Carbohydrate Polymers 79 (2010) 642–647

Contents lists available at ScienceDirect

Carbohydrate Polymers

journal homepage: www.elsevier.com/locate/carbpol

Combination of hydrophobic effect and electrostatic interaction in imprinting for achieving efficient recognition in aqueous media

Zhifeng Xu *, Daizhi Kuang, Yonglan Feng, Fuxing Zhang

Department of Chemistry and Material Science, Hengyang Normal University, Key Laboratory of Functional Organometallic Materials of Hengyang Normal University, College of Hunan Province, Hengyang 421008, PR China

ARTICLE INFO

Article history:
Received 30 June 2009
Received in revised form 29 July 2009
Accepted 14 September 2009
Available online 18 September 2009

Keywords:
Molecular imprinting
Acifluorfen
β-Cyclodextrin
Molecular recognition

ABSTRACT

An acifluorfen-imprinted polymer (P_1) was prepared by the combined use of bismethacryloyl-β-cyclodextrin (BMA-β-CD) and 4-vinylpyridine (4-VP) as functional monomers. Compared with the molecularly imprinted polymers (MIPs) using only BMA-β-CD or 4-VP as a functional monomer, P_2 and P_3, respectively, P_1 showed higher binding capacity (C_p) and imprinting factor (*IF*) for acifluorfen in aqueous media. Scatchard plot analysis revealed that two classes of binding sites were formed in the imprinted polymer P_1 with dissociation constants of 0.435 and 0.868 μmol/ml, respectively. The results of competitive binding experiments showed that P_1 can separate acifluorfen from its structural analogs. The study indicated that the combination of hydrophobic effect and electrostatic interaction in imprinting process is a feasible approach for achieving molecular recognition in aqueous media.

1. Introduction

Molecular imprinting technique is one of the most promising methodologies for synthesizing artificial receptors and can be extensively used in chromatographic separation (Baggiani, Baravalle, Giraudi, & Tozzi, 2007; Haginaka, 2002), solid-phase extraction (Puoci, Garreffa, Iemma, & Muzzalupo, 2005; Zhu, Yang, Su, Cai, & Gao, 2005), catalysis (Matsui, Nicholls, Karube, & Mosbach, 1996; Meng, Yamazaki, & Sode, 2004), binding assays and sensor (Hsu & Yang, 2008; Kröger, Turner, Mosbach, & Haupt, 1999). So far, most of the reported molecularly imprinted polymers (MIPs) only function in organic solvent. Reports on imprinted polymers, which can function in aqueous systems, are still limited. The main barrier preventing imprinting in aqueous media, is due to the nature of hydrogen bonding. Hydrogen bonding is the most commonly exploited interaction for the non-covalent molecular imprinting. However, hydrogen bonding interactions between template and functional monomers are easily destroyed in aqueous media because aqueous solvents can compete with the template for the functional monomers. Previous studies have shown that an imprinted polymer prepared based on hydrogen bonding interactions lost its molecular recognition ability in aqueous systems or organic solvents with high polarity (Xu, Liu, & Deng, 2006; Yu & Mosbach, 2000). In order to achieve effective imprinting in aqueous solution, different methods, such as metal ion mediated imprinting (Wu & Li, 2003), stoichiometric imprinting (Lübke, Lübke, Whitcombe, & Vulfson, 2000; Urraca, Moreno-Bondi, Hall, & Sellergren, 2007), have been investigated during the past few years. Recently, β-cyclodextrin (β-CD) and its derivatives have been chosen as functional monomers for making MIPs, and the synthesized MIPs were successfully used to separate some biological compounds, such as steroids (Hishiya, Shibata, Kakazu, Asanuma, & Komiyama, 1999), antibiotics (Asanuma, Akiyama, Kajiya, Hishiya, & Komiyama, 2001; Hishiya, Akiyama, Asanuma, & Komiyama, 2002), peptides (Akiyama, Hishiya, Asanuma, & Komiyama, 2001), cholesterols (Asanuma, Kakazu, Shibata, Hishiya, & Komiyama, 1998) and other compounds (Xu, Xu, Kuang, Zhang, & Wang, 2008) in aqueous solution. The main strategies to exploit β-CD and its derivatives in molecular imprinting are as follows: for those comparatively big templates, several β-CD molecules are assembled around the template and each β-CD molecule accommodates a part of the template, so that the assembled β-CD molecules can work as a whole to recognize the template precisely (Asanuma et al., 1998; Hishiya et al., 1999; Xu et al., 2008). When making MIPs for those templates whose main body could be accommodated in the cavity of β-CD, β-CD and another compound are used as combinatorial functional monomers (Piletsky, Andersson, & Nicholls, 1999).

