidinium-functionalized polymers from amine-functionalized polymers, using a piperazine-based bifunctional coupler (Scheme 2).

Reactions of piperazine with epichlorohydrine were reported in the literature.[19] By varying the reaction conditions, different products were obtained (Scheme 3). In dry ethanol at ca. 35 °C the reaction of piperazine (1equivalent) with epichlorohydrin (2 equiv) resulted in *N*,*N*′-bis(3-chloro-2-hydroxypropyl)-piperazine (**A**), which upon treatment with aqueous sodium hydroxide gave *N*,*N*′-bis(2,3-epoxy-*n*-propyl)piperazine (**B**); the chlorohydrin groups being converted to epoxide groups.[20] Alkylation of the bis(chlorohydrin) **A** with methyl iodide at 100

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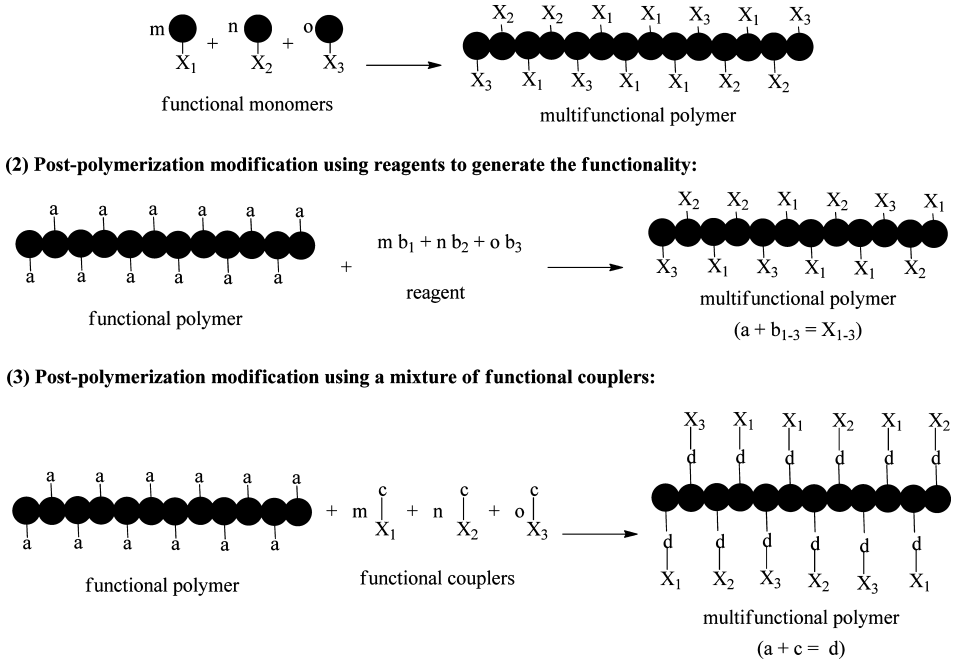
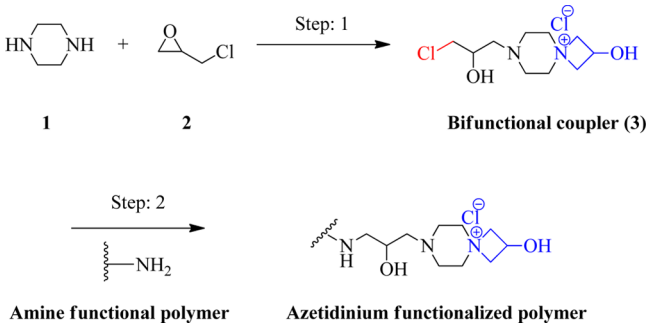


Figure 2. Different approaches to synthesize multifunctional polymers.

