ELSEVIER

Journal of Chromatography A, 697 (1995) 485–494

JOURNAL OF CHROMATOGRAPHY A

Enantiomer separation of α-campholene and fencholene derivatives by capillary gas chromatography on permethylated cyclodextrins
II☆. Compounds separable with coupled techniques

A. Steinborn[a], R. Reinhardt[b], W. Engewald[a,*], K. Wyssuwa[c], K. Schulze[c]

[a]*Institute of Analytical Chemistry, Department of Chemistry, University of Leipzig, Linnéstrasse 3, D-04103 Leipzig, Germany*
[b]*Institute of Pharmacology and Toxicology, Department of Medicine, University of Leipzig, Härtelstrasse 16–18, D-04107 Leipzig, Germany*
[c]*Institute of Organic Chemistry, Department of Chemistry, University of Leipzig, Liebigstrasse 18, D-04103 Leipzig, Germany*

Abstract

Odoriferous substances, such as sandal and woody notes of the α-campholene and fencholene type with two and more stereogenic centres, were analyzed by capillary gas chromatography on permethylated cyclodextrins dissolved in polysiloxanes. From enantiomer-enriched α-pinene compounds, received as non-racemic mixtures, the theoretically possible number of stereoisomers were determined after the introduction of additional stereogenic centres. The derivatives with two stereogenic centres were separated on single columns. In the case of substances with three stereogenic centres a serial coupling of non-chiral and chiral columns partially connected with a mass selective detector was necessary for the separation and reliable identification. For optimizing the selectivity of the serially coupled system the principle of selectivity tuning was used. This discussion also deals with the retention behaviour and the factors influencing the enantiomer separation of the α-campholene and fencholene compounds.

1. Introduction

After the introduction of derivated cyclodextrins as chiral stationary phases for capillary gas chromatography (GC) [1–6] there are various cyclodextrin derivatives for routine analysis of chiral substances nowadays known and used. However, only in the last few years attempts have been made to investigate the separation mechanism on the basis of thermodynamic data [7–9], NMR investigations [10], molecular modelling experiments [11,12], and by comparing the separation of structurally similar compounds [13,14]. The latter method was also used for the investigation of α-campholene and fencholene derivatives in this study, as described in Parts I and II of this article.

α-Campholene and fencholene aldehyde, which are easily made available by camphane or fenchane rearrangement from α-pinene via α-pineneoxide, are suitable initial substances for the synthesis of odoriferous compounds, such as wood and sandalwood notes. The α-campholene and fencholene compounds are stereoisomeric

* Corresponding author.
☆ For Part I, see Ref. [15].

0021-9673/95/$09.50
SSDI 0021-9673(94)01073-0

mixtures; one stereogenic centre is transmitted by α-pinene, others are formed by alkylations, aldol reactions and reductions. In Part I [15] we reported on the GC separation of α-campholene and fencholene derivatives with one stereogenic centre. In this part we are describing the separation of α-campholene and fencholene alcohols with two and more chiral centres.

For compounds whose separation or assignment of the enantiomers was difficult on chiral stationary phases serially coupled column systems were used. For several years this method, also known as multidimensional gas chromatography (MDGC), has been used successfully by some teams for the analysis of multicomponent mixtures [16–20]. The separation of the diastereomers takes place on an non-chiral precolumn, after which they are transmitted onto a chiral column and are separated into the enantiomers. Because of the sometimes not easily separable by-products and impurities in the stereoisomer mixtures mass selective detection was indispensable. For this purpose a commercial MDGC device with a gas chromatography–mass spectrometry (GC–MS) system was coupled via a heatable transfer line.

By means of MDGC the assignment of the pairs of enantiomers to the diastereomers was also possible beyond any doubt for compounds with three stereogenic centres .

2. Experimental

2.1. Investigated substances

α-Campholene and fencholene derivatives with two or more stereogenic centres were synthesized according the scheme given in Part I and as described earlier [21–24]. The individual structures of the substances investigated in Part II are shown in Fig. 1.

