Electronic Supplementary Material (ESI) for Polymer Chemistry.

Supporting Information

Polyrotaxanes Created by End-Capping Polypseudorotaxanes Self-assembled from β-CDs with Distal Azide Terminated PHEMA Using Propargylamine Monosubstituted β-CDs

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Contents

1. Materials

β-Cyclodextrin (99 %), ethylene glycol, copper (0) wire (0.8 mm in diameter), 2-bromoisobutyryl bromide (BiBB) and tetrahydrofuran (THF) (99.9 %, water ≤ 50 ppm) were purchased from Innochem, China. 2-Hydroxyethyl methacrylate (HEMA) (TCI, Japan) was passed over a short basic alumina column to remove the inhibitor before polymerisation. Propargylamine (98 %) and mono-6-O-(*p*-toluenesulfonyl)- β-cyclodextrin (97 %) were purchased from Macklin, China. Tris[2-(dimethylamino)-ethyl]amine (Me_6-TREN) (98 %) was available from Aladdin, China. Cellulose dialysis bags were purchased from Viskase (U. S. A.) with molecular weight cut-off (MWCO) of 3500 and 6000 Da. Dichloromethane, methanol, acetone, dimethyl sulfoxide and triethylamine were purchased from Beijing Tongguang Fine Chemical Co., Ltd., China. Triethylamine was dried with CaH_2 and distilled before use. Sodium azide, sodium hydroxide, magnesium sulfate anhydrous, sodium chloride and alkali Al_2O_3 were purchased from Beijing Chemical Works, China. All the reagents and solvents were analytical grade unless otherwise noted.

2. Measurements

Gel permeation chromatographic (GPC) measurements were carried out at 40 °C on a Waters 2410 instrument with manual syringe injection (20 μL) using DMF or DMSO (10 mg/0.5 mL) as eluent at a flow rate of 0.3 mL/min. All the GPC data were calibrated by using polystyrene (PS) standards.

Fourier transform infrared (FTIR) spectra were recorded on a Shimadzu IR Trace-100 FTIR spectrometer (KBr disk).

^{1}H NMR spectra were recorded on a Bruker AVANCE III 400 NMR instrument at the room temperature in $CDCl_3$ or DMSO-d_6 (3 mg/0.5 mL) with tetramethylsilane as internal standard.

The 2D-ROESY NMR spectra were acquired at the room temperature using D_2O as the solvent (15 mg/0.5 mL) in phase-sensitive mode on a Bruker AVANCE III 400 NMR instrument.

Thermogravimetric analysis (TGA) was performed on a TA SDT 2960 instrument with a heating rate of 10 °C/min purged with nitrogen, and the temperature was scanned from ambient temperature to 550 °C.

3. Preparation

3.1 Synthesis of bis(2-bromoisobutyryloxy) ethane (BBiBE)

To a 0 °C cooled solution of ethylene glycol (0.02 mol, 1.242 g) and triethylamine (0.045 mol, 4.56 g) in dry THF (20 mL), a solution of 2-bromoisobutyryl bromide (0.045 mol, 10.35 g) in dry THF (10 mL) was added dropwise with stirring under nitrogen atmosphere over a period of 2 h.[1] The reaction was warmed to the room temperature and continued for another 24 h. The precipitated salts were filtered off, washed with THF and the solvent was evaporated. The crude products were dissolved in CH_2Cl_2 and the solution was washed with saturated aqueous solution of $NaHCO_3$, brine, and water, respectively. The organic layer was separated and dried with magnesium sulfate anhydrous. After the solvent was evaporated, crude BBiBE was purified by recrystallisation from methanol to yield 6.5 g of pale yellow crystals in yield 56 %. ^{1}H NMR spectrum is shown in Figure S1 and was designated to δ = 1.81-

1.94 (12 H, s, 4-CH_3) and 4.32-4.43 (4 H, s, -CH_2CH_2-) ppm.

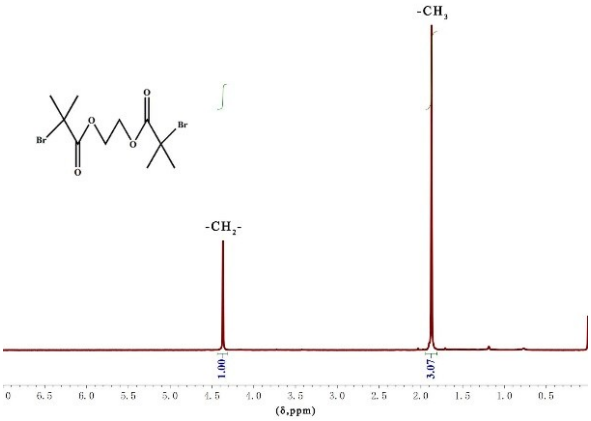


Figure S1. ^{1}H NMR spectrum of BBiBE in $CDCl_3$.