Acifluorfen is an effective and selective herbicide for control most broad-leaved weeds. The widespread use of acifluorfen has lead to increased food, soil, and water pollution by its residues. It is important to develop analytic methods for determining its present in environment at low levels. In this study, the utilization of β-CD as functional monomer in molecular imprinting is further investigated. Combining the features of β-CD and molecularly imprinting method, a MIP was fabricated using acifluorfen as the

* Corresponding author. Tel.: +86 734 8486630; fax: +86 734 8486629.
E-mail address: xuzhifenghw@163.com (Z. Xu).

0144-8617/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.carbpol.2009.09.010

template, 4-vinylpyridine (4-VP) and bismethacryloyl-cyclodextrin (BMA-β-CD) as functional monomers. To the best of our knowledge this is the first time a MIP designed for recognition of acifluorfen in aqueous media. In order to gain more insight into the origin of the recognition ability of the imprinted polymer, two referenced MIPs using only BMA-β-CD or 4-VP as a functional monomer were also prepared. The recognition abilities and binding characteristics of the synthesized polymers were evaluated by equilibrium binding experiments and competitive binding experiments.

2. Experimental

2.1. Materials and instruments

β-CD and 2,2-azobisisobutyronitrile (AIBN) were purchased from Shanghai Chemical Plant (Shanghai, China). AIBN was recrystallized from methanol and β-CD was recrystallized from water and dried under vacuum at 110.0 °C for 24 h. Acifluorfen, fomesafen were obtained from Shandong Shenxing Pharmaceutical Industry Limited Company (Qingzhou, China). Ibuprofen was obtained from South Hospital (Guangzhou, China). Ethylene dimethacrylate (EDMA) was obtained from Jiangsu Anli Chemical Plant (Suzhou, China), it was distilled under vacuum after being extracted with 10% sodium hydroxide and dried over anhydrous magnesium sulfate. 4-VP was purchased from Acros (NJ, USA) and was distilled under vacuum to remove the inhibitor. DMSO and pyridine were purchased from Guangzhou Chemical Plant (Guangzhou). Before use, they were dried by molecular sieve 3A and distilled under vacuum. DMSO-d_6 was purchased from Cambridge Isotope Laboratories Inc. (USA). HPLC grade methanol was purchased from Tianjing Damao Chemical Plant (Tianjing, China). Water was double deionised and filtered through a 0.45 μm filter. All the other solvents were of analytical grade and used as received.

Methacryloyl chloride was synthesized by the reaction of methacrylic acid and dichlorosulfoxide, 74% yield: bp 97–98.5 °C; ^{1}H NMR ($CDCl_3$) δ (ppm): 2.02 (s, 3H, CH_3); 5.03 (s, 1H, —CH_a=C—), 6.50 (s, 1H, —CH_b=C—).

^{1}H NMR spectrum was recorded on a Varian INOVA 500NB (Varian, USA). FT-IR spectrum was recorded on an EQUINOX55 FT-IR spectrophotometer (Bruker, Germany). The thermal gravimetric analysis (TGA) was performed using a TGS-2 (Perkin–Elmer, USA) at heating rate 10 °C/min under air atmosphere. UV–vis was performed on a UV2100 spectrophotometer (Unico, China). The elemental analysis was measured on a Vario EL CHNS Elemental Analyzer (Elementar, Germany).

A Shimadzu CTO-10AVP HPLC system (Shimadzu, Kyoto, Japan) equipped with a LC-10AD pump, a SPD-10AVP UV–vis detector and a Shim-pack VP-ODS C18 analytic column (150 × 6.0 mm) was used for the chromatographic experiments. The mobile phase was prepared with methanol and water (50:50, v/v). The UV detection wavelength was 254 nm and the flow rate of mobile phase was 0.8 ml/min. The column temperature was set at 33 °C and sample injection volume was 5 μl.

2.2. Synthesis of bismethacryloyl-β-cyclodextrin (BMA-β-CD)

The synthesis procedure of BMA-β-CD was as below: β-CD (18.50 g, 16.30 mmol) was dissolved in 120 ml of pyridine, the solution was cooled to 0 °C. Then, an ice-chilled solution of methacryloyl chloride (3.91 g, 37.50 mmol) in ether (20 ml) was added dropwise to this solution with stirring magnetically under nitrogen. The reactive mixture was slowly warmed to room temperature and stirred for 24 h. After that, the solvent was evaporated in rotary evaporator. The residue was washed with ethanol for several times and gave a white product in 71% yield. The product was substitutional isomers with 2.0 methacryloyl substitutions per β-cyclodextrin determined from the elemental analysis (Anal. Calcd. for BMA-β-CD: C 46.09, H 5.99%; found: C 46.31, H 5.67%). FT-IR (KBr) ν(cm^{-1}): 3600–3000, 2928, 1726, 1635, 1489, 1406, 1154, 1080, 1031, 756, 683, 579.