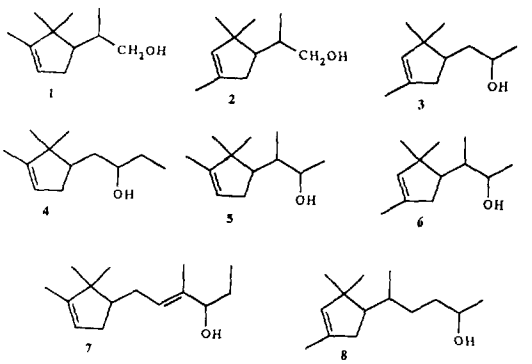

Fig. 1. Investigated Substances. **1** = 2-(2,2,3-Trimethyl-3-cyclopentenyl)propanol; **2** = 2-(2,2,4-trimethyl-3-cyclopentenyl)propanol; **3** = 1-(2,2,4-trimethyl-3-cyclopentenyl)-2-propanol; **4** = 1-(2,2,3-trimethyl-3-cyclopentenyl)-2-butanol; **5** = 3-(2,2,3-trimethyl-3-cyclopentenyl)-2-butanol; **6** = 3-(2,2,4-trimethyl-3-cyclopentenyl)-2-butanol; **7** = 4-methyl-6-(2,2,3-trimethyl-3-cyclopentenyl)-hex-4-en-3-ol; **8** = 5-(2,2,4-trimethyl-3-cyclopentenyl)-2-hexanol.

2.2. Instrumentation

A double oven GC from Siemens (Sichromat 2-8) with two flame ionization detectors (FIDs) and split injector was available for the MDGC analyses. Mass selective detection took place by coupling the Sichromat with a conventional HP 5890 II GC/HP 5971A MSD system via a heatable transfer line (laboratory made). The temperature of the transfer line was 250°C. The ionization took place by electron impact (70 eV). For the acquisition of spectra in the scan mode (mass range 35–400) helium was used as carrier gas. For all further analyses a Hewlett-Packard 5890 II gas chromatograph, equipped with FID and split/splitless injector was used. As carrier gas hydrogen with a split ratio of 1:100 was chosen.

The chiral resolution cR_s and the capacity factors k' given in the tables were calculated as given in Part I [15]. The dead times were measured by injection of methane.

2.3. Capillary columns

The internal diameter of all capillaries was 0.25 μm, the film thickness (d_f) 0.25 μm (column 7 $d_f = 0.2$ μm). The specifications of the columns are given in Table 1.

2.4. Description of the laboratory-made MDGC–MS coupling

The coupling of the Sichromat with the GC–MS system took place via a transfer line heatable

Table 1

No.	Column	Length (m)	Basic phase	Supplier
1	FS-CYCLODEX alphaI/P	50	OV-1701	CS-Chromatographie Service
2	CP-CD-β-2,3,6 M19	50	OV-1701	Chrompack
3	β-DEX 110	60	SPB 35	Supelco
4	γ-DEX 110	60	SPB 35	Supelco
5	Supelcowax	30		Supelco
6	DB-5	60		Chrompack
7	SB-11	60		IAS

in the temperature range from 30 to 380°C. It consists of a 1.25-m long steel tube (I.D. = 1 mm) through which an uncoated deactivated fused-silica capillary (Chrompack, non-polar, deactivated) runs from the second column of the Sichromat to the interface of the MSD. In order to enlarge the outside diameter and to ensure a better heat transmission a copper tube is placed on the steel tube holding the heater winding. The temperature is controlled by means of two thermo elements arranged at the two ends and an external thermo regulator (control tolerance ± 1%).

The system was tested for differently polar, high-boiling test substances (*n*-alkanes, alcohols, dimethylnaphthalene, cyclopentenyl derivatives) for a possible dependence of the peak form or the retention on the temperature of the transfer line. Any significant changes in the peak symmetry, tailing or differences in the retention times can not be proved if the temperature is equal to or higher than the one in the GC oven. By using well deactivated fused-silica no signs of adsorption effects were observed.

3. Results and discussion

3.1. Solution of difficult separation problems

With the exception of **3** and **7** the separation of the enantiomers with two stereogenic centres on the columns used was possible without any problems. The marking of the individual diastereomers was done schematically by D1 to D4, with D1 corresponding to the diastereomers eluting first on the polar stationary phases (Carbowax) and D4 corresponding to the diastereomer eluting last.

The analysis of **3** proved to be particularly difficult. On non-polar non-chiral phases the two diastereomers could only be partially separated and on medium and strong polar phases not at all. In preliminary experiments on a 25-m capillary with permethylated β-cyclodextrin (dissolved in OV-1701) a separation into two peaks took place. As enantiomer-enriched α-pinene was used in the synthesis a comparison of peak areas obtained on chiral and non-chiral phases showed that not the diastereomers were separated but the enantiomers, with each the diastereomers *RR* and *RS* as well as *SS* and *SR* overlapping in one peak. If a 50-m column with the same stationary phase (column 2) was used, all stereoisomers were able to be separated at different temperatures (Fig. 2).

