# Relative polarities of nine modified cyclodextrin commercial stationary phases in gas chromatographic capillaries

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## Abstract

"Polarities" of commercial modified cyclodextrin (CD) gas chromatographic phases were rated at 100°C by the averages of retention indices for eight McReynolds' probe solutes, by the sequence and proportion of three, and by $\Delta C$ values for two of them. All nine CDs studied are above the low polarity of a fully methyl polysiloxane, and below the high values of a polyethylene glycol. Values from some CDs are similar to those of polar substituted polysiloxanes. Modifications of $\alpha$-CD are of lower polarity than their corresponding larger CDs. Dipentyl-(hydroxy remaining)-CDs are of lowest polarity and hydroxypropyl-dimethyl-CDs the highest. Esterified-(dipentyl)-$\gamma$-CDs fall between these groups, along with a supposedly fully methyl-$\beta$-CD. Surprisingly, the butyryl ester seems to be more polar than the shorter chain propionyl one. These features can be seen from a triangular plot of retention index fractions of the sum of three McReynolds' probes.

The $c$ ratios at higher temperatures, involving two different probe solutes, only seem comparable for different modifications of the same ring size CD.

## 1. Introduction

The use of probe solutes to evaluate the "polarity" of gas chromatographic stationary phases goes back to 1959, when Rohrschneider [1] compared the response of hydrocarbons butane to butadiene. He subsequently selected [2] five probes of diverse chemical types to use at 100°C, including benzene, pyridine and ethanol. To work at 120°C, McReynolds [3] used higher-molecular-mass analogues of some of these probes like butanol, and added five more, including octyne. The retention indices of these probes can be summed (commonly of the first five) or averaged to give a sequence of phases from low to high numbers of polarity. Using many probes is justified by Kollie and Poole

because "the general concept of polarity is a measure of the capacity of a stationary phase to enter into all intermolecular interactions" with diverse solutes [4]. These interactions have recently been discussed by Yancey [5] and involve dispersion (the commonest interaction) forces, dipole interactions, electron accepting forces and solute "polarizability". Kollie and Poole used as many as 18 solutes, but had trouble grouping their phases using calculations of partial molal Gibbs free energies of solution. Although Abraham et al. [6] initially felt the need for a complex equation of five terms to indicate phase polarities, they subsequently reduced this to just two for non-polar phases [7]. Castello et al. [8] returned in 1990 to essentially two solutes for their $\Delta C$ system, which uses the difference in

apparent carbon number between an alkane and a *n*-alcohol with the same retention time.

Poole has dismissed the value of the Rohrschneider–McReynolds approach, but Rohrschneider has recently [9] defended it. "No perfect relation has been formulated for the various simultaneous intermolecular interactions responsible for retention by the stationary phase . . . (However) the model advanced by McReynolds describes the retention behaviour of stationary phases correctly and accurately . . . (It) uses actual relative retention data for real stationary phases . . . in contrast to the system of Abraham et al. . . . (In fact) in the retention index system only one parameter is (really) necessary . . . the index difference of benzene." Rohrschneider is thus not concerned that benzene and the alkanes needed to determine its index are both non-polar! Although some groups insist that nothing less than their complex mathematical procedure facilitated by computer is needed to evaluate phase polarity, they fail to group phases satisfactorily. Simple sets of retention times, perhaps converted to indices and manipulated, remain of considerable practical value to working chromatographers, if not theoretical ones.

This author has devised two methods for indicating relative phase polarity. The lower temperature one uses three of McReynolds' probes. Octyne emerging last, after butanol and pyridine, indicates a low polarity phase. Octyne first shows high polarity; with "intermediate" polarity indicated when octyne emerges between the others [10]. The fractional retention indices of their sum for the three solutes were plotted triangularly, and gave the same three polarity groupings graphically. A method for higher temperatures called *c* ratio uses two constituents of volatile oils, the polar aromatic cuminal and the bicyclic unsaturated sesquiterpene hydrocarbon caryophyllene [11]. Three-quarters of the ratio of their retention times indicates conventional low polarity phases by values less than 0.8. High polarity is shown by a ratio more than 1.2, with intermediate polarity between these numbers. This method helped assess the behaviour of some liquid crystal phases, and indicated there

were polarity changes in phases with temperature, including polyethylene glycol and polysiloxanes. This method has been applied by the author to modified cyclodextrin (CD) ring-molecular phases, with some resultant anomalies, and so these results are here compared with some other polarity-determining procedures mentioned above.