3.2 Synthesis of Br-terminated PHEMA via Cu^0-RDRP (PH-46-2Br)

In a 10 mL Schlenk tube, the reagents were added in the following orders: initiator BBiBE (74.5 mg, 0.207 mmol), DMSO (2 mL), Me_6-TREN, (4.8 mg, 5.64 μL, 0.0208 mmol) and HEMA (1.074 g, 1 mL, 8.25 mmol).[2] Cu (0) wire (4.0 cm) wrapped around a stirring bar was loaded into the reaction vessel, and the stirring was started. The mixture was deoxygenated using six vacuum/nitrogen-filling cycles and the valve was closed. The reaction vessel was placed in an oil bath thermostatted at 25 °C to start the Cu(0)-mediated reversible deactivation radical polymerisation (Cu^0-RDRP) of HEMA. At the predetermined time of 2 h, the Schlenk tube was placed in liquid nitrogen to stop the polymerisation. The products were obtained by dialysis against distilled water using a dialysis bag (MWCO 3500) for 2 h and then freeze-dried to give rise to 0.59 g PH-46-2Br in yield of 51 %. The polymer was characterised by GPC analysis. Its GPC curve is illustrated in Figure S2 and the results are summarised in Table S1. Furthermore, the degree of polymerisation (DP) of functional PHEMA was determined by ^{1}H NMR analysis to be 46, slightly higher than the feed molar

ratio 40 of HEMA to initiator. For the convenience, the resulting Br-terminated PHEMA was designated to PH-46-2Br.

Table S1. The molecular weight and yield of PH-46-2Br and PH-46-2N_3

Name	Time /h	[HEMA]:[BBiBE]: [Me_6-TREN]	M_n[a]	M_n[b]/10^3	M_w/M_n[b]	Yield[c]/%
PH-46-2Br	2	40:1:0.1	6340	6.80[c]	1.30[c]	51.3
PH-46-2N_3	/	/	6264	6.60[c]	1.31[c]	49.0

a. Determined by ^{1}H NMR analysis with DMSO-d_6.

b. Determined by GPC in DMSO with PS standards.

c. Calculated based on the product weight divided by the total raw material weight.

3.3 Synthesis of distal azide end-functionalised PHEMA (PH-46-2N_3)

PH-46-2N_3 was synthesised by the reaction of PH-46-2Br with NaN_3 in a one-pot process.[3-7] After finishing the synthesis of PH-46-2Br, NaN_3 in a 20-fold molar ratio excess (BBiBE) and DMF (8.0 mL) was immediately added to the Schlenk tube. The mixture was deoxygenated using six vacuum/nitrogen-filling cycles. The reaction was stirred at 25 °C for 48 h under nitrogen atmosphere. After purification by extensive dialysis using a dialysis bag (MWCO 3500) against distilled water for 48 h with changing every 12 h to remove the residual sodium salts and other impurities, the water soluble products in the dialysis bag were harvested by lyophilisation and obtained in 0.20 g for subsequent reactions, and the water insoluble products deposited on the bottom of the dialysis bag were dried and obtained in 0.35 g. Two parts of products were characterized by means of GPC and FTIR analyses and the results are shown in Figure S3 and S4. Both the azide end-capped PHEMA products, soluble and insoluble in water present the same GPC elution curves and FTIR spectra. It suggested that both of the products are really the same products. Consequently the

yield of PH-46-2N_3 synthesized in a one-pot process is 49.0 % based on the product weight divided by the total raw material weight. If it was calculated from PH-46-2Br as the intermediate products obtained, this value was reached to 93.2 % (Table S1).

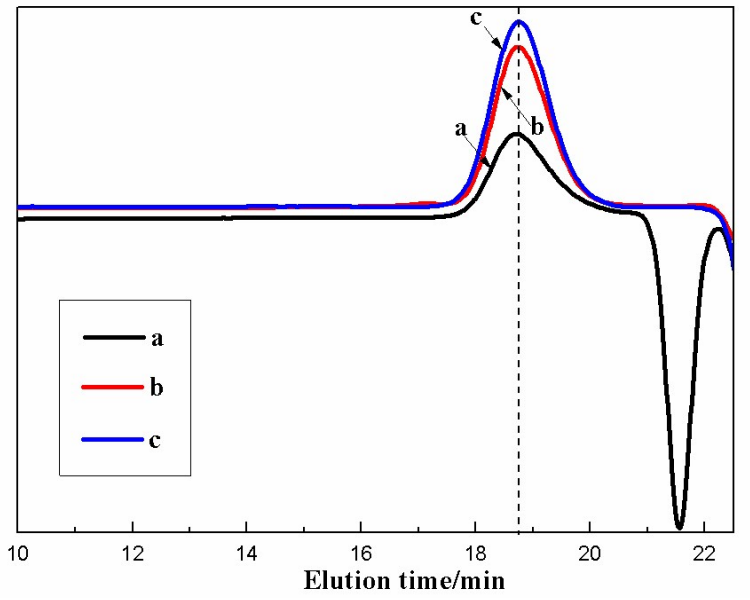


Figure S2. GPC traces of PH-46-2Br (a), and water soluble PH-46-2N_3 (b) and insoluble PH-46-2N_3 (c) using DMSO as eluent.

