ELSEVIER

Journal of Chromatography A, 673 (1994) 219–230

JOURNAL OF CHROMATOGRAPHY A

Large-rim-tethered permethyl-substituted β-cyclodextrin polysiloxanes for use as chiral stationary phases in open tubular column chromatography

Guoliang Yi, Jerald S. Bradshaw*, Bryant E. Rossiter, Abdul Malik, Wenbao Li, Hao Yun, Milton L. Lee

Department of Chemistry, Brigham Young University, Provo, UT 84602-4672, USA

(First received February 25th, 1994)

Abstract

3-O-(*p*-Allyloxybenzoyl)heptakis(2,6-di-O-methyl)-β-cyclodextrin, which was used for preparation of permethylated 3-O-(*p*-allyloxybenzoyl)-β-cyclodextrin (**4**), was produced in a 15% yield by a monoesterification of heptakis(2,6-di-O-methyl)-β-cyclodextrin. Heptakis[6-O-(*tert.*-butyl)dimethylsilyl]-β-cyclodextrin was regioselectively monoesterified with *p*-allyloxybenzoyl chloride or *p*-(*tert.*-butyl)benzoyl chloride to yield 2-O-(*p*-allyloxybenzoyl)heptakis[6-O-(*tert.*-butyl)dimethylsilyl]-β-cyclodextrin (**6**) or 2-O-[*p*-(*tert.*-butyl)benzoyl]heptakis[6-O-(*tert.*-butyl)dimethylsilyl]-β-cyclodextrin (**7**). Compound **6** was acylated to give tridecaacetate **8**, which was deprotected and methylated, to give 2^A-O-(*p*-allyloxybenzoyl)heptakis(3-O-acetyl-6-O-methyl)-2^B,2^C,2^D,2^E,2^F,2^G-hexa-O-acetyl-β-cyclodextrin (**10**). Both **6** and **7** were methylated, following by deprotection and methylation (on the 6-position), to give permethylated 2^A-O-(*p*-allyloxybenzoyl)-β-cyclodextrin (**15**) and permethylated 2^A-O-[*p*-(*tert.*-butyl)benzoyl]-β-cyclodextrin (**16**), respectively. Then, **16** was treated with lithium aluminum hydride to form monoalcohol, which was transformed into permethylated 2^A-O-(*p*-allyloxybenzyl)-β-cyclodextrin (**18**) by a nucleophilic substitution reaction. Four new permethyl- or per(methyl/acetyl)-substituted β-cyclodextrin-bound methylpolysiloxanes were prepared by a hydrosilylation reaction of the monoalkenyl-substituted β-cyclodextrin derivatives **4**, **10**, **15** and **18** with a specially prepared hydromethylpolysiloxane. The polymeric phases provide excellent enantiomeric separations of a variety of chiral solutes in open tubular column supercritical fluid chromatography and gas chromatography.

1. Introduction

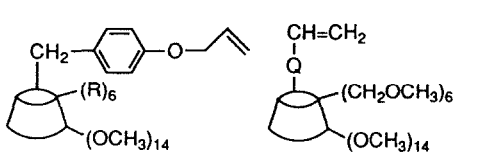
Immobilized chiral stationary phases (CSPs) derived from cyclodextrin and a polysiloxane are of interest because they provide not only excellent chromatographic performance, but also high thermal stability, and they can be prepared in a reproducible manner. Recently, we developed a new strategy to prepare cooperative copolymeric phases composed of cyclodextrin and hexasiloxane copolymeric parts [1]. These phases provided excellent resolution of a wide variety of chiral organic solutes in capillary supercritical fluid chromatography (SFC). We also reported the reproducible synthesis of new phases that have pendant cyclodextrin derivatives attached to a polysiloxane backbone by only one spacer group [2]. These latter phases provide superior

* Corresponding author.

0021-9673/94/$07.00
SSDI 0021-9673(94)00234-Z

separations in both SFC and gas chromatography (GC). Their performance appears to be better than phases prepared by Fischer *et al.* [3] and Schurig and co-workers [4–6] wherein the cyclodextrins were attached to the polysiloxane by an undetermined number of connecting groups.

Our reported cyclodextrin-bound polysiloxanes were prepared by the hydrosilylation reaction of a hydromethylpolysiloxane with permethylated 6-alkenyl-substituted β-cyclodextrins (**1a–1g**) that contained different substituents at the other 6-positions [2] (see Fig. 1). The chromatographic analysis of these phases indicates that the phase prepared from **1a** provided the best performance in both GC and SFC. The single connecting group in all these phases is tethered on the small rim of the cyclodextrin. In order to gain insight into the effect of the spacer position to chromatographic performance, four new permethyl- or per (methyl/acetyl)-substituted β-cyclodextrin polysiloxanes, wherein the cyclodextrins are attached through the 2- or 3-positions, have been synthesized. The synthetic routes to the monoalkenes needed for the hydrosilylation reaction are shown in Figs. 2 and 3, and their attachment to a polysiloxane is depicted in Fig. 4. These derivatives possess different spacers attached to different cyclodextrin positions, which provide new information for studies involving the chiral resolving abilities of cyclodextrin phases. These new cyclodextrin-containing phases provide enantiomeric resolution of a variety of chiral organic solutes in both capillary SFC and GC. Details of these chromatographic results will be reported later. This



1a. R = CH_2OCH_3
1b. R = $CH_2OC(O)CH_3$
1c. R = CH_3
1d. Q = CH_2CH_2
1e. Q = CH_2OCH_2
1f. Q = $CH_2O(CH_2)_8CH_2$
1g. Q = None

Fig. 1. Structures of persubstituted 6-O-alkenyl-β-cyclodextrins [2].

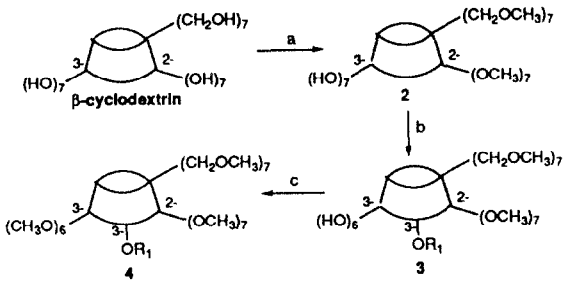


Fig. 2. Preparation of permethyl-substituted 3-O-(*p*-allyloxybenzoyl)-β-cyclodextrin **4**. a = $(CH_3)_2SO_4$, BaO, $Ba(OH)_2$, DMSO, DMF; b = *p*-allyloxybenzoyl chloride, pyridine; c = $CF_3SO_3CH_3$, 2,6-di-(*tert.*-butyl)-4-methylpyridine, CH_2Cl_2. R_1 = *p*-Allyloxybenzoyl.

paper reports the synthesis of these phases. Their utility in chromatography is shown by the separation of several racemic mixtures on three of the phases reported.

2. Experimental

Proton and carbon NMR spectra were recorded in C^2HCl_3 at 200 MHz. β-Cyclodextrin (Aldrich) was dried with P_2O_5 under vacuum at 100°C for 24 h before use. Organic extracts were dried over anhydrous $MgSO_4$. Heptakis[6-O-(*tert.*-butyl) dimethylsilyl]-β-cyclodextrin (**5**) was prepared as reported [1].