Also **7** has two asymmetric centres, and because of the double linkage in the side chain the possibility of *Z*/*E* isomerism is theoretically given. However, the formation of the *Z*-isomer on the reaction path used is unlikely [25]. Accordingly, two diastereomeric pairs of enantiomers are to be expected. On columns 2–4 altogether 3 peaks were registered for the compound, which cannot be assigned by means of peak area comparison because the separation is incomplete. Only a preseparation of the diastereomers and a subsequent transfer of single diastereomers onto a second chiral column showed that the enantiomers of the first eluting

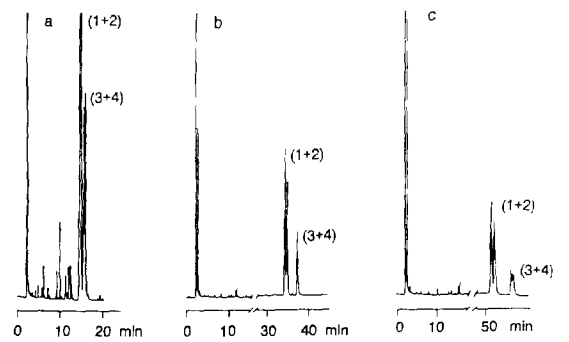

Fig. 2. Chromatogram of **3** on permethylated β-cyclodextrin (column 2). Column temperature: (a) 115°C, (b) 95°C, (c) 90°C; injection/FID: 300°C/250°C; carrier gas: hydrogen; split ratio 1:80; Peak (1) and (2): *SS*- and *SR*-stereoisomers; Peak (3) and (4): *RR*- and *RS*-stereoisomers.

diastereomer are separated but not those of the second diastereomer.

The compounds 3-(2,2,3-trimethyl-3-cyclopentenyl)-2-butanol (**5**), 3-(2,2,4-trimethyl-3-cyclopentenyl)-2-butanol (**6**) and 5-(2,2,4-trimethyl-3-cyclopentenyl)-2-hexanol (**8**) each have three stereogenic centres so that eight stereoisomers can be expected. A complete separation of all components was also not possible on a single column. The fundamental approach is explained by the example of **5**.

The chromatogram of **5** (Fig. 3a) on a non-chiral column shows a great number of peaks and those marked were identified by GC–MS as diastereomers of **5**.

A subsequent GC–MS analysis of this compound on column 4 shows seven peaks whose mass spectra are in accordance with 3-(2,2,3-trimethyl-3-cyclopentyl)-2-butanol (**5**). As eight components were expected in this mixture a co-elution of two stereoisomers was taken place in one peak, or one of the diastereomers was not separated into the optical antipodes. A complete separation was possible only when columns 4 and 5 were coupled in series. A double oven system was necessary because the temperatures of the non-chiral and the chiral column are different.

In principle it is possible in such a system to transfer individual peaks as well as groups of peaks to the second column after a preseparation on the first column. The individual peak transfer

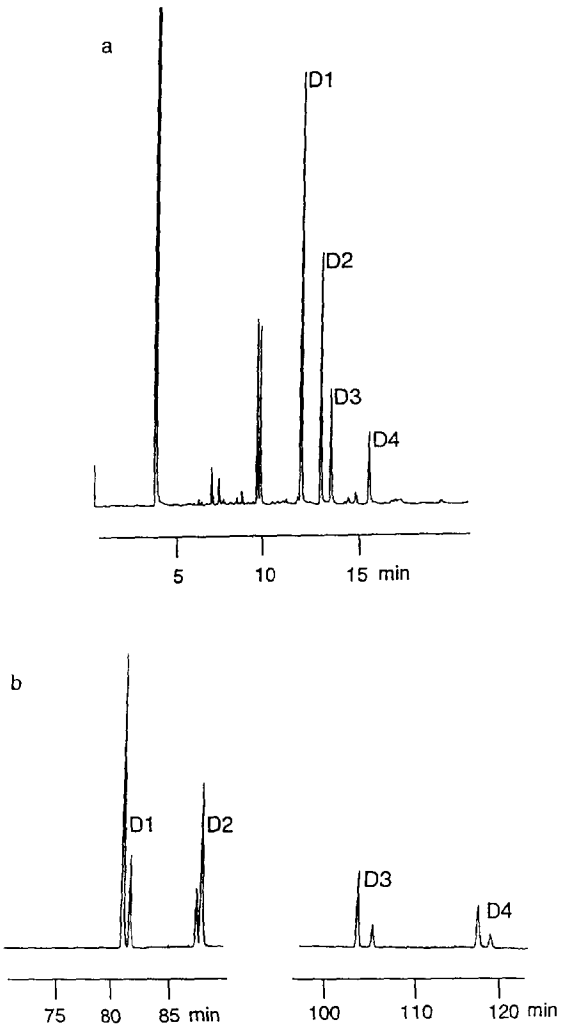

Fig. 3. (a) Separation of **5** on Carbowax (column 5). Column temperature: 160°C; injection/FID: 250°C; 55 kPa helium; split 1:30. (b) Separation of diastereomers D_1–D_4 on column 4. Column temperature: 120°C; 120 kPa Helium.