Furthermore, as shown in Figure S3 and S4, although a very small difference in the M_n determined by GPC analysis was noted before and after the azidation of PH-46-2Br, this change is well in agreement with the distal replacement of two bromine atoms by two azide groups. Moreover, the characteristic stretching vibration absorbance peak of terminal azide groups clearly appears at around 2120 cm^{-1} in PH-46-2N_3. In contrast, no such IR peak emerges in PH-46-2Br. Both the GPC and FTIR measurements provided evidence confirming the successful synthesis of azide end-capped PH-46-2N_3 in excellent yield from the azidation of distal Br-terminated PH-46-2Br.

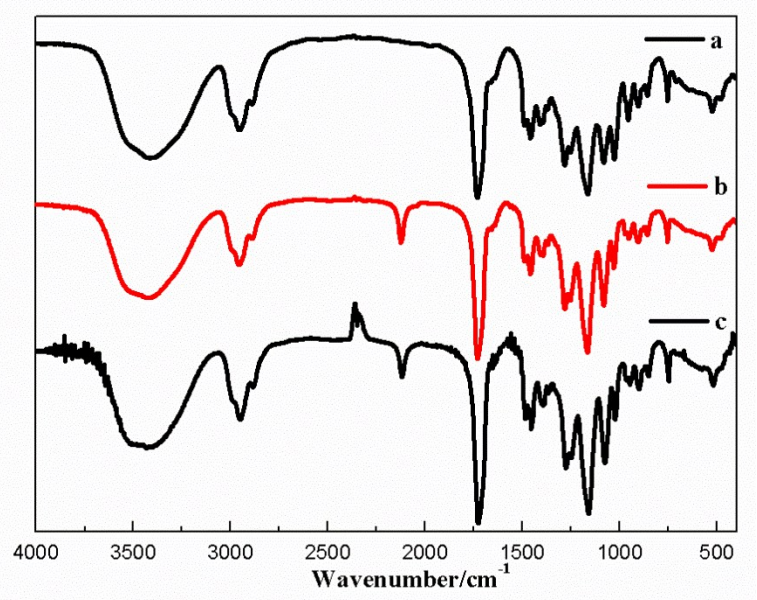


Figure S3. FTIR spectra of PH-46-2Br (a), and water soluble PH-46-2N_3 (b) and insoluble PH-46-2N_3 (c).

3.4 Synthesis of propargylamine monosubstituted β-CD (PA-β-CD)

According to the literature,[8] mono-6-O-(p-toluenesulfonyl)-β-cyclodextrin (0.5 g, 0.388 mmol) was dissolved in propargylamine (0.86 g, 1 mL, 15.6 mmol). Under nitrogen atmosphere, the mixture was stirring at 45 °C for 24 h. Then the mixture was cooled to the room temperature and precipitated into 25 mL of acetone. The precipitates were obtained and purified by dissolving in 6 mL of water-methanol mixed solvent and reprecipitating in 25 mL acetone several times to remove the unreacted propargylamine. After fully dried in a vacuum oven overnight at the room temperature, 0.39 g propargylamine monosubstituted β-CDs (PA-β-CDs) was obtained as light yellow solid products in yield 75 %. Its ^{1}H NMR spectrum is depicted in Figure S5 and designated to δ = 2.67-2.76 (1 H), 2.89-3.08 (2 H), 3.22-3.35 (14 H), 3.3-3.83 (28 H), 4.42-4.62 (6 H), 4.76-4.94 (7 H), 5.55-5.94 (12 H) ppm.

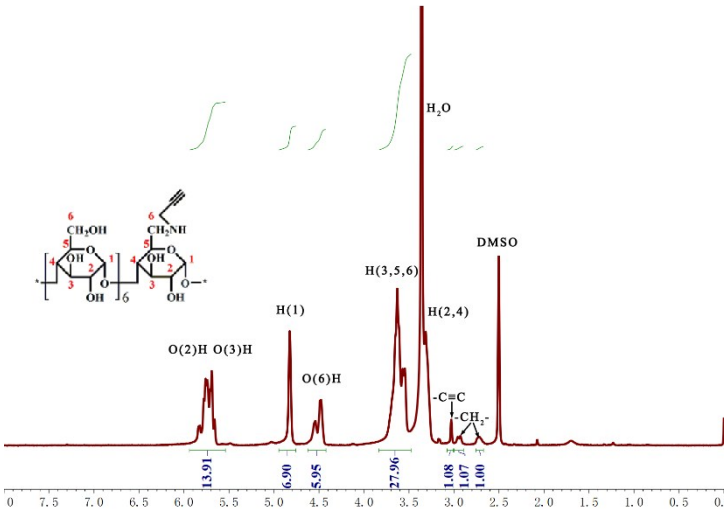
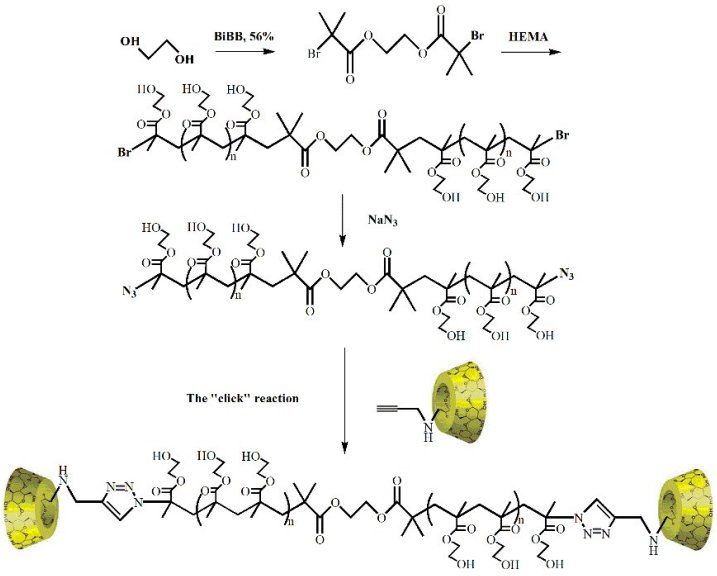