2.1. Heptakis(2,6-di-O-methyl)-β-cyclodextrin (2) (Fig. 2)

A mixture of 46.7 g (0.24 mol) of BaO and 46.7 g (0.14 mol) of $Ba(OH)_2 \cdot 8H_2O$ was slowly added at room temperature to a stirred solution of β-cyclodextrin (22.7 g, 0.02 mol) and dimethyl sulfate (93.3 g, 0.98 mol) in 280 ml of dimethyl sulfoxide (DMSO)–dimethylformamide (DMF) (1:1). The mixture was stirred at room temperature for 7 days, and the solvent was removed by vacuum distillation. The residue was extracted five times by 200-ml portions of hot $CHCl_3$ and the extract solution was washed with water, dried and concentrated. The crude product was dried under vacuum at 60°C for 24 h to remove traces of DMSO and DMF, and then

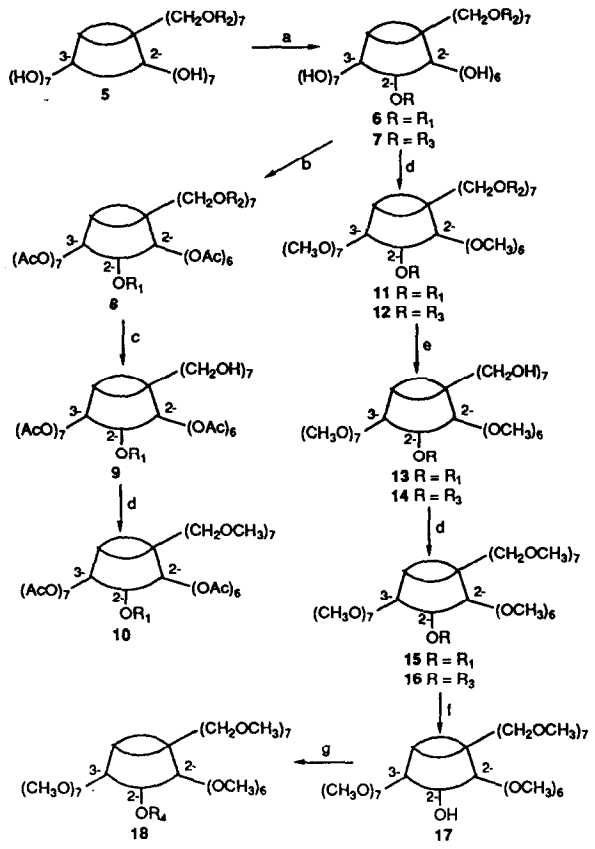
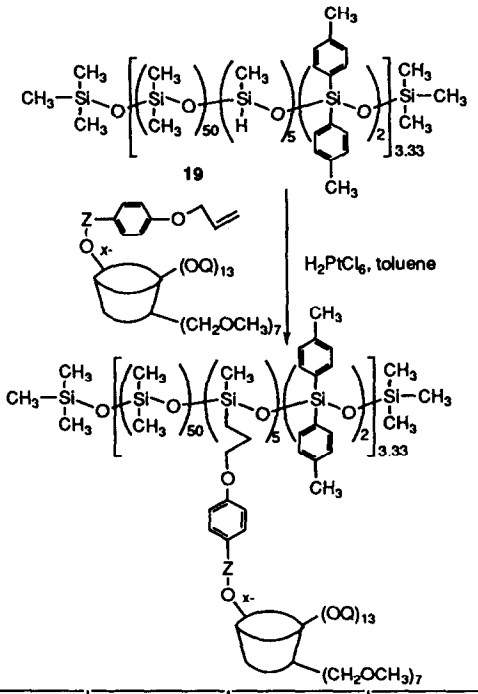


Fig. 3. Preparation of permethyl-substituted 2-O-alkenyl-β-cyclodextrins **10**, **15** and **18**. a = *p*-Allyloxybenzoyl chloride for **6** or *p-tert.*-butylbenzoyl chloride for **7**, NEt_3, toluene; b = $(CH_3CO)_2O$, pyridine; c = BF_3–OEt_2, CH_2Cl_2; d = $CF_3SO_3CH_3$, 2,6-di-(*tert.*-butyl)-4-methylpyridine, CH_2Cl_2; e = NH_4F, CH_3OH; f = $LiAlH_4$, diethyl ether (for **16**); g = NaH, *p*-allyloxybenzyl chloride. R_1 = *p*-Allyloxybenzoyl; R_2 = *tert.*-butyldimethylsilyl; R_3 = *tert.*-butylbenzoyl; R_4 = *p*-allyloxybenzyl.



Polymers	x-	Z	Q
20	3-	C=O	CH_3
21	2-	C=O	CH_3CO
22	2-	C=O	CH_3
23	2-	CH_2	CH_3

Fig. 4. Preparation of persubstituted β-cyclodextrin-bound polysiloxanes **20–23**.

subjected to column chromatography on silica gel ($CH_3C_6H_5$–C_2H_5OH, 20:1) to give crystalline **2** (14.7 g, 55%); m.p. 312–314°C (lit. [7,8] 312°C); $[\alpha]_D^{25}$ + 123.9° (*c* = 0.84, $CHCl_3$) (lit. [7,8] 122°); ^{1}H NMR δ 5.05 (s, 7 H, OH), 4.95 (d, *J* = 3.28 Hz, 7 H), 3.90 (overlapping dd, J_1 = 9.79 Hz, J_2 = 9.39 Hz, 7 H), 3.81–3.30 (m, 70 H), 3.24 (dd, J_1 = 3.28 Hz, J_2 = 9.79 Hz, 7 H); ^{13}C NMR δ 101.8, 84.1, 82.6, 73.7, 71.4, 70.8, 60.8, 59.4. Analysis for $C_{56}H_{98}O_{35}$: calculated: C, 50.52; H, 7.42; found: C, 50.69: H, 7.23.

2.2. 3-O-(p-Allyloxybenzoyl)heptakis(2,6-di-O-methyl)-β-cyclodextrin (3) (Fig. 2)

A solution of **2** (2.66 g, 2.0 mmol) and *p*-allyloxybenzoyl chloride (1.20 g, 6.0 mmol) in 100 ml of dry pyridine was stirred at 100°C for 2 days. Pyridine was removed by vacuum distillation. A solution of the residue in $CHCl_3$ was washed with water, dried and concentrated. Column chromatography ($CHCl_3$–CH_3OH, 100:1) of crude product gave 0.45 g (15%) of **3**; m.p. 273–275°C; $[\alpha]_D^{25}$ + 120.0° (*c* = 0.35, $CHCl_3$); ^{1}H NMR δ 8.01 (d, *J* = 8.82 Hz, 2 H), 6.89 (d, *J* = 8.82 Hz, 2 H), 6.00 (m, 1 H), 5.45–5.22 (m, 4 H), 5.08 (s, 6 H, OH), 5.00–4.86 (m, 4 H), 4.82 (d, *J* = 3.33 Hz, 1 H), 4.71 (d, *J* = 3.33 Hz, 1 H), 4.53 (d, *J* = 5.22 Hz, 2 H), 4.05–2.98 (m, 83 H); ^{13}C NMR δ 165.5,

133.1, 133.0, 132.2, 124.1, 118.5, 118.4, 114.6, 102.2, 102.0, 101.8, 101.7, 101.6, 84.9, 84.8, 84.7, 84.5, 84.4, 84.3, 84.1, 84.0, 83.8, 82.8, 82.5, 82.3, 81.8, 81.6, 81.5, 79.9, 78.4, 73.6, 73.5, 72.8, 72.6, 72.3, 72.2, 72.1, 71.8, 71.6, 71.4, 70.9, 70.6, 70.4, 69.3, 69.1, 61.2, 60.9, 60.8, 60.7, 59.6, 59.5, 59.4, 59.3. Analysis for $C_{66}H_{106}O_{37}$: calculated: C, 53.15; H, 7.16; found: C, 53.30; H, 7.35.

2.3. 3^A-O-(p-Allyloxybenzoyl)heptakis(2,6-di-O-methyl)-3^B,3^C,3^D,3^E,3^F,3^G-hexa-O-methyl-β-cyclodextrin (4) (Fig. 2)

A solution of **3** (0.23 g, 0.15 mmol), 2,6-di-(*tert.*-butyl)-4-methylpyridine (0.38 g, 1.9 mmol) and methyl trifluoromethanesulfonate (triflate (0.23 g, 1.4 mmol) in 5 ml of CH_2Cl_2 was stirred in a capped PTFE tube at 80°C for 2.5 h. After being dried and concentrated the crude product was purified by column chromatography ($CHCl_3$–CH_3OH, 100:1) to yield pure **4** (0.19 g, 79%); m.p. 243–244°C; $[\alpha]_D^{25}$ + 105.1° (c = 1.16, $CHCl_3$); ^{1}H NMR δ 8.04 (d, J = 8.83 Hz, 2 H), 6.91 (d, J = 8.83 Hz, 2 H), 6.04 (m, 1 H), 5.48–5.20 (m, 4 H), 5.17–5.05 (m, 4 H), 5.03 (d, J = 3.30, 1 H), 4.90 (d, J = 3.30, 1 H), 4.59 (d, J = 5.24 Hz, 2 H), 4.07–3.28 (m, 95 H), 3.18 (dd, J_1 = 3.30, J_2 = 9.60, 6 H); ^{13}C NMR δ 164.8, 133.1, 132.2, 124.4, 118.5, 114.4, 100.0, 99.8, 99.6, 99.3, 83.0, 82.9, 82.6, 82.5, 82.3, 82.2, 82.1, 82.0, 81.5, 81.3, 81.0, 80.8, 80.7, 79.2, 72.6, 72.0, 71.9, 71.7, 71.6, 71.4, 71.3, 71.2, 71.1, 71.0, 69.6, 69.3, 62.2, 62.0, 61.9, 61.8, 61.6, 60.0, 59.5, 59.4, 59.3, 59.1, 58.9, 58.7, 58.6. Analysis for $C_{72}H_{118}O_{37}$: calculated: C, 54.88; H, 7.55; found: C, 54.85; H, 7.92.