## 2. Experimental

### 2.1. Apparatus

A Hewlett-Packard 5790A gas chromatograph was used, fitted with a capillary control unit and a splitter injection port. The latter, and the flame ionisation detector, were both operated at 215°C.

The various "Chiraldex" modified CD capillaries were obtained from Advanced Separation Technologies (Whippany, NJ, USA) and were all 10 m × 0.25 mm I.D. with film thickness of 0.125 $\mu$m ± 10%. Prefixes A, B and G refer to $\alpha$, $\beta$, and $\gamma$-CD, respectively. Suffix PH refers to 2-(S)-hydroxypropyl-dimethyl-CDs, and DA refers to dipentyl-(3-hydroxyl remaining)-CDs. BP refers to dipentyl-3-butyryl-CD and PN to dipentyl-3-propionyl-CD, which are only available as $\gamma$-CDs. B-PH and G-DA capillaries used here were kindly donated. The others were purchased. The "Cyclodex-B" capillary was purchased from J&W Scientific (Folsom, CA, USA); 10 m was used of the original 30 m × 0.25 mm capillary, with the film thickness of trimethyl-$\beta$-CD given as 0.25 $\mu$m.

Helium was used as the mobile phase at a flow-rate of ca. 0.9 ml min$^{-1}$, except where a faster rate up to 1.5 ml min$^{-1}$ was used to produce narrower peaks from some solutes.

### 2.2. Methods

The eight McReynolds' probe solutes used are given in Table 1, where their results were obtained at 100°C. No deductions of squalane results were made. Cuminal and caryophyllene were needed for *c* ratios at various convenient

temperatures above 100°C given in Table 2. All capillaries were heated and cooled at less than 10°C min⁻¹ to avoid phase damage. Trace residues from an "emptied" syringe were injected. Hold-up times, obtained by extrapolating the retention times of $n$-heptane and $n$-hexane to that of methane on semi-logarithmic graph paper, were deducted from observed retention times to give adjusted observations.

Retention indices were obtained graphically, on semi-logarithmic graph paper, plotting adjusted retention times of $C_{6-12}$ $n$-alkanes on the logarithmic scale against carbon numbers. Adjusted retention times for solutes were then entered on the straight lines and projected to the apparent carbon number scale to read off their retention indices times 100. This method is preferred, with its visual limitation of index units, to the spurious precision of decimal places from using the formula. Close correspondence was obtained from runs made at different flow-rates with the same solutes. Details of manipulations of data from Table 1 for Table 2 are given in footnotes to the latter. Phase sequence is not the same in both tables. Table 1 has them in increasing average retention index order.

## 3. Results and discussion

Results and calculations are presented in Tables 1 and 2. Table 1 shows that the "polarity" of all the nine CD-phases studied is more than the low nature of a fully methyl-polysiloxane (e.g. SE-30) and may rise for some to near that of the fairly polar cyanopropyl–phenyl–methyl-(25:25:50)-polysiloxane OV-225. No CD phase is as polar as polyethylene glycol. This applies by the averages of retention indices of eight McReynolds' probe solutes; and (Table 2) by the sequence and proportion of three of them, or by $\Delta C$ determinations using not only the conventional alcohol, but also a ketone to see if this is useful.

The $c$ ratio observation that Cyclodex-B is intermediate in polarity between the other $\beta$-CD phases (-DA being low and -PH higher) is confirmed by the eight probes, even though

Cyclodex-B is supposedly fully methylated. Possibly it is not. This phase shows great similarity to the $\gamma$-CD ester phase G-PN in Table 1.

The $c$ ratio observation that the two $\gamma$-CD esters are intermediate in polarity between the other $\gamma$-CD phases is similarly confirmed. Only pyridine gives a distinctly different result for them in Table 1, a retention index over 100 units larger on G-BP, equivalent to another apparent carbon atom. The effect is seen in Fig. 1, which is discussed later. The reduced aromatic influence [12] of G-PN is apparent here. Pyridine can be easily "overloaded" on G-BP, and needs a high gas flow-rate for narrow peaks. This phase also shows higher affinity for pentanone and nitropropane, making it higher in apparent polarity than G-PN, although it has the longer ester hydrocarbon chain. The eight probes show the highest standard deviation of 85 for their retention indices on G-BP, presumably indicating most discrimination of diverse solutes by this phase, even if this is a misuse of standard deviation. This is higher than the 62 for the other ester phase G-PN and the similar 59 for G-DA. B-DA has the lowest standard deviation of 52, but A-DA is also up at 85, largely due to its high retention index for octyne. The -PH phases all show "good" standard deviations of about 71.