Figure S4. ^{1}H NMR spectrum of PA-β-CD in DMSO-d_6.

3.5 Synthesis of distal β-CD end-capped PHEMA (PH-46-2β-CD)

As outlined in Scheme S1, the preparation pathway of a distal β-CD end-capped PHEMA is as follows. PH-46-2N_3 (40 mg, 0.0065 mmol) was dissolved in 8 mL of H_2O by vigorous stirring of magneton in a 10 mL single-neck flask. PA-β-CDs (30.5 mg, 0.026 mmol at a feed molar ratio of PH-46-2N_3 to PA-β-CD 1:4), $CuSO_4 \cdot 5H_2O$ (13.0 mg, 0.052 mmol), PMDETA (10.8 μL, 0.052 mmol), and (+)-sodium L-ascorbate (20.6 mg, 0.104 mmol) were added under nitrogen atmosphere. The mixture was deoxygenated using six vacuum/nitrogen-filling cycles and the reaction was carried out at the room temperature for 24 h in the darkness. The resulting products were freeze-dried and collected. Afterwards the products were dissolved in DMSO (2.0 mL) and stirred for 40 min. After extensive purification using a dialysis bag (MWCO 3500) for 24 h against distilled water with changing every 8 h to remove the residual copper salts, PH-46-2β-CD was harvested by lyophilisation and collected in yield 90.7 %.



Scheme S1. Preparation pathway of a distal β-CDs terminated PHEMA.

3.6 Synthesis and purification of PRs via a one-pot strategy

A typical one-pot synthetic procedure of PR-46-23β-CD-8 as a selected PR sample was described as follows. PH-46-2N_3 (40 mg, 0.0065 mmol) was dissolved in 8 mL of H_2O by vigorous stirring of magneton in a 25 mL single-neck flask. An aqueous solution of β-CD (170 mg, 0.15 mmol) in 12 mL H_2O was added in the flask and the mixture was stirred for 5 days at the room temperature. Thereafter, to this mixture PA-β-CD (30.5 mg, 0.052 mmol at a feed molar ratio of PH-46-2N_3 to PA-β-CD 1:8), $CuSO_4 \cdot 5H_2O$ (13.0 mg, 0.052 mmol), PMDETA (10.8 μL, 0.052 mmol) and (+)-sodium L-ascorbate (20.6 mg, 0.104 mmol) were added under nitrogen atmosphere. The mixture was deoxygenated using six vacuum/nitrogen- filling cycles and the reaction was carried out at the room temperature for 24 h in the darkness.

To test whether the dialysis is an efficient separation technique to purify the PRs obtained, the products (100 mg) of PR-46-23β-CD-8 were dissolved in DMSO (2.0 mL) and stirred for 40 min. After purification by extensive dialysis using a cellulose

bag (MWCO 6000) for 24 h versus distilled water with changing every 8 h to remove the unwrapped and/or slid-down β-CDs, the products were freeze-dried and collected. Its GPC curves before and after dialysis are shown in Figure S6.

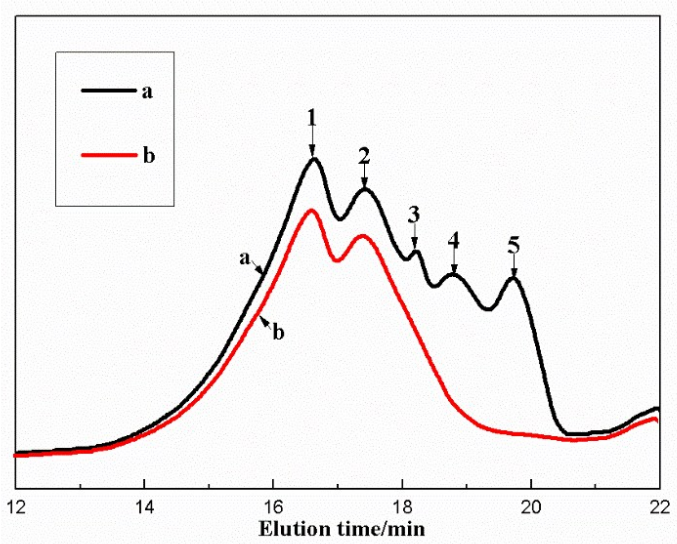


Figure S5. GPC curves of PR-46-23β-CD-8 before (a) and after dialysis purification (b) using DMSO as eluent.