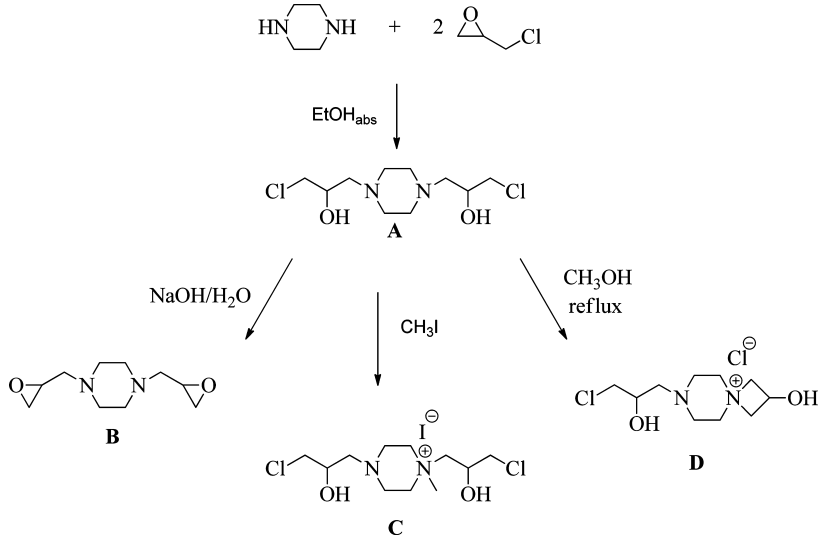
Scheme 2. Schematic Presentation for the Synthesis of Azetidinium-Functionalized Polymers Using a Bifunctional Coupler



°C resulted in the quaternary ammonium compound *N*-methyl-*N*,*N*′-bis(3-chloro-2-hydroxypropyl)piperazinium iodide (**C**), while heating with methanol yielded *N*-(3-chloro-2-hydroxypropyl)-*N*-(2-hydroxy-1,3′-trimethylene)piperazinium chloride (**D**) in 42% yield, in which one of the aminochlorohydrin groups was converted into an azetidinium group. All these reactions show that, formation of different products was possible by adjusting the reaction parameters (solvents, pH, temperature, reaction time etc.).

In the current work, one of the piperazine derivatives (**D**) was synthesized in a more simple and quantitative way (>95% yield) via the reaction of piperazine with epichlorohydrin (mole ratio 1:2) in water at ambient temperature. Obviously in the high polar solvent water the ammonium salt (the azetidinium chloride) is more stable than its covalent isomer (the aminochlorhydrin). The product has two isomeric functional

Scheme 3. Piperazine/Epichlorohydrin-Based Products



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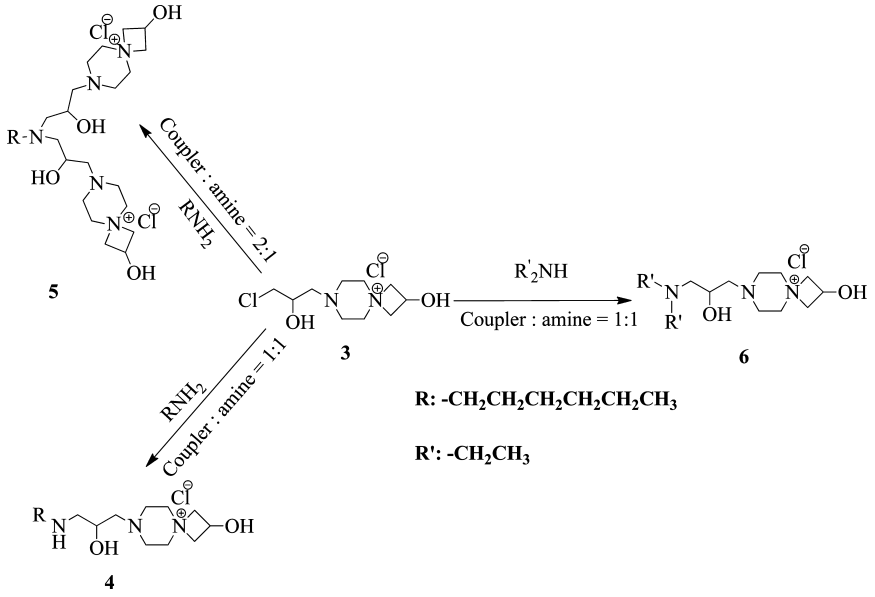
Scheme 4. Model Reactions of the Coupler with Low Molecular Weight Amines



groups with different reactivity (azetidinium chloride and aminochlorohydrin) and thus can potentially act as a bifunctional coupler. To establish the reaction conditions for preparing functional couplers model reactions with low molecular weight primary (hexylamine) and secondary amines (diethylamine) were performed (Scheme 4): (i) Model reactions with hexylamine were performed using molar ratios of coupler:amine of 1:1 and 1:2. (ii) Reaction of the coupler with diethylamine was performed using 1: 1 molar ratio.

The bifunctional coupler (**3**) and all the coupler-derived products (**4**, **5**, **6**) obtained by reactions of the coupler with amines were characterized by spectroscopic methods.