corresponds to a genuine multidimensional GC and has the advantage that any peak overlapping are to the greatest possible extent excluded; however, the analysis of mixtures needs a rather long time. Generally, an optimization of the column system is also necessary in the case of a single-peak transfer because the separation on the overall system is influenced by both columns in which the share of cyclodextrin should be as large as possible. For optimizing the selectivity in serially coupled systems the principle of selectivi-

ty tuning can be used (for theory, see Refs. [26,27]; for applications, see Refs. [28,29]). The system allows to calculate capacity factors k' for various medium pressures from the k' values for the individual columns.

The relative share, Φ, of a column used (often named relative retentivity) is expressed as ratio of the dead time of the column to the dead time of the total system. In Fig. 4 we show the relative retention of the 8 stereoisomers (related to stereoisomer **8**) calculated for different shares, Φ_2, of the cyclodextrin phase in the total system.

Here $\Phi_2 = 1$ correspond to the poor cyclodextrin phase; $\Phi_2 = 0$ to the poor Carbowax phase. For the diastereomers **2** and **3** the most favourable separation is possible at very small Φ_2 values (0.1–0.3) or at relatively large Φ_2 values (0.6–0.8). However, not all the Φ values can be realized by experimental procedures. Investigations have shown that by using this column system, selectivity tuning is only possible for Φ_2 values between 0.45 and 0.70. The chromatogram (Fig. 3) shows the separation of the diastereomers **1** and **2** as well as **3** and **4** of 3-(2,2,3-trimethyl-3-cyclopentenyl)-2-butanol (**5**) in 2 cuts at $\Phi_2 = 0.61$.

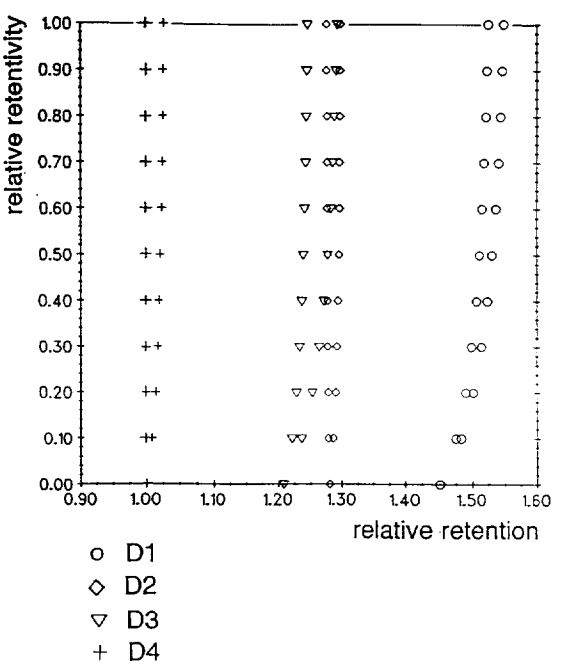

Fig. 4. Selectivity change in dependence on the share of columns.

In the case of **6** also eight stereoisomers can be expected. The chromatogram on non-chiral column (Fig. 5a) shows a coelution of the fourth diastereomer and impurities of the mixture. Therefore by coupling the non-chiral and chiral columns a mass selective detection was necessary for complete identification (Fig. 5b).

3.2. Discussion of retention behaviour

The separation factors make clear that only in few cases permethylated α-cyclodextrin is suitable as chiral selector. Having in mind the number of separable stereoisomers and the chiral resolution the best results are clearly obtained by the use of permethylated β-cyclodextrin. This was also found for the compounds investigated in Part I [15].

The results of the studies with the four permethylated cyclodextrin phases are shown in Table 2.

With growing size of the alkyl side chains also the enantioselectivity of permethylated γ-cyclodextrin will be higher, i.e. with increasing statistical space requirements of the investigated derivatives the cyclodextrin derivative with the larger cavities is more suitable. This fact underlines the importance of inclusion effects for enantiomer separation. On the other hand, permethylated α-cyclodextrin shows a certain enantioselectivity for a few stereoisomers of the larger molecules. Consequently, besides the formation of host–guest inclusion complexes also other interactions should be of importance for enantiomer differentiation, for example electrostatical ones.