4. Characterisation

4.1 FTIR measurements

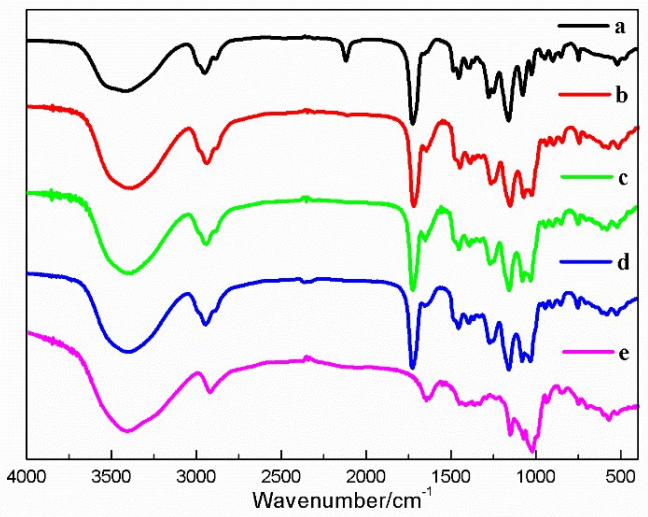


Figure S6. FTIR spectra of PH-46-2N_3 (a), PH-46-2β-CD obtained at n=2 (b), 4 (c), and 8 (d) and PA-β-CD (e).

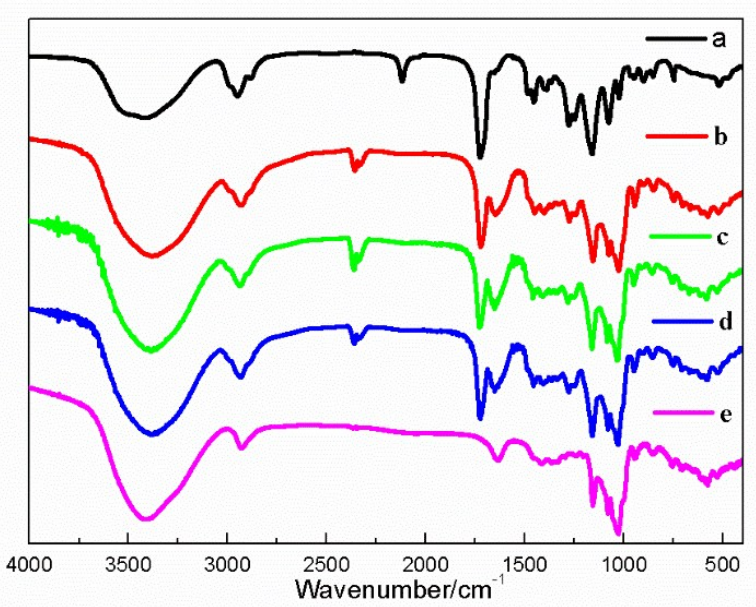


Figure S7. FTIR spectra of PH-46-2N_3 (a), PR-46-23β-CD-4 (b), PR-46-23β-CD-8 (c), PR-46-23β-CD-16 (d) and β-CD (e).

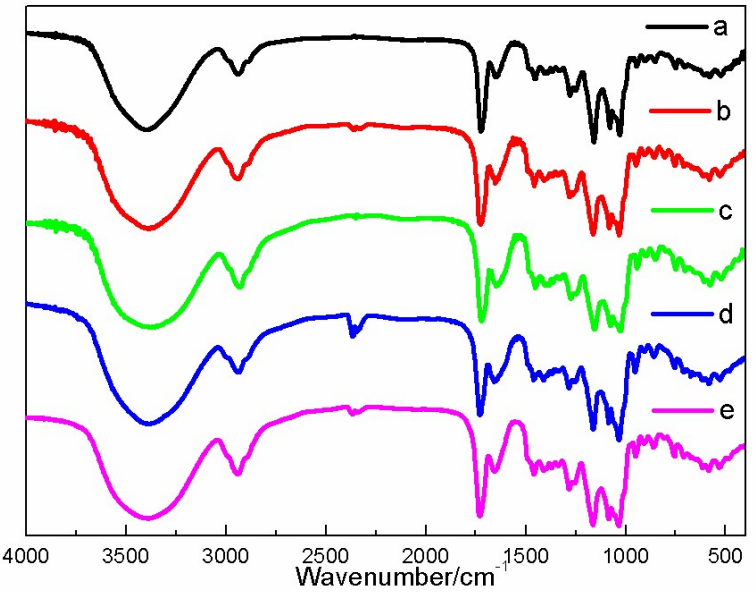


Figure S8. FTIR spectra of PR-46-11.5β-CD-8 (a), PR-46-16β-CD-8 (b), PR-46-19β-CD-8 (c), PR-46-23β-CD-8 (d) and PR-46-46β-CD-8 (e).