Spectroscopic Analysis. The ^{1}H NMR spectrum of coupler **3** (Figure 3A) shows the characteristic peaks for the azetidinium ring protons at δ = 4.1−4.7 ppm, the protons associated with the piperazine group were split into two regions—the protons adjacent to the azetidinium group at δ = 3.5 ppm and the protons adjacent to the chlorohydrin group at δ = 2.6 ppm. The characteristic peaks of the chlorohydrin groups were found at δ = 3.84 (H^6), 3.46 (H^7), and 2.4 (H^5) ppm. The secondary alcohol groups were found at δ = 5.36 ppm (OH associated with chlorohydrin group) and at δ = 6.70 ppm (OH associated with azetidinium group).

The ^{13}C NMR spectrum (Figure 4A) shows the characteristic peaks for carbon atoms associated with the azetidinium ring at δ = 70.24 (C^2, $C^{2\prime}$) and 57.72 (C^1) ppm cm^{-1} (Figure SI 1, Supporting Information, shows the CH-HSQC of coupler **3**). The signals for the carbon atoms associated with the piperazine group were found at δ = 60.58 and 59.59 (C^3, $C^{3\prime}$), 47.88 and 47.54 (C^4, $C^{4\prime}$) ppm. The characteristic peaks of the carbon atoms associated with chlorohydrin groups were found at δ = 67.83 (C^6), 58.84 (C^5) and 48.33 (C^7) ppm. In the Raman spectrum of coupler **3** the characteristic signals for the alkyl chloride bond was found at 750−650 cm^{-1} (Figure SI 2).

Reactions of the coupler with hexylamine. The reaction products of the coupler with hexylamine were analyzed by NMR spectroscopy (Figures 3 and 4). The substitution pattern of the primary amine group was determined/proven by ^{1}H NMR spectral analysis; comparison of the integration ratio of the protons associated with the methyl group (H^{13}) with the characteristic proton (H^1) of the azetidinium group (Figure 3B,C). For the mono substituted product **4** the integration ratio

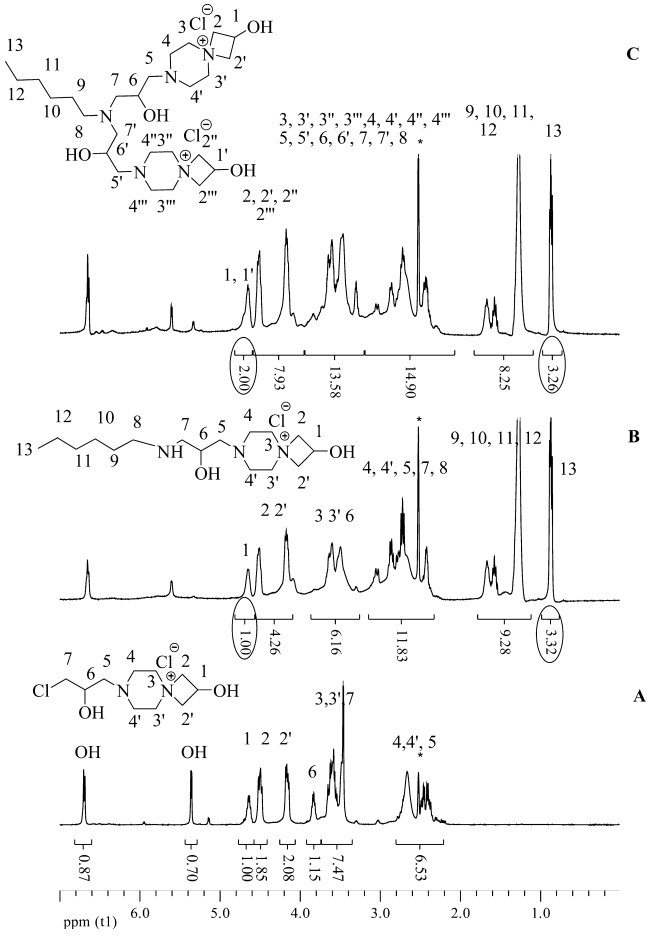


Figure 3. ^{1}H NMR spectra (in DMSO) of (A) the bifunctional coupler **3**, (B) the product **4** prepared by reacting the coupler with hexylamine in a 1:1 mol ratio and (C) the product **5** prepared by reacting the coupler with hexylamine in a 2:1 mol ratio (* DMSO).