2.4. 2-O-(p-Allyloxybenzoyl)heptakis[6-O-(tert.-butyl) dimethylsilyl]-β-cyclodextrin (6) (Fig. 3)

A mixture of **5** (5.0 g, 2.6 mmol), *p*-allyloxybenzoyl chloride (0.5 g, 2.6 mmol) and NEt_3 (0.31 g, 3.1 mmol) in 50 ml of toluene was stirred at room temperature for 24 h. The mixture was diluted with 50 ml of toluene and washed successively with cold 3% HCl, 5% aqueous $NaHCO_3$ and water. The organic layer was dried and concentrated. The residue was chromatographed on silica gel ($CHCl_3$–CH_3OH, 20:1) to produce pure compound **6** (1.12 g, 21%); m.p. 255–256°C; $[\alpha]_D^{25}$ + 105.8° (c = 3.91, $CHCl_3$); ^{1}H NMR δ 7.95 (d, J = 8.85 Hz, 2 H), 6.87 (d, J = 8.85 Hz, 2 H), 6.02 (m, 1 H), 5.70–5.15 (m, 15 H), 5.11 (d, J = 3.28 Hz, 1 H), 5.01–4.73 (m, 7 H), 4.54 (d, J = 5.22 Hz, 2 H), 4.26–3.25 (m, 41 H), 0.90 (s, 63 H), 0.05 (s, 42 H); ^{13}C NMR δ 166.8, 133.1, 133.0, 132.7, 132.4, 122.2, 118.5, 115.0, 103.2, 102.7, 102.6, 102.5, 102.1, 100.7, 82.5, 82.2, 74.7, 74.6, 74.3, 74.0, 73.8, 73.5, 73.3, 73.2, 73.0, 72.7, 69.3, 69.2, 62.1, 26.4, 26.3, 19.0, 18.8, 18.7, −4.6, −4.7, −4.8. Analysis for $C_{94}H_{176}O_{37}Si_7$: calculated: C, 53.89; H, 8.47; found: C, 53.87; H, 8.22.

2.5. 2-O-[p-(tert.-Butyl)benzoyl]heptakis[6-O-(tert.-butyl)dimethylsilyl]-β-cyclodextrin (7) (Fig. 3)

Cyclodextrin derivative **7** was prepared as **6** above from 9.7 g (5.0 mmol) of **5**, 1.0 g (5.0 mmol) of *p*-(*tert.*-butyl)benzoyl chloride and 0.56 g (5.5 mmol) of NEt_3 to give 2.00 g (19%) of **7**; m.p. 264–266°C; $[\alpha]_D^{25}$ + 102.6° (c = 3.50, $CHCl_3$); ^{1}H NMR δ 7.97 (d, J = 8.54 Hz, 2 H), 7.43 (d, J = 8.54 Hz, 2 H), 5.50 (broad s, 13 H, OH), 5.39 (d, J = 3.23 Hz, 1 H), 5.00–4.75 (m, 7 H), 4.46–3.30 (m, 41 H), 1.29 (s, 9 H), 0.88 (s, 63 H), 0.05 (s, 42 H); ^{13}C NMR δ 166.2, 130.3, 127.8, 125.8, 102.6, 102.5, 102.4, 82.2, 77.6, 74.3, 74.1, 73.9, 73.6, 73.5, 73.3, 73.2, 73.0, 72.8, 72.7, 72.4, 62.2, 62.1, 35.5, 31.6, 26.7, 26.5, 26.4, 26.3, 26.1, 19.0, 18.8, 18.7, −4.6, −4.7, −4.8. Analysis for $C_{95}H_{180}O_{36}Si_7$: calculated: C, 54.46; H, 8.66; found C, 54.62; H, 8.49.

2.6. 2^A-O-(p-Allyloxybenzoyl)heptakis[3-O-acetyl-6-O-(tert.-butyl)dimethylsilyl]-2^B,2^C,2^D,2^E,2^F,2^G-hexa-O-acetyl-β-cyclodextrin (8) (Fig. 3)

A solution of **6** (0.84 g, 0.40 mmol) in 30 ml of acetic anhydride and 30 ml of pyridine was stirred at 100°C for 4 h. The solvent was re-

moved under reduced pressure and the residue was dissolved in $CHCl_3$. The solution was washed with water twice, dried and concentrated. The crude product was purified by column chromatography ($CH_3C_6H_5$–C_2H_5OH, 200:3) to give **8** (0.77 g, 73%); m.p. 136–138°C; $[\alpha]_D^{25}$ + 89.8° (c = 0.93, $CHCl_3$); ^{1}H NMR δ 7.97 (d, J = 8.83 Hz, 2 H), 6.97 (d, J = 8.83 Hz, 2 H), 6.06 (m, 1 H), 5.50–5.22 (m, 10 H), 5.22–5.08 (m, 6 H), 4.90 (dd, J_1 = 9.61 Hz, J_2 = 3.28 Hz, 1 H), 4.70 (dd, J_1 = 9.61 Hz, J_2 = 3.28 Hz, 6 H), 4.59 (d, J = 5.22 Hz, 2 H), 4.17–3.64 (m, 28 H), 2.17–1.75 (m, 39 H), 0.90 (s, 63 H), 0.06 (s, 42 H); ^{13}C NMR δ 171.3, 171.2, 171.1, 171.0, 170.0, 169.8, 169.5, 166.5, 133.1, 132.8, 122.1, 118.5, 114.9, 100.0, 96.8, 96.6, 77.7, 75.8, 75.7, 75.6, 72.6, 72.3, 72.2, 72.1, 71.9, 71.8, 71.7, 69.6, 69.3, 62.4, 62.3, 62.2, 26.3, 21.4, 21.2, 18.3, −4.5, −4.7, −4.8. Analysis for $C_{120}H_{202}O_{50}Si_7$: calculated: C, 54.56; H, 7.71; found: C, 54.36; H, 7.70.

*2.7. 2^A-O-(p-Allyloxybenzoyl)heptakis(3-O-acetyl)-2^B,2^C,2^D,2^E,2^F,2^G-hexa-O-acetyl-β-cyclodextrin (**9**) (Fig. 3)*

A solution of **8** (0.70 g, 0.27 mmol) in 15 ml of CH_2Cl_2 was stirred with BF_3–OEt_2 (0.32 g, 2.2 mmol) at room temperature for 6 h. The mixture was diluted with CH_2Cl_2 and poured into ice–water. The organic layer was separated, washed with water, aqueous $NaHCO_3$ and water, and then dried and concentrated. Column chromatography ($CHCl_3$–CH_3OH, 7:1, then 4:1) of the residue gave **9** (0.38 g, 78%); m.p. 178–179°C; $[\alpha]_D^{25}$ + 102.8° (c = 1.07, $CHCl_3$); ^{1}H NMR δ 7.95 (d, J = 8.72 Hz, 2 H), 6.95 (d, J = 8.72 Hz, 2 H), 6.03 (m, 1 H), 5.89–5.50 (m, 10 H), 5.50–5.17 (m, 6 H), 5.17–4.62 (m, 14 H), 4.57 (d, J = 5.24 Hz, 2 H), 4.40–3.40 (m, 28 H), 2.30–1.80 (m, 39 H); ^{13}C NMR δ 171.3, 171.2, 171.1, 169.8, 169.7, 166.5, 133.1, 133.0, 122.1, 118.6, 114.9, 97.4, 97.3, 97.2, 77.7, 73.0, 72.9, 72.8, 72.7, 72.5, 72.4, 72.3, 72.2, 72.1, 72.0, 71.9, 71.8, 71.7, 71.6, 71.5, 71.4, 71.3, 71.2, 71.1, 71.0, 70.8, 69.3, 61.2, 21.3, 21.2. Analysis for $C_{78}H_{104}O_{50}$: calculated: C, 50.87; H, 5.69; found: C, 50.96; H, 5.71.