4.2 ^{1}H NMR analyses

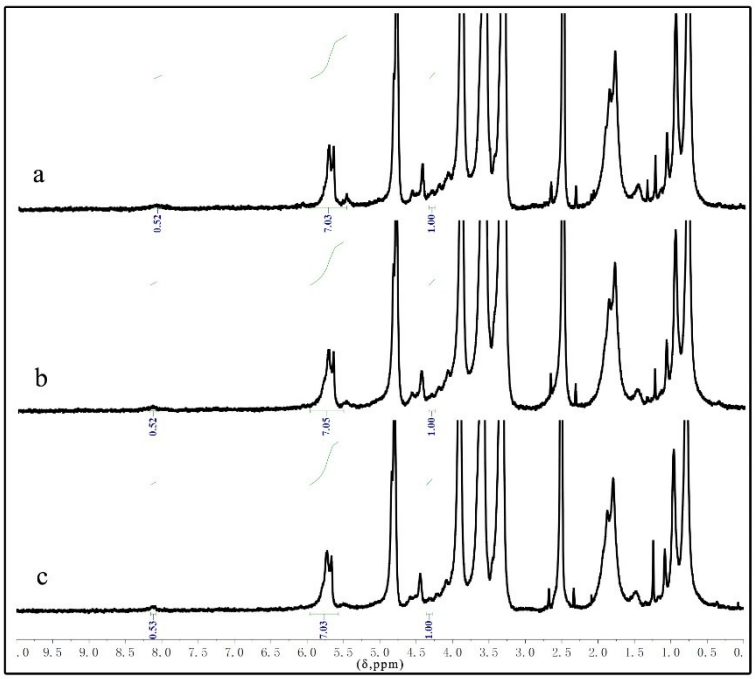


Figure S9. ^{1}H NMR spectra of PH-46-2β-CD obtained at n=2 (a), 4 (b), and 8 (c) in DMSO-d_6.

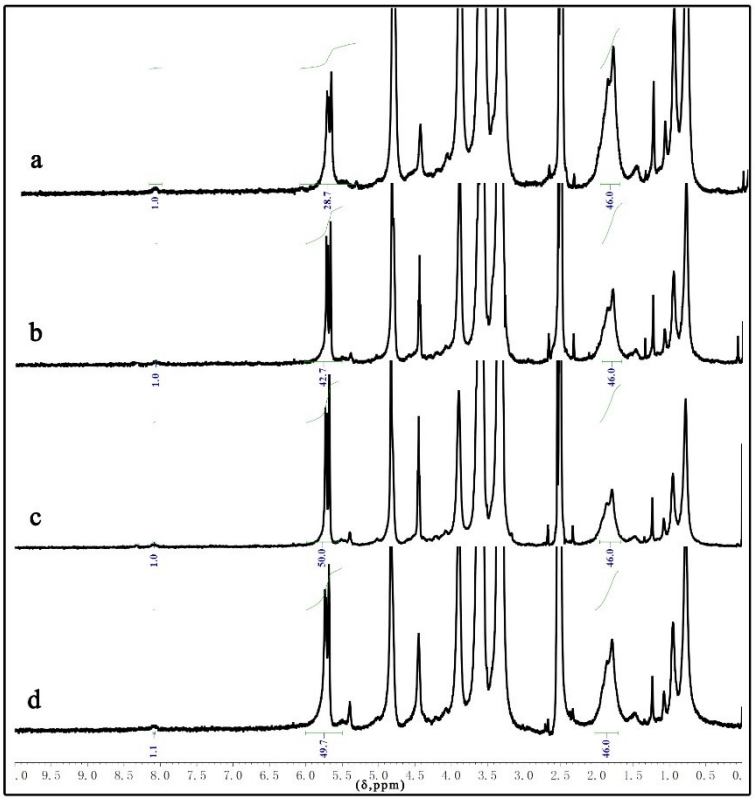


Figure S10. ^{1}H NMR spectra of PR-46-11.5β-CD-8 (a), PR-46-16β-CD-8 (b), PR-46-19β-CD-8 (c) and PR-46-46β-CD-8 (d) in DMSO-d_6.