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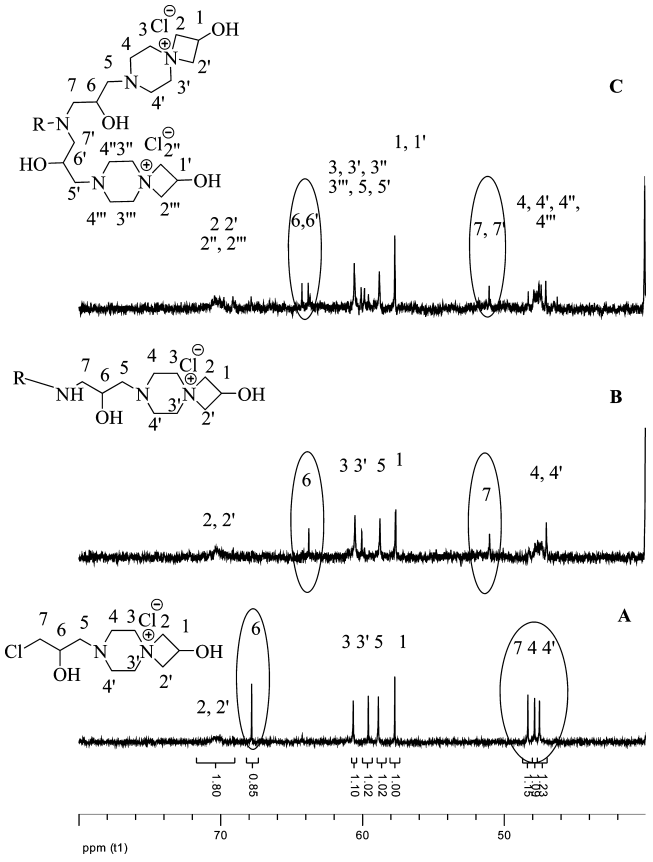

Figure 4. ^{13}C NMR spectra (in DMSO, $R = C_6H_{13}$): (A) Bifunctional coupler **3**, (B) mono-substituted product **4**, prepared via the reaction of coupler with hexylamine in a 1:1 mol ratio, and (C) bis-substituted product **5**, prepared via the reaction of coupler with hexylamine in a 2:1 mol ratio.

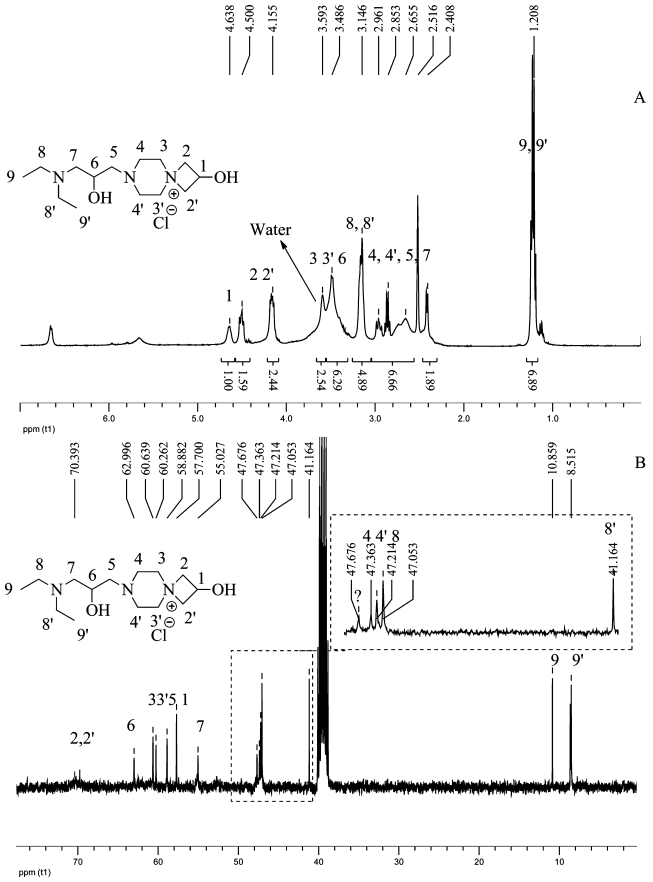

Figure 5. ^1H NMR (A) and ^{13}C NMR spectra (B) of product **6** obtained by the reaction of the coupler **3** with diethylamine (coupler:diethylamine = 1:1).