2.3. ^{1}H NMR experiments

^{1}H NMR experiments were used to study the interactions between β-CD and acifluorfen. The ^{1}H NMR spectra were recorded in DMSO-d_6 using TMS as the internal standard. The concentration of the acifluorfen or β-CD unitary solution in DMSO-d_6 was kept at 0.02 mmol ml^{-1}. The initial β-CD and acifluorfen concentrations of the mixed solution were 0.02 mmol ml^{-1} also.

2.4. Polymer synthesis

The components of the reaction mixtures for making imprinted (P_1) and non-imprinted (NP_1) polymers are listed in Table 1. P_1 was prepared by the "one-step method" (Hishiya et al., 1999). The synthesis procedure of P_1 is as follows: BMA-β-CD and acifluorfen were dissolved in DMSO in a 50 ml glass ampoule. After being magnetically stirred at room temperature for 2.0 h, 4-VP, EDMA and AIBN were added. After degassing and nitrogen purging, the ampoule was sealed under vacuum and the mixture was kept in a water bath at 60 °C for 36 h. The resultant rigid polymer was ground and passed through a 90 μm sieve. Fine particles were removed by repeated sedimentation in acetone. The obtained particles were Soxhlet extracted with a mixture of methanol–acetic acid (9:1, v/v) until acifluorfen in the elution could no longer be detected by spectrophotometer. Then the particles were washed with methanol to remove residual acetic acid and dried under vacuum at 60 °C. The corresponding non-imprinted polymer (NP_1) was prepared similarly. Two reference imprinted polymers (P_2, P_3) using only BMA-β-CD or 4-VP as a functional monomer and their corresponding non-imprinted polymers (NP_2, NP_3) were also prepared (Table 1).

2.5. Equilibrium binding experiments

Equilibrium binding experiments were conducted to evaluate the binding properties of the polymers. The polymer particles (20.0 mg) were put in a 10 ml conical flask and mixed with 3.0 ml of a known concentration of selected substrate solution. The conical flask was oscillated for 6 h at 30 °C. Then, the mixture was filtrated through a 0.45 μm filter. The concentration of the filtrate was determined by spectrophotometer. The amount of substrate bound to the polymer Q (μmol) was calculated according to

$$Q\ (\mu\text{mol}) = V(C_i - C_l)$$

where V, C_i and C_l represent the volume of the solution (ml), initial solution concentration and the concentration after adsorption (concentration at equilibrium) (μmol/ml), respectively. The average data of triplicate independent results were used for the following discussion.

2.6. Competitive binding experiments

Acifluorfen was mixed with its analog compounds, fomesafen and ibuprofen to form a mixture solution. The initial concentration of each compound was the same (2.0 mmol/l). The polymer particles (P_1 or NP_1) (30.0 mg) were placed in a conical flask and mixed with 3.0 ml of the mixture solution. After being shaken for 6.0 h at 30 °C, the mixture was filtrated through a 0.45 μm filter. The filtrate (1.0 ml) was diluted to 5.0 ml with solvent. Then, the analytes in the solution were analyzed by HPLC.

Table 1
Composition of the polymerization mixtures for synthesizing polymers.

Polymer	BMA-β-CD (mmol)	4-VP (mmol)	Acifluorfen (mmol)	EDMA (mmol)	DMSO (ml)
P_1	0.50	0.50	0.50	5.0	8
NP_1	0.50	0.50	–	5.0	8
P_2	0.50	–	0.50	5.25	7
NP_2	0.50	–	–	5.25	7
P_3	–	0.50	0.50	8.26	6
NP_3	–	0.50	–	8.26	6

3. Results and discussion

3.1. Method for preparation of MIPs

In non-covalent approaches to molecular imprinting, non-covalent interactions such as hydrogen bonding, π–π bonding, electrostatic interaction, hydrophobic effect and metal ion-coordination, can be exploited to organize the functional monomers around the template. While hydrogen bonding interactions between template and functional monomers are destroyed in aqueous media, hydrophobic effect can be exploited. However, hydrophobic effect is less specific because it is applicable to broad groups of compounds. A solution to this problem is to combine hydrophobic effect with other types of interactions (for instance, electrostatic interaction, metal ion-coordination, etc.) in the imprinting process (Piletsky et al., 1999).

β-CD molecule is a torus-shaped cyclicoligosaccharide consisting of 1,4-linked D-glucopyranose units with an internal hydrophobic cavity. This structure enables it to form inclusion compounds with many compounds in aqueous media or organic solvents with high polarity through hydrophobic interactions. In the present study, the lipophilic aromatic rings of acifluorfen can be inserted into the cavity of BMA-β-CD to form inclusion complex in DMSO. ^{1}H NMR experiments were conducted to study the interactions between β-CD and acifluorfen in DMSO. The results of the ^{1}H NMR experiments indicated that the proton chemical shifts of β-CD and acifluorfen almost did not change whether β-CD and BPP are mixed or not. But, the NMR signals shapes of the protons on the C-3, C-5, C-6 (marked as H_3, H_5 and H_6, respectively) in the glucopyranose ring of β-CD have changed, as shown in Fig. 1. This indicates that acifluorfen can be inserted into the cavity of β-CD and can change the circumstance of the inner core of β-CD (Tong, 2001).