4.3 GPC measurements

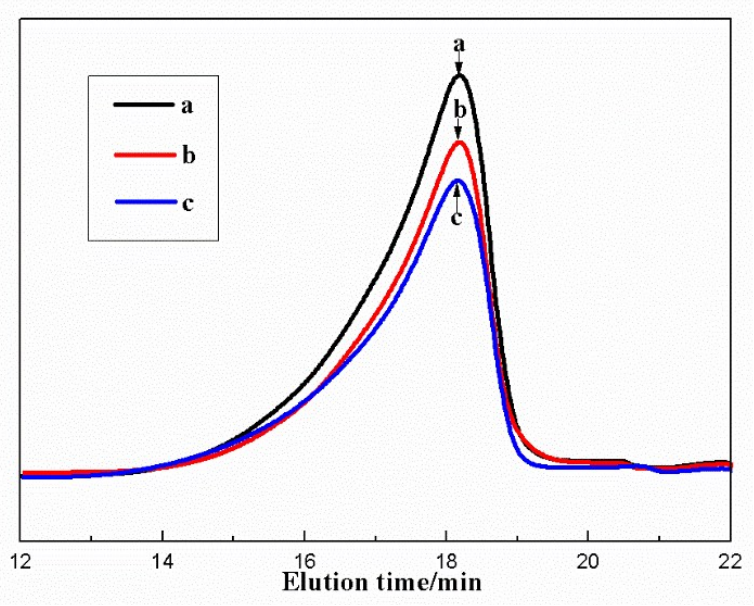


Figure S11. GPC traces of PH-46-2β-CD at 15 mg/0.5 mL (a), 10 mg/0.5 mL (b) and 5 mg/0.5 mL (c) using DMSO as eluent.

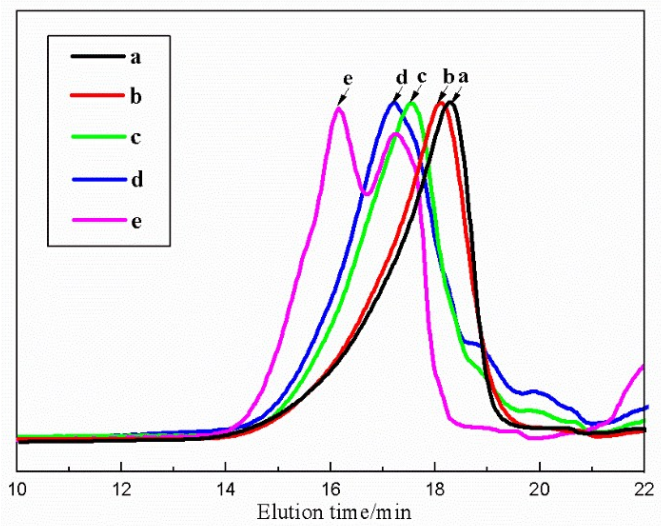


Figure S12. GPC traces of PH-46-2β-CD (a), PR-46-11.5β-CD-8 (b), PR-46-16β-CD-8 (c), PR-46-19β-CD-8 (d) and PR-46-46β-CD-8 (e) using DMSO as eluent.

4.4 TGA measurements

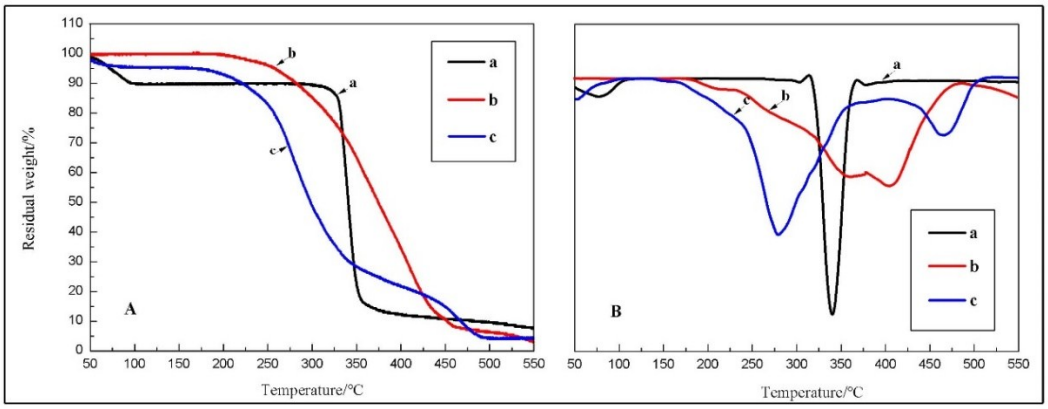


Figure S13. TGA (A) and DTG (B) traces of β-CD (a), PH-46-2N_3 (b) and PH-46-2β-CD (c).