H^{13}: H^1 is ca. 3:1 and for the bis substituted product **5** the integration ratio H^{13}: (H^1 +$H^{1\prime}$) is ca. 3:2.

In addition, formation of the two different products was proven by the appearance of characteristic signals for the carbon atoms marked as C^6, C^7 at δ = 63.78 and 51.04 ppm (for the mono-substituted product **4**) (Figure 4B) and at δ = 64.27, 63.82, and 51.06 ppm (for the bis-substituted product, **5**) (Figure 4C), respectively.

Reaction of the Coupler with Diethylamine (1:1 Mol Ratio). Reaction of the coupler with diethylamine (molar ratio 1:1) leads to the corresponding azetidinium-functionalized amine as the only product. The ^1H NMR spectrum of product 6 (Figure 5A) shows characteristic signals for the protons associated with the azetidinium group at δ = 4.10- 4.65 ppm. The signals characteristic for the carbon atoms marked as C^6 and C^7 (Figure 5B) are found at δ = 62.99 and 55.03 ppm.

Synthesis of Azetidinium-Functionalized Polymers Using the Bifunctional Coupler. On the basis of the model reactions using low molecular weight amines, two different azetidinium-functionalized polytetrahydrofurans, containing the same backbone and different concentration of azetidinium groups were prepared from aminotelechelic polytetrahydrofuran XTJ-548. (Scheme 5).

Formation of the azetidinium-functionalized polytetrahydrofurans was proven by ^1H NMR spectral analysis (Figure 6). The disappearance of the characteristic peak for the proton (H^6) at δ = 3.84 ppm of the chlorohydrin group and the presence of the characteristic peaks of protons associated with azetidinium group (H^1 and H^2) at δ = 4.1- 4.7 ppm confirm the formation of azetidinium-functionalized polytetrahydrofuran.

This result was confirmed by Raman spectroscopy. Here the disappearance of the characteristic peaks at 750−650 cm^{-1} of the alkyl halide bond proves the formation of functionalized polytetrahydrofurans (Figure 7).

Another important aspect during the preparation of azetidinium-functionalized polymers is the stability of the highly reactive azetidinium groups in the polymer backbone, in the presence of free secondary amine groups.

For Hercosett [poly(aminoamide)/epichlorohydrin adduct], it is known that the unreacted secondary amine groups of the polymer backbone react with the formed azetidinium groups leading to chain coupling. This reaction occurs as parallel or consecutive reaction to the desired conversion of the secondary amine groups with epichlorohydrin.

The current synthetic strategy in which a bifunctional coupler was used to introduce azetidinium groups within an amino functional polymer was found to avoid further reaction of these reactive cationic groups with the newly formed secondary amine groups.

The ^1H NMR spectra for the azetidinium-functionalized polymers ($PTHFAz^{pz}{}_3$, $PTHFAz^{pz}{}_5$) are given below (Figure 8).

The integration ratio I(3−2.5 ppm):I(4.6 ppm) is 12:1 (for $PTHFAz^{pz}{}_3$) and 10:1 (for $PTHFAz^{pz}{}_5$), proving that the azetidinium groups remained intact under the reaction

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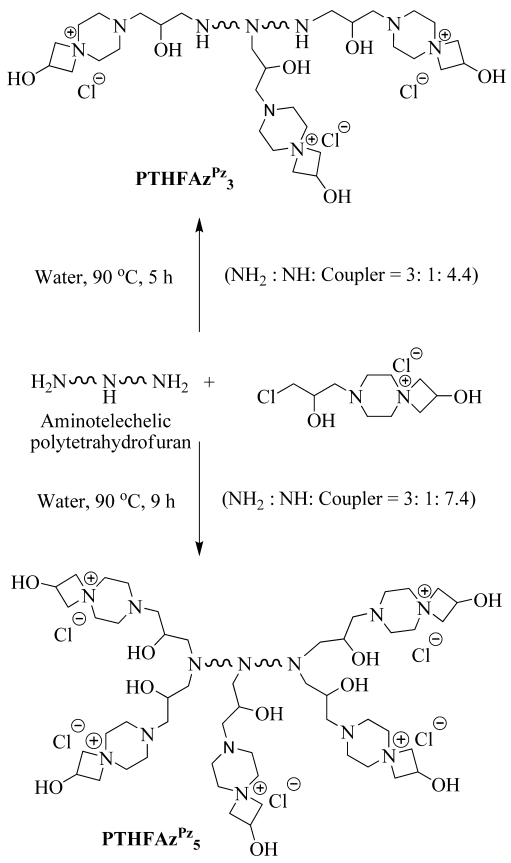
Scheme 5. Synthesis of Azetidinium-Functionalized Polymers Using the Bifunctional Coupler[a]