In the pre-polymerization mixture for synthesis P_1, when BMA-β-CD was mixed with acifluorfen in DMSO, the aromatic rings of acifluorfen were entrapped inside the hydrophobic core of BMA-β-CD and the more polar carboxyl group (–COOH) of acifluorfen was left outside the cavity. When 4-VP was added, the carboxyl group can form strong ionic interactions with this basic functional monomer. Thus, the BMA-β-CD molecule and 4-VP molecule are regularly placed. The positions and mutual conformations of BMA-β-CD molecule and 4-VP molecule are fixed by cross-linking. This imprinting process is schematic illustrated in Fig. 2.

To investigate the contribution of the used functional monomers, the other two reference imprinted polymers (P_2, P_3) and their corresponding non-imprinted polymers were also prepared. To ensure that the concentrations of the β-CD residues in P_2 and NP_2 and the 4-VP residues in P_3 and NP_3 are equal to that in the P_1 and NP_1, different amounts of cross-linkers were used (Table 1).

3.2. Properties of the polymers P_1 and NP_1

The results of the elemental analysis of P_1 and NP_1 were as follows: P_1 found: C 55.18, H 6.35, N 0.396%; NP_1 found: C 55.34, H 6.42, N 0.385%. Anal. Calcd. for P_1 and NP_1 (calculated according to the chemical composition for making these polymers): C 55.60, H 6.64, N 0.41%. These indicated that most of the components for making the polymers had participated in the polymeric reactions. The stability of the polymers was investigated by the TGA analysis. The results indicated that both P_1 and NP_1 begin to decompose at around 270 °C. FT-IR (KBr) ν(cm^{-1}) of P_1: 3600–3000, 2927, 1730, 1637, 1457, 1391, 1260, 1156, 925, 735, 621. The location and shape of the major bands in FT-IR spectrum of NP_1 are very similar to those of P_1.

3.3. Binding characteristics of the polymers for acifluorfen

The amount of acifluorfen bound to the polymers was determined by equilibrium binding experiments. The affinity of the polymers was estimated by the distribution coefficients of acifluorfen between polymer and solution. The distribution coefficient K_d (ml/g) is defined as (Zhu, Haupt, & Knopp, 2002):

$$K_d(\mathrm{ml/g}) = C_p/C_l$$

C_p (μmol/g) is the binding capacity of the polymer, it was calculated according to

$$C_p(\mu\mathrm{mol/g}) = \frac{Q(\mu\mathrm{mol})}{(\text{mass of polymer in g})}$$

The specific binding capacity ΔC_p *(μmol/g)* was calculated according to

$$\Delta C_P = C_{p(\mathrm{MIP})} - C_{p(\mathrm{NP})}$$

The molecular imprinting factor *IF* was used to evaluate the imprinting effect. *IF* was calculated according to

$$IF = K_{d(\mathrm{MIP})}/K_{d(\mathrm{NP})}.$$

The obtained C_p, ΔC_p, K_d and *IF* values are listed in Table 2.

The polymer P_1, containing both functional monomers, BMA-β-CD and 4-VP, and imprinted with acifluorfen, demonstrated superior selectivity to the reference polymer (NP_1). Compared with P_2

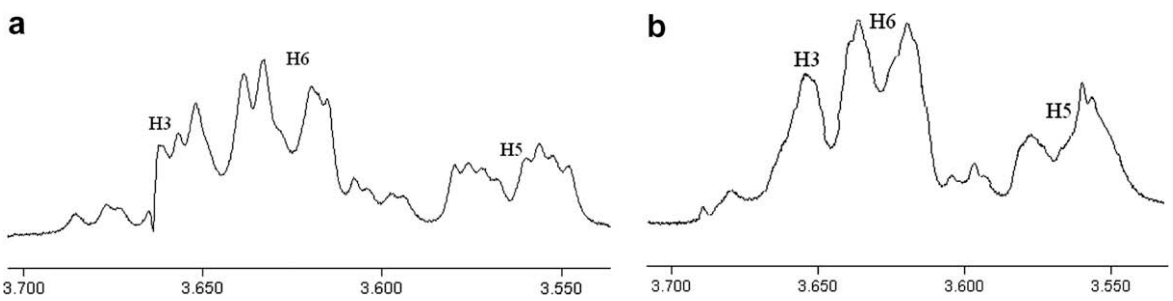

Fig. 1. Part of enlarged ^{1}H NMR spectra of β-CD: before (a) and after (b) mixed with acifluorfen in DMSO-d_6. H_3, H_5 and H_6 represent the protons on the C-3, C-5 and C-6 in the glucopyranose ring of β-CD, respectively.