*2.8. 2^A-O-(p-Allyloxybenzoyl)heptakis(3-O-acetyl-6-O-methyl)-2^B,2^C,2^D,2^E,2^F,2^G-hexa-O-acetyl-β-cyclodextrin (**10**) (Fig. 3)*

A mixture of **9** (0.38 g, 0.21 mmol), methyl triflate (0.49 ml, 4.3 mmol) and 2,6-di(*tert.*-butyl)-4-methylpyridine (1.2 g, 5.8 mmol) in 6 ml of CH_2Cl_2 was heated in a sealed tube at 80°C for 2.5 h and cooled. CH_3OH (6 ml) was added, and the mixture was stirred at room temperature for 1 h, and concentrated. A solution of the residue in $CHCl_3$ was washed successively with water, cold 3% HCl, aqueous $NaHCO_3$ and water, and then dried and concentrated. The product was subjected to column chromatography ($CHCl_3$–CH_3OH, 20:1) to give **10** (0.19 g, 50%); m.p. 127–128°C; $[\alpha]_D^{25}$ + 100.2° (c = 1.85, $CHCl_3$); ^{1}H NMR δ 7.95 (d, J = 8.78 Hz, 2 H), 6.94 (d, J = 8.78 Hz, 2 H), 6.02 (m, 1 H), 5.62–5.19 (m, 10 H), 5.19–5.00 (m, 6 H), 4.95 (dd, J_1 = 9.67 Hz, J_2 = 3.32 Hz, 1 H), 4.78 (dd, J_1 = 9.67 Hz, J_2 = 3.32 Hz, 6 H), 4.57 (d, J = 5.22 Hz, 2 H), 4.10–3.70 (m, 21 H), 3.65–3.43 (m, 7 H), 3.38 (s, 21 H), 2.15–1.70 (m, 39 H); ^{13}C NMR δ 171.2, 171.1, 170.1, 169.8, 169.5, 166.4, 133.0, 132.8, 121.2, 118.5, 114.9, 97.6, 96.9, 76.5, 76.2 75.7, 71.7, 71.3, 71.1, 70.9, 69.3, 59.6, 21.3, 21.1. Analysis for $C_{85}H_{118}O_{50}$: calculated: C, 52.63; H, 6.13; found: C, 52.45; H, 6.34.

*2.9. 2^A-O-(p-Allyloxybenzoyl)heptakis[6-O-(tert.-butyl)dimethylsilyl-3-O-methyl]-2^B,2^C,2^D,2^E,2^F,2^G-hexa-O-methyl-β-cyclodextrin (**11**) (Fig. 3)*

A mixture of **6** (0.80 g, 0.38 mmol), 2,6-di(*tert.*-butyl)-4-methylpyridine (2.6 g, 12.5 mmol) and methyl triflate (1.6 g, 10 mmol) in 6 ml of CH_2Cl_2 was stirred in a capped PTFE tube at 80°C for 2.5 h. After being cooled, 10 ml of CH_3OH was added, and the mixture was stirred at room temperature for 1 h. The solvent was removed under a reduced pressure to yield a solid mixture, which was dissolved in CH_2Cl_2. The organic solution was washed successively with 3% cold HCl, 5% aqueous $NaHCO_3$ and water, and then dried and concentrated. Crude

product was chromatographed (C_6H_{14}–$CH_3CO_2C_2H_5$–C_2H_5OH, 80:20:1) to give 0.65 g (75%) of **11**; m.p. 136–138°C; $[\alpha]_D^{25}$ + 97.5° (c = 2.68, $CHCl_3$); ^{1}H NMR δ 8.08 (d, J = 8.67 Hz, 2 H), 6.87 (d, J = 8.67 Hz, 2 H), 6.04 (m, 1 H), 5.49–5.10 (m, 9 H), 4.92 (dd, J_1 = 3.28 Hz, J_2 = 9.72 Hz, 1 H), 4.57 (d, J = 5.26 Hz, 2 H), 4.23–3.30 (m, 74 H), 3.05 (dd, J_1 = 3.28 Hz, J_2 = 9.72 Hz, 6 H), 0.88 (s, 63 H), 0.05 (s, 42 H); ^{13}C NMR δ 166.1, 133.1, 132.4, 123.4, 118.5, 114.6, 98.7, 98.6, 98.5, 98.2, 97.6, 82.9, 82.7, 82.6, 82.4, 82.3, 80.8, 79.4, 79.3, 79.2, 78.9, 78.7, 77.0, 72.3, 72.7, 72.6, 69.3, 62.7, 62.1, 62.9, 61.8, 61.3, 59.2, 59.0, 58.9, 58.8, 26.4, 18.8, −4.4, −4.5, −4.7, −4.8. Analysis for $C_{107}H_{202}O_{37}Si_7$: calculated: C, 56.43; H, 8.94; found: C, 56.53; H, 9.01.

*2.10. 2^A-O-[p-(tert.-Butyl)benzoyl]heptakis[6-O-(tert.-butyl)dimethylsilyl-3-O-methyl]-2^B,2^C,2^D,2^E,2^F,2^G-hexa-O-methyl-β-cyclodextrin (**12**) (Fig. 3)*

Compound **12** was prepared as **11** above from 2.0 g (1.0 mmol) of **7**, 3.8 g (18.3 mmol) of 2,6-di(*tert.*-butyl)-4-methylpyridine and 2.43 g (14.8 mmol) of methyl triflate to produce 1.72 g (80%) of **12**; m.p. 148–150°C; $[\alpha]_D^{25}$ + 93.0° (c = 2.11, $CHCl_3$); ^{1}H NMR δ 8.06 (d, J = 8.83 Hz, 2 H), 7.40 (d, J = 8.83 Hz, 2 H), 5.47 (d, J = 3.32 Hz, 1 H), 5.30–5.10 (m, 6 H), 4.97 (dd, J_1 = 3.32 Hz, J_2 = 9.65 Hz, 1 H), 4.29–3.30 (m, 74 H), 3.15–2.92 (m, 6 H), 1.34 (s, 9 H), 0.89 (s, 63 H), 0.07 (s, 42 H); ^{13}C NMR δ 166.2, 130.2, 128.0, 125.6, 98.7, 98.6, 98.4, 98.0, 82.6, 82.5, 82.3, 80.8, 79.5, 79.4, 79.2, 76.9, 74.2, 72.7, 72.6, 72.5, 62.7, 62.2, 62.0, 61.8, 61.3, 59.4, 59.1, 58.9, 58.6, 35.6, 31.6, 26.4, 18.8, −4.4, −4.5, −4.6, −4.8. Analysis for $C_{108}H_{206}O_{36}Si_7$: calculated: C, 56.96; H, 9.12; found: C, 57.16; H, 8.95.

*2.11. 2^A-O-(p-Allyloxybenzoyl)heptakis(3-O-methyl)-2^B,2^C,2^D,2^E,2^F,2^G-hexa-O-methyl-β-cyclodextrin (**13**) (Fig. 3)*

A solution of **11** (0.62 g, 0.27 mmol) in 100 ml of CH_3OH was refluxed with NH_4F (0.71 g, 19.1 mmol) for 24 h and evaporated to dryness. A solution of the residue in $CHCl_3$ was washed with water twice, dried and concentrated. Crude product was subjected to column chromatography ($CHCl_3$–CH_3OH, 8:1) to yield 0.34 g (85%) of **13**; m.p. 175–176°C; $[\alpha]_D^{25}$ + 156.2° (c = 1.15, $CHCl_3$); ^{1}H NMR δ 8.05 (d, J = 8.63 Hz, 2 H), 6.91 (d, J = 8.63 Hz, 2 H), 6.04 (m, 1 H), 5.50–5.25 (m, 3 H), 5.20–5.00 (m, 6 H), 4.89 (dd, J_1 = 3.29 Hz, J_2 = 9.56 Hz, 1 H), 4.72 (s, 7 H, OH), 4.57 (d, J = 5.29 Hz, 2 H), 4.12–2.95 (m, 80 H); ^{13}C NMR δ 166.3, 133.0, 132.4, 123.1, 118.6, 114.8, 99.1, 99.0, 82.5, 82.4, 82.1, 80.8, 77.7, 74.5, 73.0, 72.9, 72.8, 69.6, 69.3, 62.0, 61.8, 61.7, 61.4, 59.2, 59.0, 58.9. Analysis for $C_{65}H_{104}O_{37}$: calculated: C, 52.84; H, 7.09; found: C, 52.87; H, 7.00.