[a](a) **PTHFAz$^{pz}_3$**, was synthesized from aminotelechelic polytetrahydrofuran and bifunctional coupler, using one equivalent of coupler per nitrogen atom. (b) **PTHFAz$^{pz}_5$**, was synthesized from aminotelechelic polytetrahydrofuran and bifunctional coupler, using one equivalent of coupler per nitrogen−hydrogen (N−H) bond.

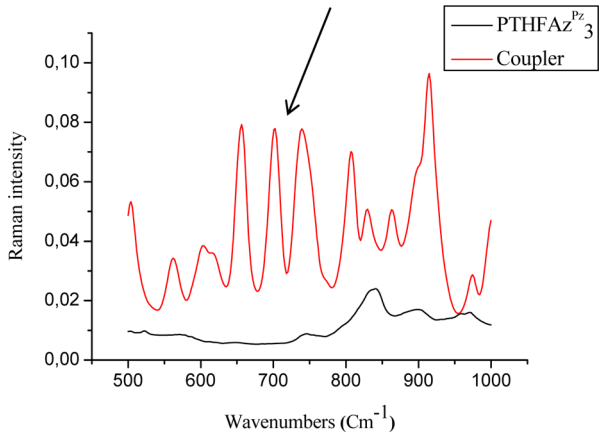


Figure 7. Reaction of aminotelechelic PTHF with the coupler (−NH$_2$:−NH:coupler = 3:1:4.4 mol ratio): Raman spectroscopic analysis.

conditions. This was further confirmed by the GPC data (Table SI 1, Supporting Information).

CONCLUSION

In the current work a piperazine based bifunctional coupler was designed, synthesized and characterized by NMR and Raman spectroscopy. Reaction of the bifunctional coupler—with an amino chlorohydrine and an isomeric azetidinium functional group—with a primary amine (hexylamine) and a secondary amine (diethylamine) in water—a highly polar solvent—were studied to determine the relative reactivity of the two isomeric functional groups. It was shown that reaction of the coupler with amines results in opening of the azetidinium ring and formation of an 3-alkyl- (dialkyl-) amino-2-hydroxypropyl-piperazine unit and isomerization of the existing 3-chloro-2-hydroxypropylpiperazine unit in a new azetidinium group.

This piperazine based coupler was successfully used to prepare azetidinium-functionalized polytetrahydrofurans in a controlled way starting with aminotelechelic polytetrahydrofur-

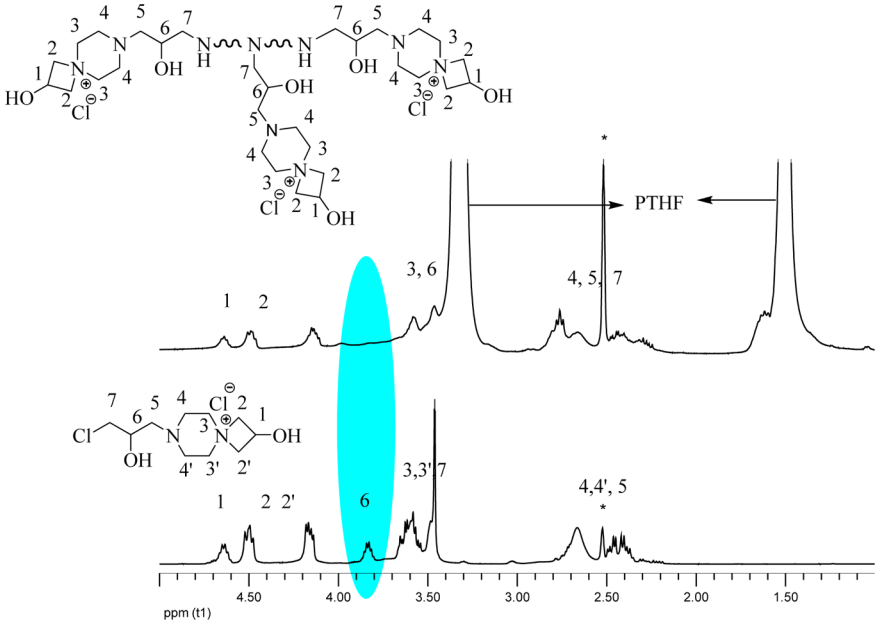


Figure 6. Reaction of aminotelechelic PTHF with the coupler (−NH$_2$:−NH:coupler = 3:1:4.4 mol ratio): ^{1}H NMR spectral analysis (* DMSO).