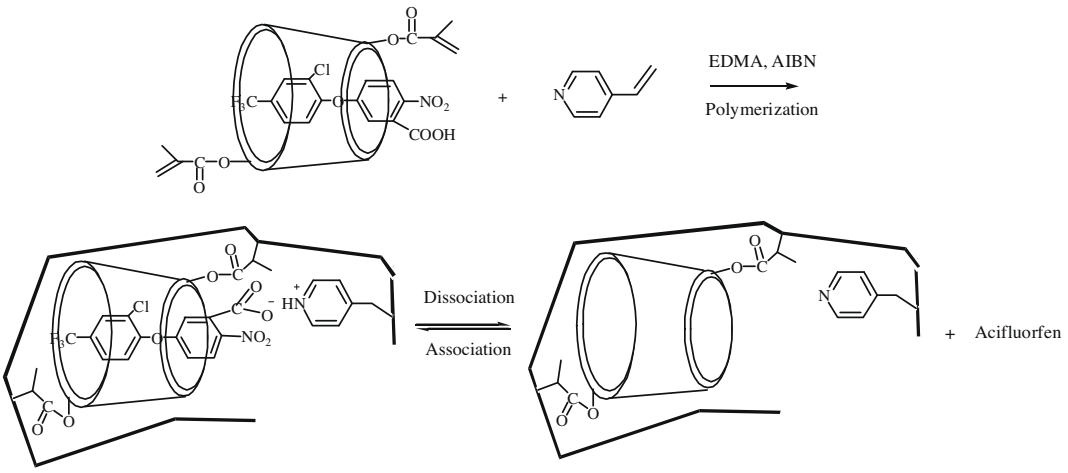

Fig. 2. Schematic illustration of the molecular imprinting procedure.

Table 2
Recognition of acifluorfen on polymers prepared with different functional monomers.[a]

	P_1	NP_1	P_2	NP_2	P_3	NP_3
C_p	47.63	28.45	23.54	21.67	31.24	20.16
ΔC_p	19.18		1.87		11.08	
K_d	28.32	15.72	12.77	11.68	17.43	10.81
IF	1.80		1.09		1.61	

[a] Initial concentration: 2.0 mmol/l; solvent:methanol/water (1:1, v/v); volume: 3 ml.

and P_3, P_1 showed the highest C_p, ΔC_p, K_d and *IF* values. In the recognition process, while the lipophilic aromatic rings of acifluorfen insert in the cavity of the modified β-CD through hydrophobic effects, the carboxyl group of acifluorfen can form strong ionic interactions with the basic functional group of 4-VP residues. The results of binding experiments demonstrated that the combined functional monomers imprinting strategy can increase the specific binding sites in the cavities of the polymer and thus enhances the molecular recognition ability. The polymer P_2, which was imprinted with acifluorfen only using the BMA-β-CD as the functional monomer, showed almost no imprinting effect. Table 2 shows that P_3 also has binding affinity for the template. P_3 was prepared in the absence of the BMA-β-CD monomer, there have electrostatic interactions between the templates and the basic monomers, and the electrostatic interactions also induced the imprinting effect. It is worthy of note that the binding capacity (C_p) of P_3 is much lower than P_1, although the concentrations of 4-VP residues in P_3 is equal to that in the P_1.

3.4. Adsorption isotherm

In an attempt to investigate the binding performance of the polymer, the binding isotherm of acifluorfen to polymers P_1 and NP_1 was determined in the 0–2.5 mmol/l range of initial concentration of acifluorfen. The results are shown in Fig. 3. It can be seen that the amount of acifluorfen bound to both polymers at equilibrium C_p increased along with increasing the initial concentration of acifluorfen, but the binding amount of acifluorfen on the imprinted polymer P_1 was more than that on the non-imprinted polymer NP_1 in the whole concentration range, reflecting the molecular imprinting effect.

The obtained binding data of acifluorfen to P_1 were further processed with Scatchard equation to estimate the binding properties of MIP (Matsui, Miyoshi, Doblhoff-Dier, & Takeuchi, 1995).

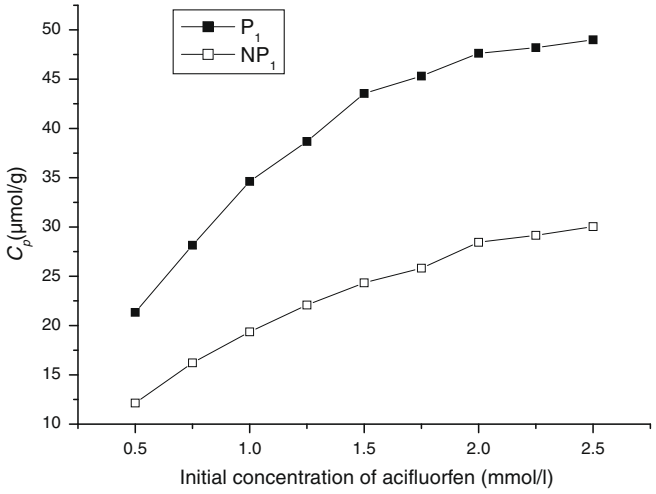

Fig. 3. Binding isotherm of P_1 and NP_1. solvent:methanol/water (1:1, v/v); volume: 3 ml.