*2.12. 2^A-O-[p-(tert.-Butyl)benzoyl]heptakis(3-O-methyl)-2^B,2^C,2^D,2^E,2^F,2^G-hexa-O-methyl-β-cyclodextrin (**14**) (Fig. 3)*

Cyclodextrin derivative **14** was prepared as **13** above from 0.88 g (0.39 mmol) of **12** and 0.61 g (16.2 mmol) of NH_4F to give 0.53 g (93%) of **14**; m.p. 197–199°C; $[\alpha]_D^{25}$ + 150.3° (c = 1.54, $CHCl_3$); ^{1}H NMR δ 8.02 (d, J = 8.57 Hz, 2 H), 7.42 (d, J = 8.57 Hz, 2 H), 5.30 (d, J = 3.31 Hz, 1 H), 5.25–4.98 (m, 6 H), 4.89 (dd, J_1 = 3.31 Hz, J_2 = 9.65 Hz, 1 H), 4.73 (broad s, 7 H, OH), 4.12–3.29 (m, 74 H), 3.29–3.03 (m, 6 H), 1.33 (s, 9 H); ^{13}C NMR δ 166.6, 130.3, 127.7, 125.8, 99.4, 99.2, 99.1, 82.5, 82.4, 82.2, 82.0, 81.9, 81.0, 80.8, 79.8, 77.7, 73.1, 73.0, 72.9, 72.8, 72.7, 62.1, 61.9, 61.7, 61.5, 58.8, 35.6, 31.6. Analysis for $C_{66}H_{108}O_{36}$: calculated: C, 53.64; H, 7.37; found: C, 53.63; H, 7.42.

*2.13. 2^A-O-(p-Allyloxybenzoyl)heptakis(3,6-di-O-methyl)-2^B,2^C,2^D,2^E,2^F,2^G-hexa-O-methyl-β-cyclodextrin (**15**) (Fig. 3)*

Permethylated monoalkenyl-β-cyclodextrin **15** was prepared as above for **10** from 0.19 g (0.13 mmol) of **13**, 0.37 g (1.80 mmol) of 2,6-di(*tert.*-butyl)-4-methylpyridine and 0.22 g (1.35 mmol) of methyl triflate to give **15** (0.10 g, 59%); m.p. 107–109°C; $[\alpha]_D^{25}$ + 130.7° (c = 0.99, $CHCl_3$); ^{1}H

NMR δ 8.10 (d, $J = 8.90$ Hz, 2 H), 6.90 (d, $J = 8.90$ Hz, 2 H), 6.04 (m, 1 H), 5.48–5.21 (m, 3 H), 5.18–5.05 (m, 6 H), 4.93 (dd, $J_1 = 3.30$ Hz, $J_2 = 9.62$ Hz, 1 H), 4.57 (d, $J = 5.24$ Hz, 2 H), 4.00–3.20 (m, 95 H), 3.24–3.05 (m, 6 H); ^{13}C NMR δ 166.3, 133.0, 132.5, 123.2, 118.6, 114.7, 99.5, 99.4, 99.2, 98.4, 82.5, 82.3, 82.0, 81.0, 80.9, 80.5, 80.0, 79.0, 74.4, 72.0, 71.8, 71.5, 71.3, 69.3, 62.0, 61.8, 61.6, 61.5, 59.4, 59.1, 59.0, 58.8. Analysis for $C_{72}H_{118}O_{37}$: calculated: C, 54.88; H, 7.55; found: C, 55.13; H, 7.63.

2.14. 2^A-O-[p-(tert.-Butyl)benzoyl]heptakis(3,6-di-O-methyl)-2^B,2^C,2^D,2^E,2^F,2^G-hexa-O-methyl-β-cyclodextrin (16) (Fig. 3)

A compound **16** was prepared as above for **10** from 1.00 g (0.68 mmol) of **14**, 1.94 g (9.46 mmol) of 2,6-di(*tert.*-butyl)-4-methylpyridine and 1.17 g (7.10 mmol) of methyl triflate to give 0.88 g (82%) of **16**; m.p. 132–134°C; $[\alpha]_D^{25} + 142.7°$ ($c = 1.52$, $CHCl_3$); ^{1}H NMR δ 8.10 (d, $J = 8.71$ Hz, 2 H), 7.43 (d, $J = 8.71$ Hz, 2 H), 5.34 (d, $J = 3.31$ Hz, 1 H), 5.22–5.08 (m, 6 H), 5.00 (dd, $J_1 = 3.31$ Hz, $J_2 = 9.64$ Hz, 1 H), 4.03–3.30 (m, 95 H), 3.26–3.06 (m, 6 H), 1.35 (s, 9 H); ^{13}C NMR δ 166.6, 130.3, 127.8, 125.7, 99.5, 99.4, 99.1, 98.2, 82.5, 82.2, 82.1, 81.9, 81.2, 80.9, 80.8, 80.5, 79.9, 79.0, 77.6, 74.5, 71.8, 71.4, 71.3, 62.0, 61.8, 61.6, 61.5, 59.4, 59.1, 59.0, 58.9, 35.5, 31.6. Analysis for $C_{73}H_{122}O_{36}$: calculated: C, 55.64; H, 7.80; found: C, 55.45; H, 7.75.

2.15. Heptakis(3,6-di-O-methyl)-2^A,2^B,2^C,2^D,2^E,2^F-hexa-O-methyl-β-cyclodextrin (17) (Fig. 3)

A solution of **16** (0.50 g, 0.32 mmol) in diethyl ether (7 ml) was refluxed with $LiAlH_4$ (0.058 g, 1.53 mmol) for 24 h. Moist ether was added to decompose the excess $LiAlH_4$ and the mixture was concentrated. The residue was partitioned between $CHCl_3$ and water, and the organic layer was separated and washed with water two more times. After being dried and concentrated, the residue was subjected to column chromatography ($CHCl_3$–CH_3OH, 80:1) to give 0.39 g (87%) of **17**; m.p. 105–107°C; $[\alpha]_D^{25} + 145.0°$ ($c = 0.36$, $CHCl_3$): ^{1}H NMR δ 5.20–5.06 (m, 6 H), 4.89 (d, $J = 3.27$ Hz, 1 H), 4.34 (d, $J = 7.13$ Hz, 1 H, OH), 3.95–3.31 (m, 96 H), 3.27–3.10 (m, 6 H); ^{13}C NMR δ 102.4, 100.1, 99.9, 99.8, 99.6, 99.3, 99.1, 84.5, 83.4, 82.9, 82.6, 82.5, 82.4, 82.2, 81.6, 81.3, 81.2, 81.1, 80.7, 80.5, 79.1, 74.6, 72.3, 72.0, 71.8, 71.4, 71.3, 70.7, 62.4, 61.9, 61.8, 61.7, 61.3, 59.5, 59.3, 59.2, 59.0, 58.8, 58.7. Analysis for $C_{62}H_{110}O_{35}$: calculated: C, 52.61; H, 7.83; found: C, 52.62; H, 8.00.