In the following it is shown that the enantiomer differentiation of the α-campholene and fencholene derivatives is influenced by the structure of the compound, i.e. by steric effects. On all cyclodextrin phases the fencholene compounds are better separated than their analogous α-campholene derivatives although they differ from each other only in the position of the methyl group on the cyclopentenyl ring (α-cam-

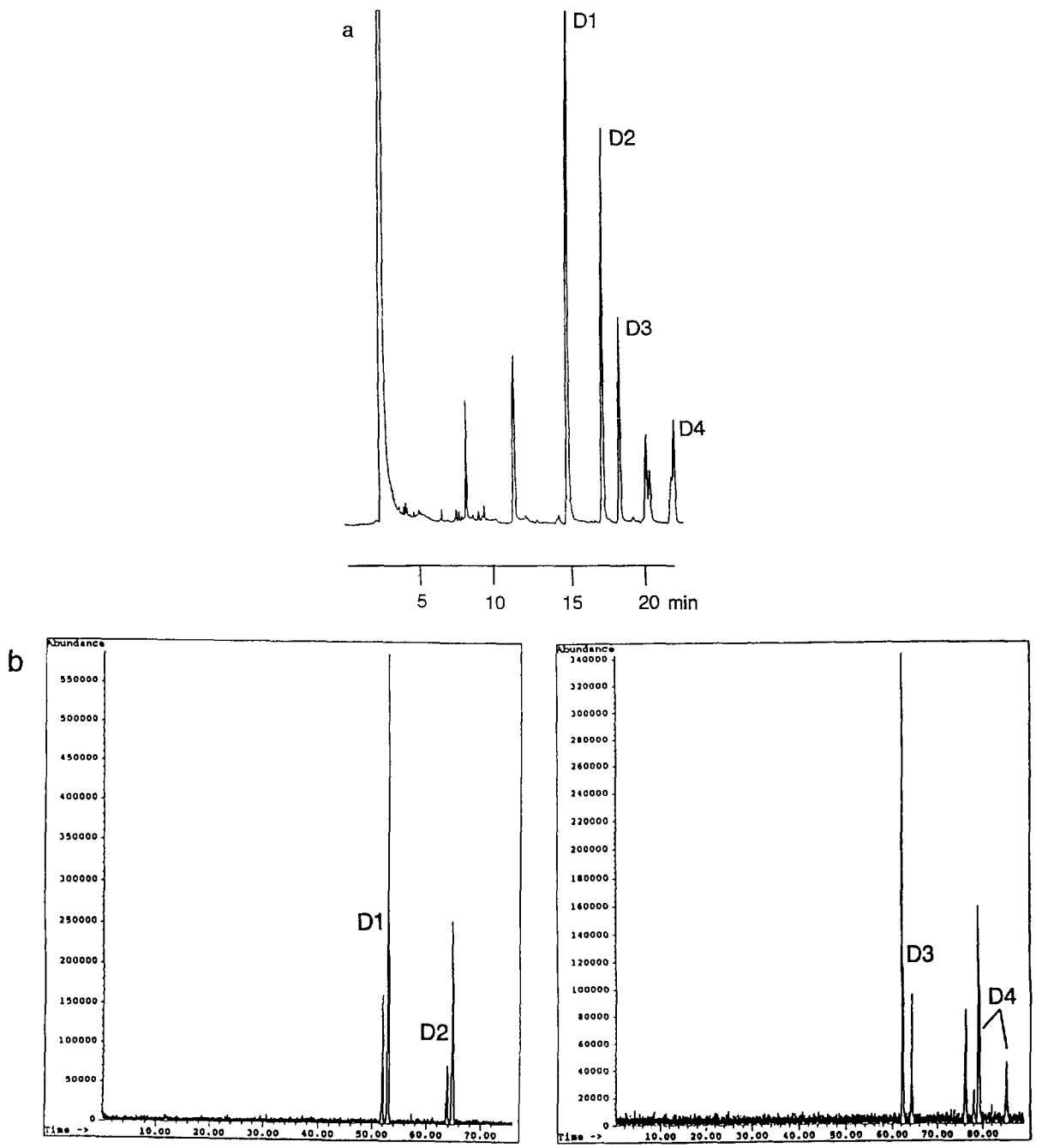

Fig. 5. Analysis of **6** with MDGC–MS. (a) Chromatogram of the diastereomers on column 5. Column temperature: 140°C; injection/FID: 300°C; 50 kPa helium; split 1:30. (b) Separation of the four diastereomers after peak transfer onto column 3. Column temperature: 120°C; 150 kPa helium; detector: MS, transferline: 280°C.

pholene = 3-methyl; fencholene = 4-methyl). If the five-membered ring enters the cyclodextrin cavity, the methyl group in the 4-position is possibly capable of additional dispersive interactions within the cyclodextrin because they are sterically less influenced by the geminal methyl substituents on the ring. Obviously, for α-campholene derivates such interactions are not that typical.