$$\frac{C_p}{C_l} = \frac{C_{p\max} - C_p}{K}$$

where $C_{p\max}$ (μmol/g) is the apparent maximum number of binding sites and K (μmol/ml) is the dissociation constant. As shown in Fig. 4, the Scatchard plot is not a single straight line, but consists of two linear parts with different slope. The linear regression equations for the two linear regions are $C_p/C_l = -1.152C_p + 83.87$ ($r = 0.994$) and $C_p/C_l = -2.298C_p + 136.04$ ($r = 0.980$), respectively. This suggests that the binding sites in P_1 are heterogeneous in respect to the affinity for acifluorfen, and indicates that the binding sites could be classified into two groups with specific binding properties. The K and $C_{p\max}$ of the higher affinity binding sites can be calculated to be 0.435 μmol/ml and 59.20 μmol/g, respectively, from the slope and the intercept of the Scatchard plot. Similarly, the K and $C_{p\max}$ of the lower affinity binding sites were found to be 0.868 μmol/ml and 72.80 μmol/g, respectively.

3.5. Influence of H_2O content in methanol on adsorption

Different contents of H_2O in methanol (v/v) were used as solvents to evaluate the influence of H_2O on the binding of acifluorfen on the polymers P_1 and NP_1 (Fig. 5). It can be seen that the distribution coefficients of acifluorfen on P_1 and NP_1 increased with increasing the H_2O content in the range of 10–50% (v/v). As we

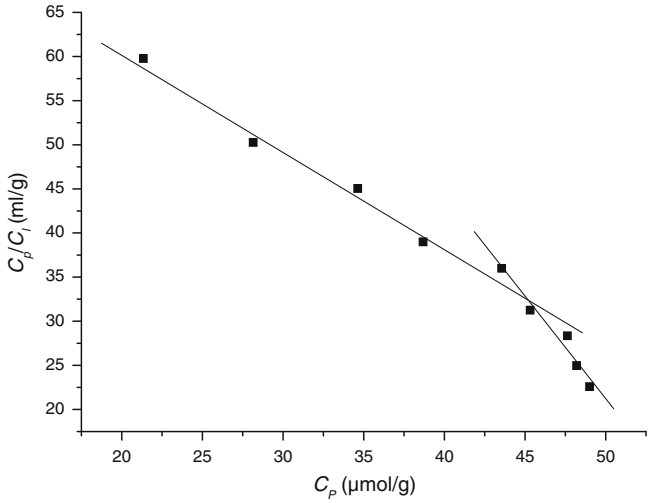

Fig. 4. Scatchard plot analysis of the binding of acifluorfen to P_1.

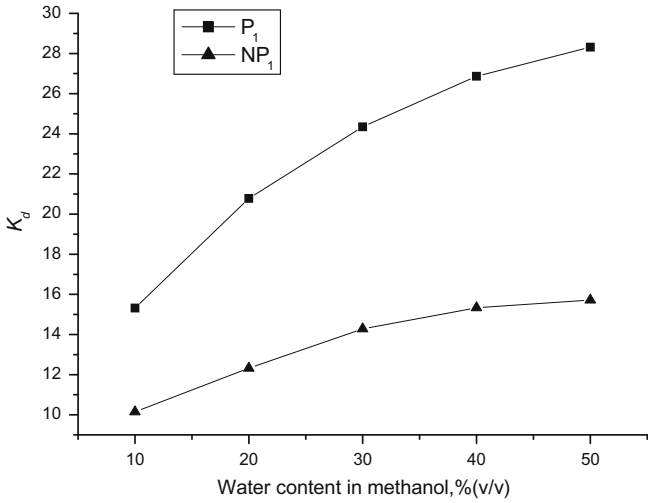

Fig. 5. The influence of H_2O content on adsorption. Initial concentration: 2.0 mmol/l; volume: 3 ml.

know, the cavity of β-CD is relatively hydrophobic compared to water. When the content of H_2O increased in the solvent, the hydrophobic effect increased also, more template molecules have been driven into the cavities of the polymers. The binding of acifluorfen to P_1 was caused by (1) insertion of acifluorfen into cavities created during the imprinting process, which are complementary both in shape and functional group arrangement to the template molecule, (2) insertion of acifluorfen into the cavities of β-CD residues which were random arrangement, and (3) unspecific interactions (e.g. electrostatic interaction, hydrophobic effect) between acifluorfen and polymers. The binding of acifluorfen to NP_1 was caused by points (2) and (3) mentioned above. The difference in binding mechanism between P_1 and NP_1 gives rise to the observed difference in the values of K_d between P_1 and NP_1.