2.16. 2^A-O-(p-Allyloxybenzyl)heptakis(3,6-di-O-methyl)-2^B,2^C,2^D,2^E,2^F,2^G-hexa-O-methyl-β-cyclodextrin (18) (Fig. 3)

Compound **17** (0.24 g, 0.17 mmol) in 5 ml of DMF was treated with NaH (0.041 g, 1.7 mmol) at room temperature for 2 h, and then 0.31 g (1.7 mmol) of *p*-allyloxybenzyl chloride were added. The mixture was stirred at room temperature for 24 h, and CH_3OH was added to decompose the excess NaH. The solvent was removed under reduced pressure to produce a slurry which was partitioned between $CHCl_3$ and water. The organic layer was separated, and washed with water. After being dried and concentrated, the crude product was chromatographed ($CHCl_3$–CH_3OH, 80:1) to give 0.17 g (64%) of **18**; m.p. 100–102°C; $[\alpha]_D^{25} + 136.3°$ ($c = 0.60$, $CHCl_3$); ^{1}H NMR δ 7.33 (d, $J = 8.83$ Hz, 2 H), 6.85 (d, $J = 8.83$ Hz, 2 H), 6.05 (m, 1 H), 5.32 (m, 2 H), 5.20–5.05 (m, 6 H), 4.93 (d, $J = 3.31$ Hz, 1 H), 4.64 (s, 2 H), 4.51 (d, $J = 5.27$ Hz, 2 H), 3.94–3.26 (m, 95 H), 3.19 (dd, $J_1 = 3.31$ Hz, $J_2 = 9.65$ Hz, 7 H); ^{13}C NMR δ 133.8, 131.9, 131.5, 129.8, 118.0, 114.9, 114.8, 99.8, 99.4, 82.5, 82.3, 82.2, 80.9, 80.8, 80.6, 80.4, 80.0, 72.7, 72.1, 72.0, 71.8, 71.7, 71.6, 71.4, 71.3, 69.6, 69.3, 62.0, 61.9, 59.4, 59.1, 59.0, 58.9. Analysis for $C_{72}H_{120}O_{36}$: calculated: C, 55.37; H, 7.75; found: C, 55.15; H, 7.84.

2.17. Preparation of copolymer 19

A mixture of 1.64 g (5.50 mmol) of 1, 1, 3, 3, 5, 5, 7, 7-octamethylcyclotetrasiloxane

(D_4), 0.13 g (0.56 mmol) of 1,3,5,7-tetramethylcyclotetrasiloxane (D'_4), 0.24 g (0.89 mmol) of dimethoxyditolylsilane and 0.022 g (0.13 mmol) of hexamethyldisiloxane was stirred with 4 mg of triflic acid in a 50-ml PTFE centrifuge tube at room temperature for 50 h. This reaction was similar to that reported [9]. This mixture was neutralized with 30 mg of hexamethyldisilazane while being stirred for 5 min. The resulting polymer (M_r about 15 000) was dissolved in 10 ml of CH_2Cl_2 and then precipitated by adding 30 ml of CH_3OH. The mixture was centrifuged, and the solvent was decanted. The polymer was again dissolved in CH_2Cl_2 and precipitated by CH_3OH for a total of four more times, and then dried under vacuum for 10 h.

2.18. General procedure for the preparation of β-cyclodextrin-containing methylpolysiloxanes ***20–23*** *(Fig. 4)*

A typical synthetic procedure is given for polymer **20**. Alkene **4** (0.15 g, 0.094 mmol), hydromethylpolysiloxane **19** (0.084 g, 0.094 mmol of Si–H) and 5 g of toluene were placed in a 50-ml PTFE centrifuge tube. Parafilm was placed around the cap to keep out moisture. The mixture was heated in an oil bath at 85–90°C for 72 h, and the solvent was evaporated. A solution of the residue in CH_2Cl_2 (10 ml) was washed with 10 ml of CH_3OH and 10 ml of water. The mixture was centrifuged and the water–CH_3OH layer was removed. This process was repeated three more times. The solvent was evaporated and the residue was dried under vacuum at 60°C for 20 h to give 0.20 (84%) of **20**. The proton NMR spectrum of **20** was consistent with the structure shown in Fig. 4. The other polymers were prepared in a like manner.

2.19. Preparation of open tubular chromatographic columns

Open tubular columns were prepared using cyano-deactivated [10] fused-silica capillaries obtained from Dionex (Sunnyvale, CA, USA). The GC and the SFC columns were 320 and 50 μm I.D., respectively. All four stationary phases were used to prepare a total of eight columns: four 15 m long GC columns and four 10 m long SFC columns. The static coating technique [11] was employed for column preparation. An *n*-pentane–methylene chloride (1:1) mixture was used as the coating solvent. Appropriate coating solution concentrations for the preparation of GC and SFC columns were calculated as described [12]. The coating was carried out at 40°C. For GC and SFC columns, the vacuum was equivalent to 200 and 10 μmHg (1 mmHg = 133.322 Pa), respectively.

After coating, the columns were purged with nitrogen for 30 min and then cross-linked using azo-*tert.*-butane (ATB) as a free radical initiator [13]. For cross-linking, the coated stationary phase film was saturated with ATB vapor for 30 min. The columns were then sealed at both ends using an oxyacetylene flame, heated by programming the temperature from 40 to 220°C at a rate of 4°C min^{-1}, and were held at the final temperature for 40 min. Finally, the columns were rinsed with 1 ml of the coating solvent, purged with nitrogen again for 1 h, and conditioned. The conditioning was accomplished by slowly ramping the temperature (1°C min^{-1}) from 40 to 200°C, and holding the column at the final temperature for 2 h. During conditioning, the columns were continuously purged with helium.

3. Results and discussion

3.1. Permethyl-substituted 3-O-(p-allyloxybenzoyl)-β-cyclodextrin ***(4)*** *(Fig. 2)*

Heptakis(2,6-di-O-methyl)-β-cyclodextrin (**2**) was conveniently obtained from native β-cyclodextrin in a 55% yield as reported [7,8]. The hydroxy groups at the 3-positions of cyclodextrin are the least reactive and resist functionalization, as described by Menger and Dulany [14]. In fact, treatment of **2** with *p*-allyloxybenzoyl chloride and triethylamine (NEt_3) in dry toluene produced no product even at reflux temperature or using N,N-dimethylaminopyridine instead of NEt_3. When NaH was used as a base, the

reaction of **2** with *p*-allyloxybenzoyl chloride or *p*-allyloxybenzyl chloride in dry DMF gave mixtures from which the expected product could not be isolated. It was found that treatment of **2** with *p*-allyloxybenzoyl chloride in dry pyridine at 100°C produced 3-O-(*p*-allyloxybenzoyl)heptakis(2,6-di-O-methyl)-β-cyclodextrin (**3**) which was purified by silica gel chromatography. Methylation of **3** with methyl triflate and 2,6-di(*tert.*-butyl)-4-methylpyridine in CH_2Cl_2 give **4** in an excellent yield.

3.2. Permethyl- or per(methyl/acetyl)-substituted 2-O-alkenyl-β-cyclodextrins (10, 15, 18) (Fig. 3)

Although selective mono-functionalization of the hydroxy groups at the 2-positions of native β-cyclodextrin was done by other groups [21–23], we preferred using heptakis[6-O-(*tert.*-butyl)dimethylsilyl]-β-cyclodextrin (**5**) [1] as a starting material to make mono-2-O-alkenyl-β-cyclodextrin derivatives. Treatment of **5** with *p*-allyloxybenzoyl chloride or *p*-(*tert.*-butyl)benzoyl chloride and triethylamine in toluene gave 2-O-(*p*-allyloxybenzoyl)heptakis [6-O-(*tert.*-butyl) dimethylsilyl]-β-cyclodextrin (**6**) or 2-O-[*p*-(*tert.*-butyl)benzoyl]heptakis[6 - O - (*tert.*-butyl)dimethylsilyl]-β-cyclodextrin (**7**), respectively (see Fig. 3). Acylation of **6** with acetic anhydride in pyridine gave tridecaacetate **8** in a 73% yield. The silyl groups of **8** were removed with BF_3–OEt in CH_2Cl_2 to produce 2^A-O-(*p*-allyloxybenzoyl)heptakis(3-O-acetyl)-2^B, 2^C, 2^D, 2^E, 2^F, 2^G-hexa-O-acetyl-β-cyclodextrin (**9**) in a yield of 78%. Methylation of **9** with methyl triflate and 2,6-di(*tert.*-butyl)-4-methylpyridine in CH_2Cl_2 gave 2^A-O-(*p*-allyloxybenzoyl)heptakis(3-O-acetyl-6-O-methyl)-2^B, 2^C, 2^D, 2^E, 2^F, 2^G-hexa-O-acetyl-β-cyclodextrin (**10**).