The results for the alcohols **1** and **2** are remarkable. The diastereomers of the α-campholene compounds are partially separated on permethylated α-cyclodextrin but not those of the fencholene analogue. On permethylated β-cyclodextrin, however, it are only the diastereomers of the fencholene compounds that are better separable, those of the α-campholene derivate can only be partially separated. In the case of these substances they hinder each other by the methyl group in the side chain which is in the α-position of the five-membered ring and the two geminal methyl substituents on cyclopentene, or they cause a different conformation of the side chain. Additionally, another steric hin-

Table 2
Separation factors, α, capacity factors, k' and chiral resolution, cR_S, on permethylated α-, β- and γ-cyclodextrins dissolved in polysiloxanes

No.		α-CD (column 1)				β-CD (column 2)			
		α	k'	T (°C)	cR_S	α	k'	T (°C)	cR_S
1	D1	1.017	27.87 28.34	95	0.94	1.030	15.20 15.66	110	2.14
	D2	1.017	30.80 31.32	95	0.94	1.00	16.66	110	0.00
2	D1	1.00	21.10	95	0.00	1.045	12.25 12.80	110	3.46
	D2	1.00	23.40	95	0.00	1.021	13.04 13.31	110	1.57
3	D1	1.00	18.16	90	0.00	1.059	9.65 10.22	105	5.37
	D2	1.00	18.16	90	0.00	1.054	9.75 10.28	105	3.29
4	D1	1.00	12.84	115	0.00	1.021	25.06 25.59	100	1.79
	D2	1.00	13.08	115	0.00	1.025	26.14 26.79	100	1.79
5	D1	1.00	28.73	95	0.00	1.00	14.13	110	0.00
	D2	1.015	33.79 34.28	95	0.89	1.015	17.05 17.30	110	1.50
	D3	1.032	34.84 35.94	95	1.84	1.013	17.42 17.65	110	0.94
	D4	1.00	44.10	95	0.00	1.053	22.16 23.34	110	4.34
6	D1	1.00	12.55	105	0.00	1.043	10.06 10.49	110	3.49
	D2	1.00	15.11	105	0.00	1.069	12.83 13.72	110	5.99
	D3	1.016	15.51 15.76	105	0.90	1.030	13.46 13.86	110	2.37
	D4	1.017	18.48 18.79	105	0.93	1.143	17.62 20.14	110	10.99

(*Continued on p. 492*)

Table 2 (*continued*)

No.		β-CD (column 3)				γ-CD (column 4)			
		α	k'	T (°C)	cR_S	α	k'	T (°C)	cR_S
1	D1	1.024	14.01 14.35	110	2.21	1.021	15.78 16.12	110	2.03
	D2	1.00	15.47	110	0.00	1.00	16.80	110	0.00
2	D1	1.038	10.97 11.39	110	3.39	1.021	11.46 11.70	110	1.86
	D2	1.023	11.71 11.98	110	2.16	1.00	12.70	110	0.00
3	D1	1.042	8.39 8.75	105	3.29	1.00	17.68	100	0.00
	D2	1.061	8.39 8.90	105	4.48	1.013	18.10 18.36	100	0.95
4	D1	1.031	21.82 22.50	100	3.01	1.00	18.03	105	0.00
	D2	1.014	22.96 23.27	100	1.26	1.00	18.68	105	0.00
5	D1	1.009	13.18 13.30	110	0.87	1.026	14.69 15.07	110	2.71
	D2	1.015	15.72 15.95	110	1.39	1.015	17.77 18.04	110	1.73
	D3	1.011	16.52 16.71	110	1.13	1.044	17.77 18.55	110	4.39
	D4	1.052	20.87 21.96	110	4.31	1.030	22.62 23.30	110	3.96
6	D1	1.040	9.24 9.61	110	3.74	1.009	10.51 10.61	110	0.88
	D2	1.066	11.59 12.36	110	6.25	1.048	12.99 13.61	110	4.38
	D3	1.031	12.36 12.74	110	2.86	1.048	12.99 13.61	110	4.38
	D4	1.143	15.99 18.27	110	13.01	1.015	17.13 17.39	110	[a]
8	D1	1.019	30.04 30.62	110	1.47		[a]		
	D2	1.012	30.68 31.04	110	1.23				
	D3	1.013	33.88 34.30	110	1.21				
	D4	1.011	34.69 35.07	110	1.20				

[a] No values determined.

drance of this methyl group takes place with the one in 3-position on the five-membered ring. On the basis of this the steric effects for **1** and **2** as compared with **3** and **4** in [15] should have a stronger influence on the enantiomer differentiation. This assumption is in agreement with the measured values on all cyclodextrin phases used. The changes on the two permethylated β-cyclodextrin phases being the largest.