3.6. Specific binding effect of the polymer P_1 in mixture solution

In this work, the recognition ability of the imprinted polymer P_1 toward acifluorfen was directly observed from the competitive adsorption experiment. To demonstrate the binding specificity of P_1, two analog molecules of acifluorfen, fomesafen and ibuprofen, were chosen. They were mixed with acifluorfen to form a mixture solution for adsorption. The adsorption amount of each component (C_p) by the polymer was determined by measuring the residual concentration of each component in the bulk solution. The samples were analyzed with HPLC and external standard method was used for quantification.

Fig. 6a and b are the chromatographs of the mixture solutions before and after being binding by P_1 (both solutions were diluted five times with THF before HPLC test). The binding capacity of P_1 for acifluorfen, ibuprofen and fomesafen can be calculated to be 38.45, 11.22 and 9.48 μmol/g, respectively. The binding capacity of NP_1 for acifluorfen, ibuprofen and fomesafen found to be 16.40, 8.55 and 9.12 μmol/g, respectively. The results of competitive adsorption experiment further confirmed that the imprinted polymer has molecular recognition ability.

After binding the compounds, P_1 was Soxhlet extracted with 6.0 ml of a methanol–acetic acid mixture (9:1, v/v). The eluate was concentrated to dryness by a nitrogen stream. The dry residue was dissolved in methanol and the volume of the solution was set at 3 ml. Then, the solution was analyzed by HPLC. The resulting chromatogram is presented in Fig. 6c. We can see that the main component of the eluate is acifluorfen. The concentration of acifluorfen is 0.317 mmol/l. The recovery efficiency of the polymer P_1 can be calculated to be 31.70 μmol/g. Compared with its C_p value (38.45 μmol/g), a recovery of 82.4% was obtained. These results indicated that the imprinted polymer P_1 can be used as a solid-phase extraction sorbent to separate the template from its analogs.

4. Conclusions

In this work, an acifluorfen-imprinted polymer (P_1) was prepared by using 4-VP and BMA-β-CD as bi-functional monomers. Using BMA-β-CD or 4-VP as the functional monomers, two reference imprinted polymers (P_2, P_3) were also synthesized. The imprinted polymer P_1 demonstrated superior selectivity to the

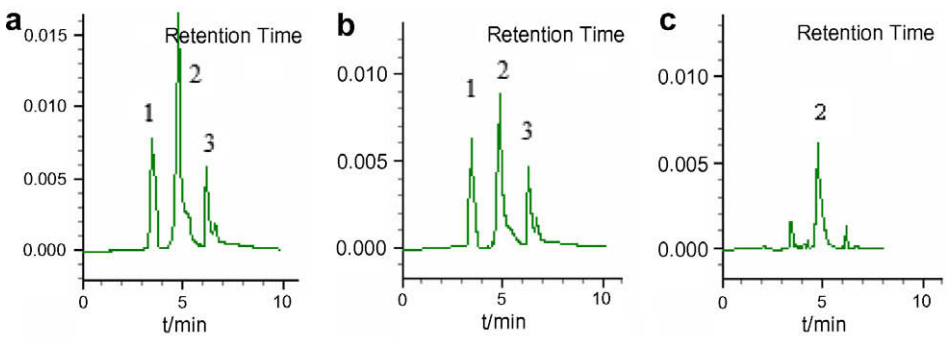

Fig. 6. Chromatographs on high performance liquid chromatography. (a) Mixture solution before adsorption, (b) mixture solution after adsorption by P_1, (c) eluate of P_1. 1 – Ibuprofen; 2 – acifluorfen; 3 – fomesafen.

polymers synthesized with a single functional monomer (P_2, P_3). The study revealed that the combination of hydrophobic and electrostatic interactions in molecular imprinting can effectively improve the recognition ability of the imprinted polymer. The MIP synthesis strategy is promising for realizing effective imprinting in aqueous media. The competitive binding experiments indicated that the imprinted polymer P_1 can be used as a solid-phase extraction sorbent to separate the template from its structural analogs.

Acknowledgement

This study was supported by the Open Fund Project of Key Laboratory in Hunan Universities and Scientific Research Program of Hengyang Science and Technology Bureau (No. 2008KS035).

References

Akiyama, T., Hishiya, T., Asanuma, H., & Komiyama, M. (2001). Molecular imprinting of cyclodextrin on silica-gel support for the stationary phase of high-performance-liquid-chromatography. *Journal of Inclusion Phenomena and Macrocyclic Chemistry, 41*, 149–153.

Asanuma, H., Akiyama, T., Kajiya, K., Hishiya, T., & Komiyama, M. (2001). Molecular imprinting of cyclodextrin in water for the recognition of nanometer-scaled guests. *Analytica Chimica Acta, 435*, 25–33.