Both **6** and **7** were methylated under mild conditions (same as above) to produce permethylated 2^A-O-benzoyl-substituted heptakis[6-O-(*tert.*-butyl)dimethylsilyl]-β-cyclodextrins **11** and **12**, respectively (see Fig. 3). These latter compounds were transformed into heptaols **13** and **14** by treatment with NH_4F in CH_3OH. The yields of each of the above reactions were excellent. Methylation of **13** and **14** under the mild conditions gave permethylated 2^A-O-(*p*-allyloxybenzoyl)-β-cyclodextrin (**15**) and permethylated 2^A-O-[*p*-(*tert.*-butyl)benzoyl]-β-cyclodextrin (**16**) in good yields. Compound **16** was stable in a hot solution of LiOH in tetrahydrofuran–ethanol–water, but was reduced with $LiAlH_4$ in diethyl ether to give monoalcohol **17**. Compound **17** was converted to permethylated 2^A-O-(*p*-allyloxy)benzyl-β-cyclodextrin (**18**) in a 64% yield by treatment with NaH and (*p*-allyloxy)benzyl chloride in DMF.

Permethyl-substituted 3^A-O-(*p*-allyloxybenzoyl-β-cyclodextrin (**4**) was prepared from **2** which has only position 3 on each glucose unit unsubstituted so that, in this case, the allyloxybenzoyl group has to be on position 3. Alkene-substituted cyclodextrins **10**, **15** and **18**, on the other hand, were prepared from **5** which is unsubstituted in positions 2 and 3. Therefore **10**, **15** and **18** could have the allyloxybenzoyl or allyloxybenzyl group in the 2-O or 3-O position. Meier-Augenstein *et al.* [15] reported that the coupling constants for the protons at positions 2

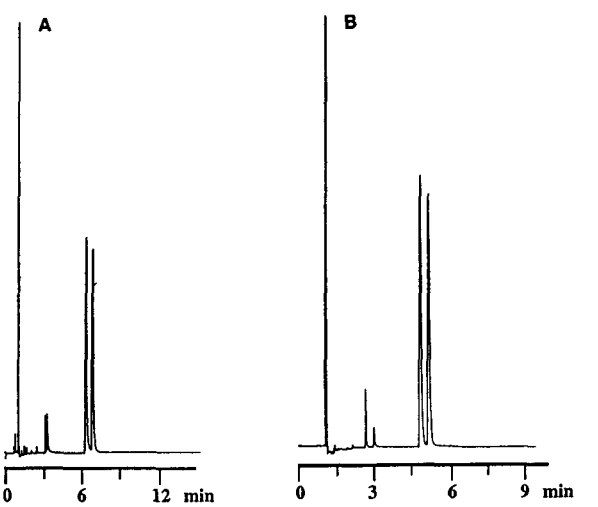


Fig. 5. Gas chromatograms of pantolactone enantiomers obtained on (A) large-rim-tethered (**22**) and (B) small-rim-tethered (polymer made from **1a**) [2] cyclodextrin stationary phases. Conditions: 15 m × 320 μm I.D. cyano-deactivated fused-silica columns, 0.25 μm film thickness; 130°C column temperature; helium carrier gas; split injection (100:1); flame ionization detection.

and 3 of heptakis(2,6-di-O-pentyl)-β-cyclodextrin were $J_{1,2} = 3.7$ Hz, $J_{2,3} = 9.6$ Hz and $J_{3,4} = 9.2$ Hz. We assigned the double doublet at $\delta = 4.90$ ($J_1 = 9.61$ Hz, $J_2 = 3.28$ Hz) in the NMR spectrum of **8** (a precursor to **10**) to the proton at the position 2 of the glucose containing the *p*-allyloxybenzoyl group and the double doublet at $\delta = 4.70$ ($J_1 = 9.61$ Hz, $J_2 = 3.28$ Hz) to the six protons at the other 2-positions containing the acetyl groups. These *J* values are similar to those reported above for the 2-substituted cyclodextrins [15]. The signal for the protons at the 3-positions of **8** was overlapped by peaks attributable to the protons of the vinyl group. This assignment was also confirmed in the ^{1}H NMR spectra of **11** and **12** which exhibited similar *J* values for single proton peaks at $\delta = 4.92$ and 4.97, respectively.

3.3. Preparation and testing of polymers **20–23**

In order to have phases that easily coat on the fused-silica columns and that can be cross-linked, hydromethylpolysiloxanes containing tolyl groups were prepared by copolymerizing 10 parts of the cyclic tetramer of dimethylsiloxane, 1 part of the cyclic tetramer of hydromethylsiloxane and 1.6 parts of dimethoxyditolylsilane in a manner similar to that reported [9]. The tolyl substituents were found to be excellent cross-linking agents in polysiloxane systems [16]. The molecular mass of resulting copolymer **19** was 15 000 as determined by the amount of hexamethyldisiloxane, the endcapping reagent, used in the reaction. Persubstituted β-cyclodextrin-bound polymethylsiloxanes **20–23**, shown in Fig. 4, were synthesized by the hydrosilylation of **4**,

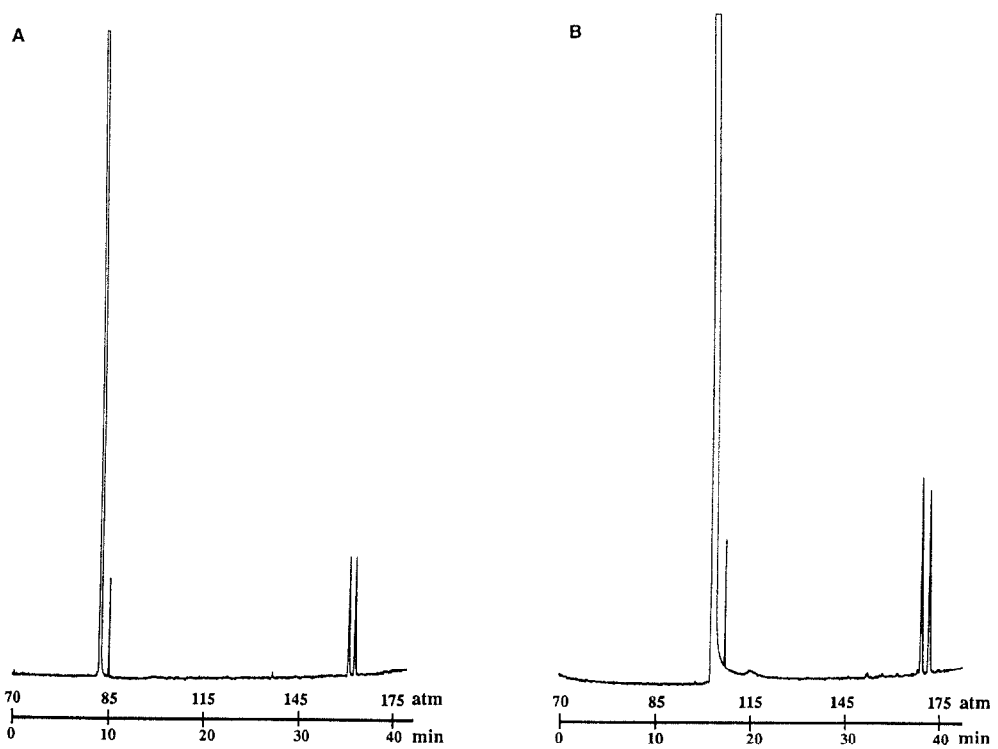


Fig. 6. SFC chromatograms of *tert.*-2-phenyl-1-cyclohexanol enantiomers obtained on (A) large-rim-tethered (**23**) and (B) small-rim-tethered (polymer made from **1c**) [2] cyclodextrin stationary phases. Conditions: 10 m × 50 μm I.D. cyano-deactivated fused-silica columns, 0.20 μm film thickness; 60°C column temperature; pressure program from 70 atm (5 min hold) to 200 atm (1 atm = 101 325 Pa) at a rate of 3 atm min^{-1}; neat carbon dioxide mobile phase; timed-split injection; flame ionization detection.