If a compound is a mixture of two or more independent diastereomers with very similar chemical and physical properties (e.g. **2**/**3**) only a very narrow temperature range will exist for an optimum resolution of all the stereoisomers

present in the mixture. If there are deviations from this optimum column temperature by only 5°C there will be peak overlapping (Fig. 6) or an inversion of the elution sequence, as was observed for **3** (Fig. 2).

The cause for this behaviour is the different temperature dependence of the retention of the diastereomers and the enantiomers. With the change of the column temperature the difference in the retentions of both the diastereomers and the enantiomers will be changing. Both changes neither need to be equal in their extent nor need the retention difference of two (neighbouring) stereoisomers become altogether bigger in the case of a change in the column temperature. The probability of overlapping or of elution sequence inversion of various stereoisomers due to the change in the column temperature is the higher, the smaller the selectivity of the stationary phase used is against the diastereomers, and the more independent stereogenous centres are included in the compound. By analogy with the iso-enantioselective temperature [30–32] at which two enantiomers are overlapping this point could be called the pseudo-iso-enantioselective temperature.

As the compounds were stereoisomer mixtures no clear configuration assignment was possible for the various peaks. However, the following can be derived from the path of synthesis. The α-pinene used for the synthesis showed a clear excess of (*R*)-(+)-enantiomers (40% ee). As neither epoxidation nor camphane and fenchane rearrangement will change the ratio of the enantiomers, α-campholene and fencholene aldehyde are received with 40% ee of the resulting (*S*)-(−) enantiomers. The subsequent Grignard reaction to alcohol **3** leads to the formation of a new stereogenic centre which is not diastereoselectively influenced by the one already existing.

Because of the non-racemic ratio of the enantiomers in the pinene the ratio of the enantiomers in the alcohol **3** can therefore not be expected to be racemic. According to this, the stereoisomers *SS*/*SR* to *RR*/*RS* must behave like *R* to *S* in the pinene used (*S* to *R* in the α-campholene aldehyde).

As there is no change in the priority of the substituents on the asymmetric carbon of the five-membered ring beginning with the aldehyde it can be deduced from the peak area ratios that for **3** the *SS* elutes before the *RR* and, likewise, the *SR* elutes before the *RS* enantiomers. By analogy to this an assignment was made for **2** in Fig. 6, and for **7** in Fig. 3.

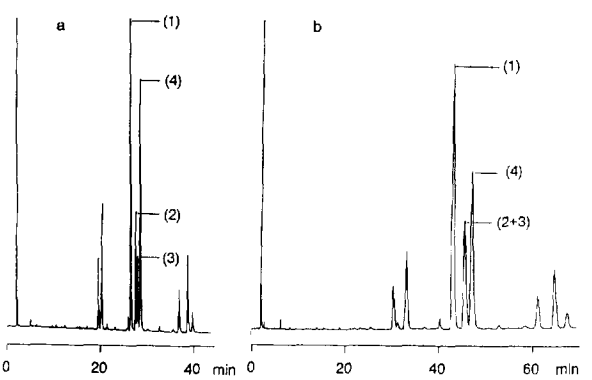

Fig. 6. Chromatogram of **2** on permethylated β-cyclodextrin (column 2), column temperature: (a) 110°C, (b) 105°C; injection/FID: 300°C/250°C; carrier gas: hydrogen; split ratio 1:80; Peak (1) and (4): *SS*- and *SR*-stereoisomers; Peak (2) and (3): *RR*- and *RS*-stereoisomers.

4. Conclusion

On permethylated α-, β- and γ-cyclodextrins dissolved in polysiloxanes it is possible to separate stereoisomer mixtures of α-campholene and fencholene derivatives with up to three stereogenic centres into the enantiomers in an excellent way.

For compounds with two stereogenic centres the separation is possible on single columns. It needs to be considered that the diastereomer selectivity of the basic phases and the enantiomer selectivity of the chiral selector are temperature-dependent to a different extent so that peak overlapping and elution sequence inversions were often observed.

Especially the steric structure of the compounds has an influence on the enantiomer

separation. If methyl substituents of the substances hinder each other the separation is clearly impaired. This effect was also found for the ethers and esters discussed in Part I.

For compounds with three stereogenic centres couplings of the non-chiral precolumn and the chiral main column are necessary in order to guarantee a complete separation of the mixture. For a reliable identification of the derivatives with two asymmetric centres and for separation of impurities it is helpful — and for the derivatives with three stereogenic centres absolutely necessary — that the considerably better separation by column coupling is combined with the advantages of mass selective detection. Such coupling is easily realized between commercial instruments.