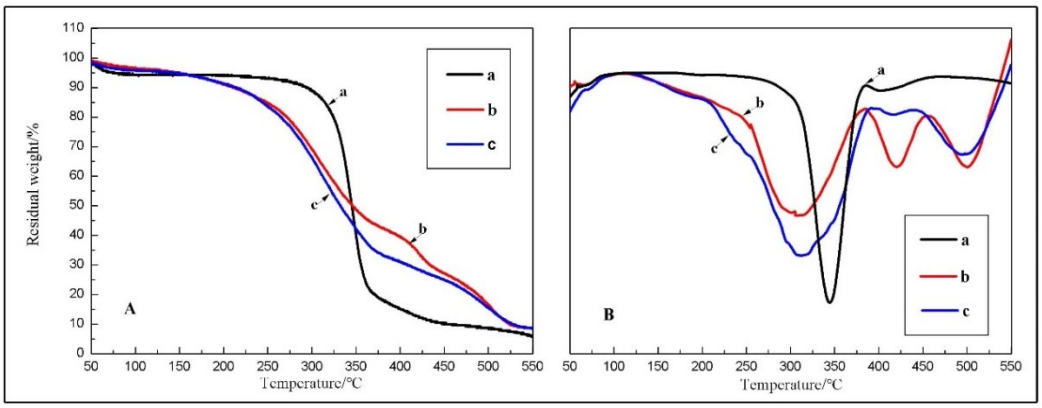


Figure S14. TGA (A) and DTG (B) traces of PPR-46-23β-CD (a), PR-46-23β-CD-4 (b) and PR-46-23β-CD-16 (c).

4.5 2D-ROESY NMR measurements.

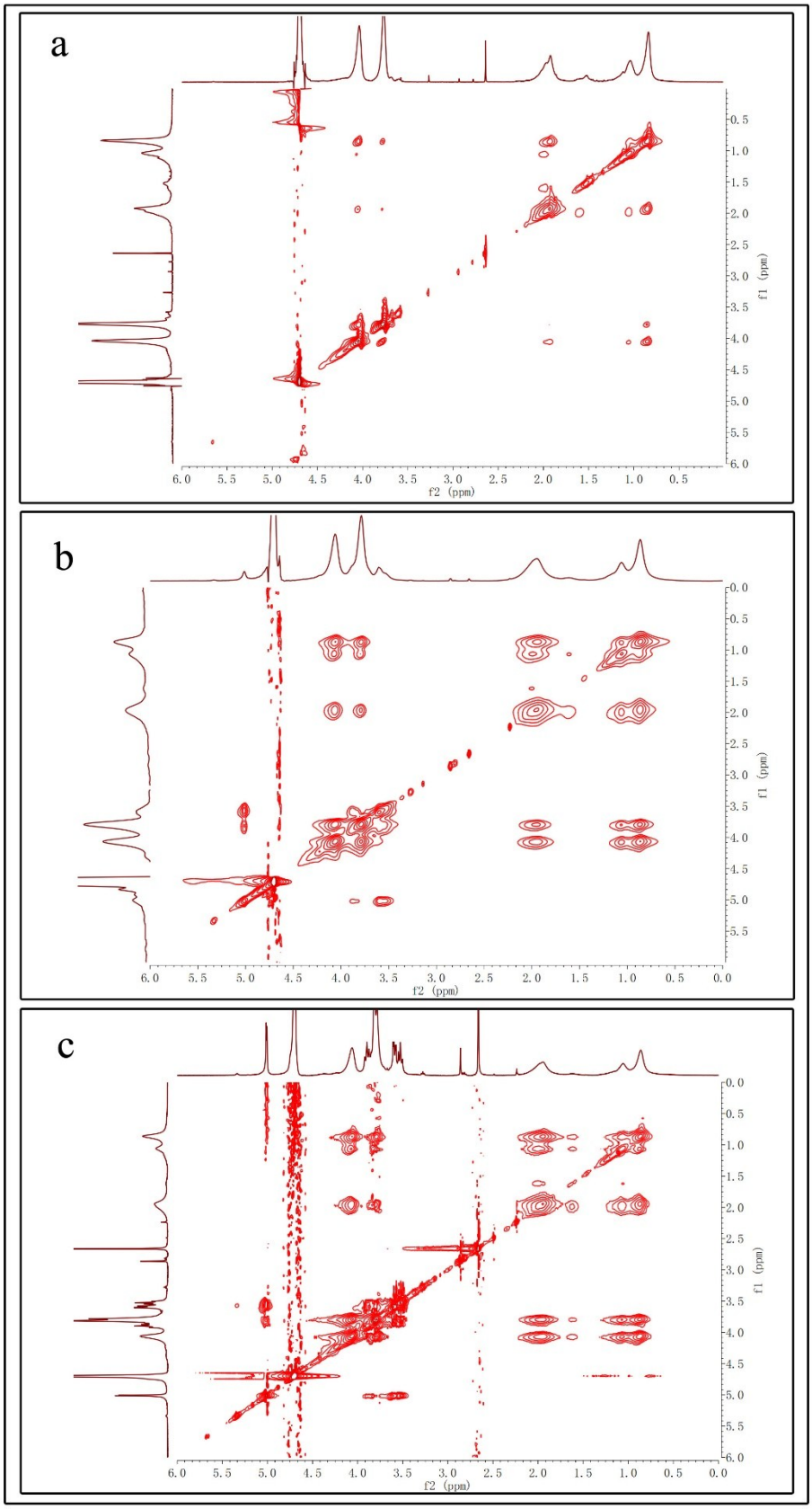


Figure S15. 2D-ROESY NMR spectra of PH-46-2N_3 (a), PH-46-2β-CD (b) and PR-46-23β-CD-4 (c).

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