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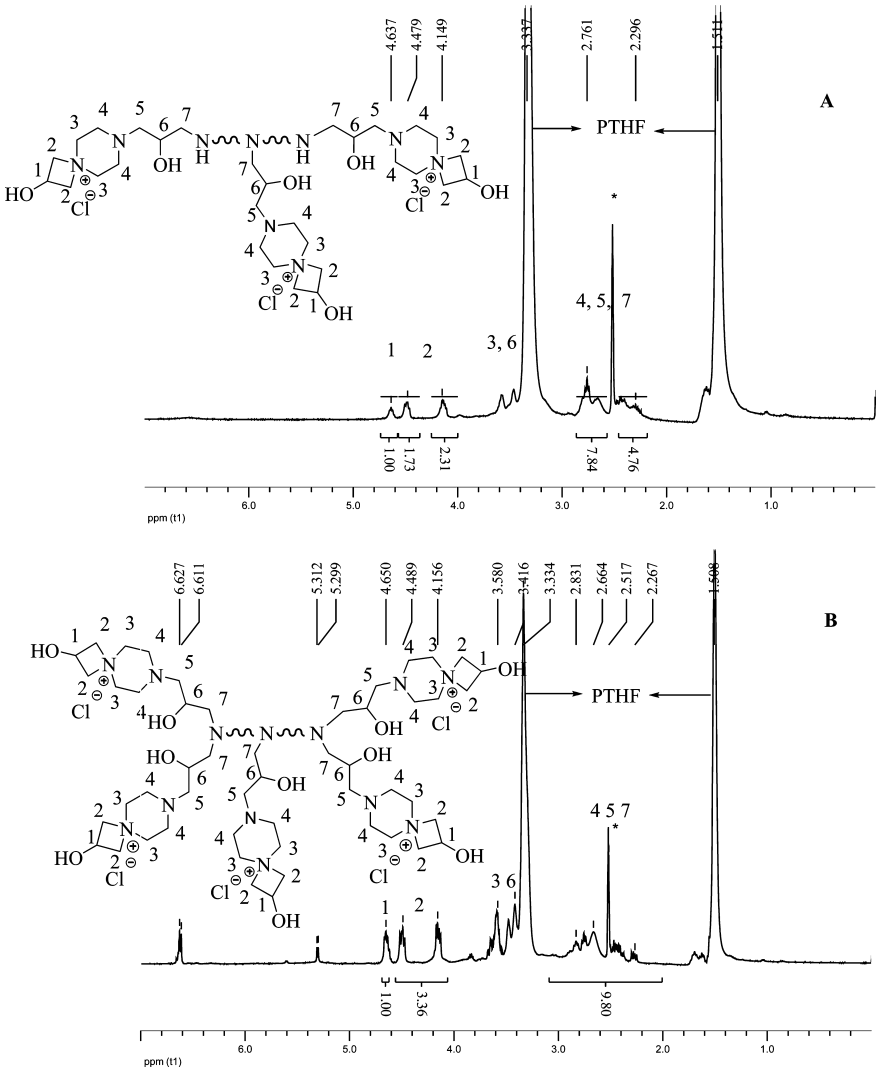

Figure 8. ^{1}H NMR spectra of azetidinium-functionalized PTHFs: (A) PTHFAz$^{pz}_{3}$; (B) PTHFAz$^{pz}_{5}$ (* DMSO).

an. It is expected that other amine functional polymers can be transformed in a similar way to azetidinium-functionalized polymers.

■ ASSOCIATED CONTENT

Supporting Information

Heteronuclear single quantum coherence (C−H HSQC) spectrum of the coupler, Raman spectrum of the coupler. GPC data for PTHFAz$^{pz}_{3}$ and PTHFAz$^{pz}_{5}$, and MALDI analysis of compounds **3**, **4**, and **5**. This material is available free of charge via the Internet at http://pubs.acs.org/.

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Notes

The authors declare no competing financial interest.

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