Acknowledgement

We wish to thank Supelco Deutschland/Bad Homburg for capillary columns 3 and 4. The financial support for this work by the Deutsche Forschungsgemeinschaft and the Fonds der Chemischen Industrie is gratefully acknowledged.

References

[1] V. Schurig and H.-P. Nowotny, *J. Chromatogr.*, 441 (1988) 155–163.
[2] W.A. König, S. Lutz, and G. Wenz, *Angew. Chem.*, 100 (1988) 989–990.
[3] D.W. Armstrong, W. Li, and J. Pitha, *Anal. Chem.*, 62 (1990) 214–217.
[4] D.W. Armstrong, W. Li, C.D. Chang and J. Pitha, *Anal. Chem.*, 62 (1990) 914–923.
[5] Z. Juvancz, G. Alexander and J. Szejtli, *J. High Resolut. Chromatogr. Chromatogr. Commun.*, 10 (1987) 105.
[6] A. Venema and P.J.A. Tolsma, *J. High Resolut. Chromatogr. Chromatogr. Commun.*, 12 (1989) 32.
[7] A. Berthod, W. Li and D.W. Armstrong, *Anal. Chem.*, 64 (1992) 873–879.
[8] V. Schurig, D. Schmalzing and M. Jung, *J. Chromatogr.*, 552 (1991) 43–57.
[9] R. Reinhardt, W. Engewald, G. Haufe and O. Goj, *Chromatographia*, 39 (1994) 192–199.
[10] W. Meier-Augenstein, B.V. Burger, H.S.C. Spies and W.J.G. Burger, *Z. Naturforsch.*, 47b (1992) 877–886.
[11] F. Kobor, K. Angermund and G. Schomburg, *J. High Resolut. Chromatogr.*, 16 (1993) 299–311.
[12] N. Koen de Vries, B. Coussens, R.J. Meier and G. Heemels, *J. High Resolut. Chromatogr.*, 15 (1992) 499–504.
[13] A. Venema, H. Hendriks and R. v. Geest, *J. High Resolut. Chromatogr. Chromatogr. Commun.*, 14 (1991) 676–680.
[14] I.D. Smith and C.F. Simpson, *J. High Resolut. Chromatogr.*, 15 (1992) 800–806.
[15] R. Reinhardt, A. Steinborn, W. Engewald, K. Anhalt and K. Schulze, *J. Chromatogr. A*, 697 (1995) 475–484.
[16] P. Werkhoff, S. Brennecke and W. Brettschneider, *Chem. Mikrobiol. Technol. Lebensm.*, 13 (1991) 129–152.
[17] A. Mosandl, *J. Chromatogr.*, 624 (1992) 267–292.
[18] A. Bernreuther and P. Schreier, *Phytochem. Anal.*, 2 (1991) 167–170.
[19] P. Kreis and A. Mosandl, *Flavour Frag. J.*, 7 (1992) 187–193.
[20] S. Nitz, H. Kollmannsberger and F. Drawert, *Chem. Mikrobiol. Technol. Lebensm.*, 12 (1989) 75–80.
[21] B. Arbusov, *Ber. Dtsch. Chem. Ges.*, 68 (1935) 1430–1435.
[22] H. Uhlig, M. Mühlstädt and K. Schulze, *Miltitzer Ber.*, (1985) 23–40.
[23] M. Mühlstädt, G. Feustel, M. Hermann and W. Dollase, *DD-Pat.*, 68936 (1969), *C.A.* 72 (1969) P125008.
[24] E.-J. Brunke and E. Klein, *DBP*, 2827957 (1978), *C.A.*, 93 (1980) P137899.
[25] K. Schulze and H. Uhlig, *Monatsh. Chem.*, 120 (1989) 547–559.
[26] J.V. Hinshow and L.S. Ettre, *Chromatographia*, 21 (1986) 561–572.
[27] J.V. Hinshow and L.S. Ettre, *Chromatographia*, 21 (1986) 669–680.
[28] T. Maurer, W. Engewald and A. Steinborn, *J. Chromatogr.*, 517 (1990) 77–86.
[29] A. Steinborn, W. Engewald and R. Reinhardt, in P. Sandra (Editor), *Proceedings of the 15th International Symposium on Capillary Chromatography, Riva del Garda, May 1993*, Hüthig, Heidelberg, 1993, pp. 892–900.
[30] B. Koppenhöfer and E. Bayer, *Chromatographia*, 19 (1984) 123–130.
[31] K. Watabe, R. Charles and E. Gil-Av, *Angew. Chem.*, 101 (1989) 195–197.
[32] V. Schurig, J. Ossig and R. Link, *Angew. Chem.*, 101 (1989) 197–198.