In Table 1 the eight solute probes are arranged in the most common sequence of increasing retention indices. Results distinctly out of "normal" sequence for a phase are italicised to emphasize these stronger or weaker affinities. Thus Chiraldex B-DA shows weaker retention of pentanone and stronger retention of methyl-pentanol than expected. Pyridine is usually seventh (or eighth with higher polarity phases) in probe sequence, but is equal fourth on A-DA. The B- and G-PH phases respond very similarly to pyridine, and to dioxane and the methyl-pentanol. The lattermost branched-molecular hexanol is commonly fifth in sequence, but is delayed until later on B- and G-DA. The extra affinity for alcohols of these phases with their one underivatised hydroxyl is apparent. G-DA in fact behaves very similarly to the two ester phases G-PN and -BP in respect of five of the eight probes used.

Table 1
Retention indices of eight McReynolds' probe solutes at 100°C on nine modified cyclodextrin phase capillaries

| Phase | Benzene | 2-Pentanone | 4-Dioxane | 1-Butanol | 2-Me,2-pentanol | 1-Nitropropane | Pyridine | 2-Octyne | Average[b] | Std. Dev. |
|---|---|---|---|---|---|---|---|---|---|---|
| SE-30 methyl PSX[a] | 678[c] | 685[c] | 715[c] | 645[d] | 739[c] | | 743[d] | 860[d] | (724) | |
| Chiraldex A-DA | 676 | 710 | 737 | 797 | 810 | 820 | 797 | 953 | 788 | 85 |
| Chiraldex B-DA | 749 | 725 | 785 | 785 | 857 | 797 | 850 | 865 | 802 | 52 |
| OV-17 phenyl, methyl PSX[a] | 779[c] | 798[c] | | 747[d] | | | 871[d] | 930[d] | (825) | |
| Chiraldex G-DA | 748 | 763 | 804 | 840 | 881 | 866 | 886 | 907 | 837 | 59 |
| Cyclodex-B | 754 | 790 | 827 | 824 | 874 | 895 | 874 | 907 | 843 | 54 |
| Chiraldex G-PN | 752 | 772 | 800 | 836 | 877 | 892 | 907 | 906 | 843 | 62 |
| Chiraldex G-BP | 747 | 790 | 801 | 829 | 868 | 918 | 1010 | 904 | 858 | 85 |
| Chiraldex A-PH | 775 | 786 | 860 | 913 | 900 | 940 | 936 | 961 | 884 | 71 |
| OV-210 trifluor-propyl, Me PSX[a] | 806[c] | 994[c] | | 815[d] | | | 977[d] | 891[d] | (897) | |
| Chiraldex B-PH | 814 | 831 | 925 | 953 | 966 | 987 | 1011 | 938 | 928 | 71 |
| Chiraldex G-PH | 828 | 852 | 922 | 972 | 966 | 1021 | 1021 | 978 | 945 | 72 |
| OV-225 cyanopropyl, phenyl, Me PSX[a] | 888[c] | 974[c] | | 939[d] | | | 1046[d] | 980[d] | (965) | |
| Polyethylene glycol 20M | 961[c] | 983[c] | 1073[c] | 1104[d] | 1066[c] | | 1180[d] | 1041[d] | (1058) | |

Results in italics are strongly out of increasing numerical sequence from left to right. Literature values are given for some conventional phases at 120°C. PSX means polysiloxane, with side chains as indicated (Me = methyl). Values at 120°C.
[a] PSX means polysiloxane, with side chains as indicated (Me = methyl).
[b] Averages in brackets are from fewer than eight solutes.
[c] Values from, or calculated using Ref. [13].
[d] From Ref. [10].

Table 2
Phase polarity parameters derived from Table 1 and elsewhere, at 100°C (unless indicated otherwise)