Asanuma, H., Kakazu, M., Shibata, M., Hishiya, T., & Komiyama, M. (1998). Synthesis of molecularly imprinted polymer of β-cyclodextrin for the efficient recognition of cholesterol. *Supramolecular Science, 5*, 417–421.

Baggiani, C., Baravalle, P., Giraudi, G., & Tozzi, C. (2007). Molecularly imprinted solid-phase extraction method for the high-performance liquid chromatographic analysis of fungicide pyrimethanil in wine. *Journal of Chromatography A, 1141*, 158–164.

Haginaka, J. (2002). HPLC-based bioseparation using molecularly imprinted polymers. *Bioseparation, 10*, 337–351.

Hishiya, T., Akiyama, T., Asanuma, H., & Komiyama, M. (2002). Molecular imprinting of cyclodextrins leading to synthetic antibodies. *Journal of Inclusion Phenomena and Macrocyclic Chemistry, 44*, 365–367.

Hishiya, T., Shibata, M., Kakazu, M., Asanuma, H., & Komiyama, M. (1999). Molecularly imprinted cyclodextrins as selective receptors for steroids. *Macromolecules, 32*, 2265–2269.

Hsu, C. W., & Yang, M. C. (2008). Electrochemical epinephrine sensor using artificial receptor synthesized by sol–gel process. *Sensors and Actuators B, 134*, 680–686.

Kröger, S., Turner, A. P. F., Mosbach, K., & Haupt, K. (1999). Imprinted polymer based sensor system for herbicides using differential pulse voltammetry on screen printed electrodes. *Analytical Chemistry, 71*, 3698–3702.

Lübke, C., Lübke, M., Whitcombe, M. J., & Vulfson, E. N. (2000). Imprinted polymers prepared with stoichiometric template–monomer complexes: Efficient binding of ampicillin from aqueous solutions. *Macromolecules, 33*, 5098–5105.

Matsui, J., Miyoshi, Y., Doblhoff-Dier, O., & Takeuchi, T. A. (1995). Molecularly imprinted synthetic polymer receptor selective for atrazine. *Analytical Chemistry, 67*, 4404–4408.

Matsui, J., Nicholls, I. A., Karube, I., & Mosbach, K. (1996). Carbon–carbon bond formation using substrate selective catalytic polymers prepared by molecular imprinting: An artificial class II aldolase. *Journal of Organic Chemistry, 61*, 5414–5417.

Meng, Z. H., Yamazaki, T., & Sode, K. (2004). A molecularly imprinted catalyst designed by a computational approach in catalysing a transesterification process. *Biosensors and Bioelectronics, 20*, 1068–1075.

Piletsky, S. A., Andersson, H. S., & Nicholls, I. A. (1999). Combined hydrophobic and electrostatic interaction-based recognition in molecularly imprinted polymers. *Macromolecules, 32*, 633–636.

Puoci, F., Garreffa, C., Iemma, F., & Muzzalupo, R. (2005). Molecularly imprinted solid phase extraction for detection of Sudan I in food matrices. *Food Chemistry, 93*, 349–353.

Tong, L. H. (2001). *Chemistry of cyclodextrin: Foundation and application*. Beijing: Scientific Press.

Urraca, J. L., Moreno-Bondi, M. C., Hall, A. J., & Sellergren, B. (2007). Direct extraction of penicillin G and derivatives from aqueous samples using a stoichiometrically imprinted polymer. *Analytical Chemistry, 79*, 695–701.

Wu, L. Q., & Li, Y. Z. (2003). Picolinamide–$Cu(Ac)_2$-imprinted polymer with high potential for recognition of picolinamide–copper acetate complex. *Analytica Chimica Acta, 482*, 175–181.

Xu, Z. F., Liu, L., & Deng, Q. Y. (2006). Study on the mechanism of binding specificity of metoclopramide-imprinted polymers. *Journal of Pharmaceutical and Biomedical Analysis, 41*, 701–706.

Xu, Z. F., Xu, L., Kuang, D. Z., Zhang, F. X., & Wang, J. Q. (2008). Exploiting β-cyclodextrin as functional monomer in molecular imprinting for achieving recognition in aqueous media. *Material Science and Engineer C, 28*, 1516–1521.

Yu, C., & Mosbach, K. (2000). Influence of mobile phase composition and cross-linking density on the enantiomeric recognition properties of molecularly imprinted polymers. *Journal of Chromatography A, 888*, 63–72.

Zhu, Q. Z., Haupt, K., & Knopp, D. (2002). Molecularly imprinting polymer for metsulfuron-methyl and its binding characteristics for sulfonylurea herbicides. *Analytica Chimica Acta, 468*, 217–227.

Zhu, X. L., Yang, J., Su, Q. D., Cai, J. B., & Gao, Y. (2005). Selective solid-phase extraction using molecularly imprinted polymer for the analysis of polar organophosphorus pesticides in water and soil samples. *Journal of Chromatography A, 1092*, 161–169.