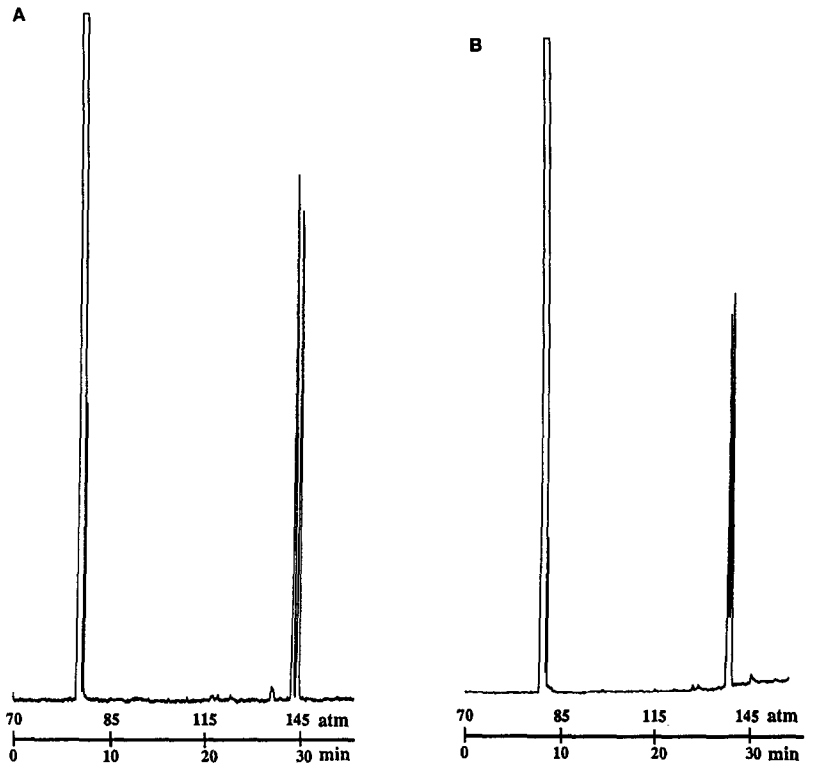


Fig. 7. Comparison of SFC separation of γ-phenyl-γ-butyrolactone enantiomers on (A) large-rim-tethered (**20**) and (B) copolymeric [1] cyclodextrin stationary phases. Conditions as in Fig. 6.

10, **15** and **18** onto copolymer **19** in a manner similar to that previously reported [17]. Equimolar amounts of cyclodextrin and Si–H functional groups on the polymer were used in the hydrosilylation reaction. Assuming that all of the alkene-substituted cyclodextrin reacted with **19**, the resulting polymer would have a ratio of 50 dimethylsiloxanes to 5 methylcyclodextrin-substituted siloxanes to 2 ditolylsiloxanes.

The newly synthesized, large-rim-tethered β-cyclodextrin polysiloxanes were evaluated as stationary phases for open tubular column GC and SFC. Chromatographic efficiencies and chiral selectivities of the new phases were evaluated and compared to analogous parameters of previously reported small-rim-tethered [2] and copolymeric [1] β-cyclodextrin phases.

The columns demonstrated excellent efficiencies and chiral selectivities for a wide variety of solutes. Efficiency values for the GC columns varied in the range of 3000–3500 theoretical plates/m. The SFC column efficiencies were on the order of 4000–5000 plates/m. These values are comparable to those previously obtained by us for small-rim-tethered β-cyclodextrin phases [2], and are much higher than those recently reported by Schurig and co-workers [18,19]. The highest efficiency reported by those authors in GC was 2300 effective theoretical plates/m; although for more than 70% of the tested solutes, their efficiency values were under 1500 effective plates/m, including as low an efficiency value as 300 effective plates/m for 3-hydroxybutan-2-one. In SFC, column efficiencies on the order of only 2000 theoretical plates/m were reported by those authors, indicating that their SFC column efficiency was barely half of that achieved by us in the present work for large-rim-

tethered β-cyclodextrin phases, as well as for the small-rim-tethered phases reported earlier [2].

The newly synthesized large-rim-tethered cyclodextrin phases exhibited chiral selectivities comparable to those obtained previously on small-rim-tethered analogues. Fig. 5 illustrates this by gas chromatograms of pantolactone enantiomers obtained on (A) large-rim- (**22**) and (B) small-rim-tethered (polymer prepared from **1a**) [2] cyclodextrin phase columns. Analogous results were obtained in SFC. Fig. 6 demonstrates SFC chromatograms of *tert.*-2-phenyl-1-cyclohexanol enantiomers obtained on columns using the two types of cyclodextrin phases (**23** for large-rim and polymer prepared from **1c** for small-rim-tethered phases). As can be seen, very similar chromatographic performance (efficiency and selectivity) was obtained on both column types. However, compared to the copolymeric cyclodextrin phases reported earlier [1], both types of pendant cyclodextrin phases demonstrated higher selectivities in SFC for some of the tested chiral compounds. Fig. 7 illustrates this point.

A detailed chromatographic study of the newly synthesized cyclodextrin phases, as well as a comparison of various aspects of their chromatographic performances with other types of cyclodextrin phases will be presented elsewhere [20].

Acknowledgements

This work was supported by a grant from Supelco. We thank Dr. Shawn L. Reese for providing us with starting D'_4.

References

[1] G.-L. Yi, J.S. Bradshaw, B.E. Rossiter, S.L. Reese, P. Petersson, K.E. Markides and M.L. Lee, *J. Org. Chem.*, 58 (1993) 2561.

[2] G.-L. Yi, J.S. Bradshaw, B.E. Rossiter, A. Malik, W.-B. Li and M.L. Lee, *J. Org. Chem.*, 58 (1993) 4844.

[3] P. Fisher, R. Aichholz, U. Bolz, M. Juza and S. Krimmer, *Angew. Chem., Int. Ed. Engl.*, 29 (1990) 427.

[4] V. Schurig, D. Schmalzing, U. Muhleck, M. Jung, M. Schleimer, P. Mussche, C. Duvekot and J.C. Buyten, *J. High Resolut. Chromatogr.*, 13 (1990) 713.

[5] V. Schurig, Z. Juvancz, G.J. Nicholson and D. Schmalzing, *J. High Resolut. Chromatogr.*, 14 (1991) 58.

[6] M. Jung and V. Schurig, *J. Microcol. Sep.*, 5 (1993) 11.

[7] B. Casu, M. Reggiani, G.G. Gallo and A. Vigevani, *Tetrahedron*, 24 (1968) 803.

[8] J. Szejtli, A. Liptak, I. Jodal, P. Fugedi, P. Nanasi and A. Neszmelyi, *Starch/Stärke*, 32 (1980) 165.

[9] J.M. Bayona, B.J. Tarbet, H.-C.K. Chang, C.M. Schregenberger, M. Nishioka, K.E. Markides, J.S. Bradshaw and M.L. Lee, *Int. J. Environ. Anal. Chem.*, 28 (1987) 163.

[10] K.E. Markides, B.J. Tarbet, C.M. Schregenberger, J.S. Bradshaw, M.L. Lee and K.D. Bartle, *J. High Resolut. Chromatogr. Chromatogr. Commun.*, 8 (1985) 741.

[11] J. Bouche and M. Verzele, *J. Gas Chromatogr.*, 6 (1968) 501.

[12] S.R. Sumpter, C.L. Woolley, E.C. Huang, K.E. Markides and M.L. Lee, *J. Chromatogr.*, 517 (1990) 503.

[13] B.W. Wright, P.A. Peaden, M.L. Lee and T.J. Stark, *J. Chromatogr.*, 248 (1982) 17.

[14] F.M. Menger and M.A. Dulany, *Tetrahedron Lett.*, 26 (1985) 267.

[15] W. Meier-Augenstein, B.V. Burger and H.S.C. Spies, *Magn. Reson. Chem.*, 29 (1991) 681.

[16] B.E. Richter, J.C. Kuei, J.I. Shelton, L.W. Castle, J.S. Bradshaw and M.L. Lee, *J. Chromatogr.*, 279 (1983) 21.

[17] J.S. Bradshaw, S.K. Aggarwal, B.J. Tarbet, K.E. Markides and M.L. Lee, *J. Chromatogr.*, 405 (1987) 169.

[18] D. Schmalzing, M. Jung, S. Mayer, J. Rickert and V. Schurig, *J. High Resolut. Chromatogr.*, 15 (1992) 723.

[19] M. Jung and V. Schurig, *J. High Resolut. Chromatogr.*, 16 (1993) 215.

[20] A. Malik, H. Yun, G.-L. Yi, J.S. Bradshaw, B.E. Rossiter, K.E. Markides and M.L. Lee, in preparation.

[21] A. Ueno and R. Breslow, *Tetrahedron Lett.*, 23 (1982) 3451.

[22] D. Rong and V.T. D'Souza, *Tetrahedron Lett.*, 31 (1990) 4275.

[23] C.T. Rao, B. Lindberg, J. Lindberg and J. Pitha, *J. Org. Chem.*, 56 (1991) 1327.