| Phase | Butanol fr.[a] | Pyridine fr.[a] | Octyne fr.[a] | B-P-O seq.[a] | ΔC-Pentanone[b] | ΔC-Butanol[c] | c-Ratio[d] at temp.(°C) |
|---|---|---|---|---|---|---|---|
| SE-30[e] | 0.287 | 0.330 | 0.383 | B-P-O | 1.85 | 2.45 | 0.27 (140) |
| Chiraldex A-DA | 0.313 | 0.313 | 0.374 | B-P-O | 2.10 | 3.97 | 0.65 (110) |
| OV-17[e] | 0.293 | 0.342 | 0.365 | B-P-O | 2.98 | 3.47 | 0.49 (140) |
| Chiraldex B-DA | 0.314 | 0.340 | 0.346 | B-P-O | 2.25 | 3.85 | 0.28 (125) |
| Chiraldex G-DA | 0.319 | 0.337 | 0.344 | B-P-O | 2.63 | 4.40 | 0.26 (170) |
| Chiraldex G-PN | 0.317 | 0.339 | 0.344 | B-P-O | 2.72 | 4.36 | 0.40 (125) |
| Cyclodex-B | 0.316 | 0.336 | 0.348 | B-P-O | 2.90 | 4.24 | 0.52 (125) |
| Chiraldex A-PH | 0.325 | 0.333 | 0.342 | B-P-O | 2.86 | 5.13 | 1.03 (110) |
| OV-225[f] | 0.317 | 0.353 | 0.330 | B-O-P | 4.74 | 5.39 | 1.03 (140) |
| Chiraldex G-BP | 0.302 | 0.368 | 0.330 | B-O-P | 2.90 | 4.29 | 0.46 (125) |
| OV-210[e] | 0.304 | 0.364 | 0.332 | B-O-P | 4.94 | 4.15 | 0.64 (125) |
| Chiraldex G-PH | 0.327 | 0.344 | 0.329 | B-O-P | 3.52 | 5.72 | |
| Chiraldex B-PH | 0.328 | 0.349 | 0.323 | O-B-P | 3.31 | 5.53 | 0.76 (125) |
| PEG 20M[e] | 0.332 | 0.355 | 0.313 | O-B-P | 4.83 | 7.04 | 1.58 (120) |

[a] fr. = Fraction of the sum of the retention indices of Butanol, Pyridine and Octyne, and their elution sequence from a phase.
[b] Retention index for pentanone divided by 100 minus five (carbons in pentane).
[c] Retention index for butanol divided by 100 minus four (carbons in butane).
[d] 3(retention time of cuminal)/4(retention time of caryophyllene), Ref. [11].
[e] At 120°C, Ref. [10].
[f] At 120°C, Ref. [14].

By the average of eight solute probe retention indices in Table 1, for the same modification, γ-CDs show higher polarity than β-CDs, which are higher than the same α-CDs. The set of -DA modifications are all of lower polarity than the -PH derivatives. In Table 2 ΔC values for pentanone agree with this; and also ΔC for butanol, except on A-DA, where it has a higher retention index than B-DA. Using two quite different solute probes with larger molecules, the c ratios again make A-DA more polar than B-DA (and G-DA). A-PH is also more polar than B- and G-PH by this method. Solute inclusion is noted as possible within the molecular rings of dipentyl (-DA) CDs [12] and this may happen with cuminal and the α-CDs, giving anomalously high c ratios. If the bigger molecule of the pair, caryophyllene, should be retained in the larger γ-CD rings, it would give anomalously low c

ratios. Whatever the reason, c ratios are only comparable for a given size CD ring. The smaller McReynolds' probe molecules are unlikely to be retained in CD-rings, although octyne gives an unusually high retention index on both the α-CDs.

The triangular plot in Fig. 1 of butanol-pyridine-octyne fractions from Table 2 data shows five phases with all the possible CD ring sizes are very similar in proportional responses. Chiraldex A-DA (AA in Fig. 1) is clearly the least polar, being nearest to the hydrocarbon octyne apex, and well away from the other CDs. It provides chromatographers with a different type of low polarity phase to the polysiloxanes SE-30 and OV-17. Similarly, G-BP (GB in Fig. 1) shows much greater affinity for the aromatic pyridine than any other CD phase. The three PH phases have roughly similar butanol fractions,
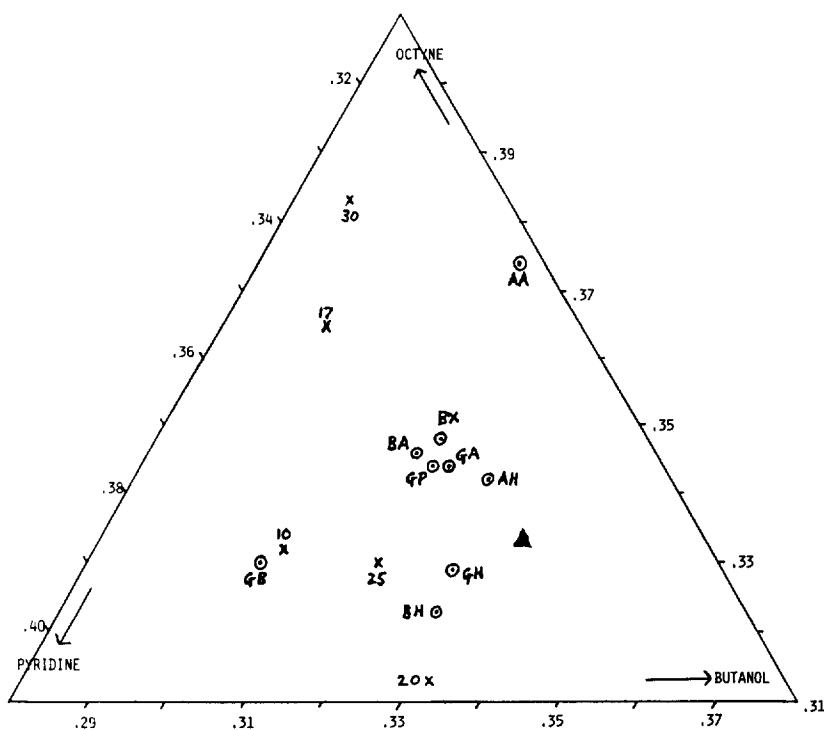


Fig. 1. Plot of retention index fractions of the sum of the indices of butanol, pyridine and octyne (Table 2) for modified cyclodextrins (⊙) and some conventional phases (×). ▲ = midpoint of the full triangular plot (0.333 for all three solutes). Prefixes A, B and G refer to α-, β- and γ-cyclodextrins, respectively. Suffix A = dipentyl cyclodextrin, B = butyryl (dipentyl), H = hydroxy-propyl (dimethyl), P = propionyl (dipentyl), X = permethyl. Conventional phases are numbered: 10 = OV-210, 17 = OV-17, 20 = PEG 20M, 25 = OV-225, 30 = SE-30; observations at 120°C. Cyclodextrin studies at 100°C.

suggesting they show similar affinity for alcohols. Chiraldex B-PH (BH) is the most polar CD from this plot, with the lowest octyne fraction, situated between polyethylene glycol 20M and OV-225. There is an absence of CD phases near to the butanol apex, beyond the midpoint of the triangular plot; but this is true for conventional phases, too. From Fig. 1, the most diverse set of modified CD gas chromatographic phases is Chiraldexes A-DA, B-PH and G-BP.

The butanol (fastest)-pyridine-octyne sequence of probes in Table 2 typical of low polarity phases is shown by all three-DAs, G-PN, Cyclodex-B and by A-PH (inappropriately). The "intermediate" polarity indicated by butanol-octyne-pyridine is given by the ester phase G-BP and G-PH. Only B-PH has the "high" polarity sequence of octyne-butanol-pyridine, supporting the $c$ ratio evaluation that it is more polar than G-PH. The retention index fractions show very similar values for G-PN, G-DA, B-DA and Cyclodex-B despite their different CD ring-sizes. This also applies to G-PH and B-PH. Thus the butanol, pyridine, octyne sequence assessment appears satisfactory for the group of modified-CDs apart from a question over strong octyne retention by $\alpha$-CDs. Table 2 suggests G-BP and G-PN are different. That these two ester phases are unalike can be demonstrated using cyclic monoterpenoids. On the three probe fractional assessment G-BP behaves like the trifluoropropyl-methyl-polysiloxane OV-210 (but not from $\Delta C$-pentanone); and B-PH is approaching polyethyleneglycol 20M, confirming its high polarity rating, and indicating this modified $\beta$-CD may be more polar than its $\gamma$-equivalent. $\Delta C$ values do not confirm this, but they utilise only one probe, in effect. Of the two $\Delta C$ determinations applied here, pentanone seems to provide the most logical results, although the nine retention indices used for it only span a range of 142. A ketone series of compounds was not used by Castello et al. [8], who relied on alcohols only. In contrast, butanol results span 187 retention indices, implying more discrimination by this probe.

The superiority of pentanone over butanol is

confirmed by plotting $\Delta C$ values against retention indices as in Fig. 2. $\Delta C$-pentanone against pentanone indices of course gives a perfectly straight line for all nine CD phases, revealing that $\Delta C$ values alone offer no more information than retention indices. If $\Delta C$-pentanone values are plotted against benzene indices only, as advocated by Rohrschneider [9], plot B shows five CD phases giving a nearly linear plot. These all have a hydroxy-group per $\alpha$-glucose of the CDs. However, B-DA falls well away from this line, as do Cyclodex-B and the two $\gamma$-CD esters. Benzene as a sole probe seems inadequate, for five modified CDs all have retention indices using it of about 750. Using the average of eight solutes reduces this to three phases around 840. These are G-DA, G-PN and Cyclodex-B, shown
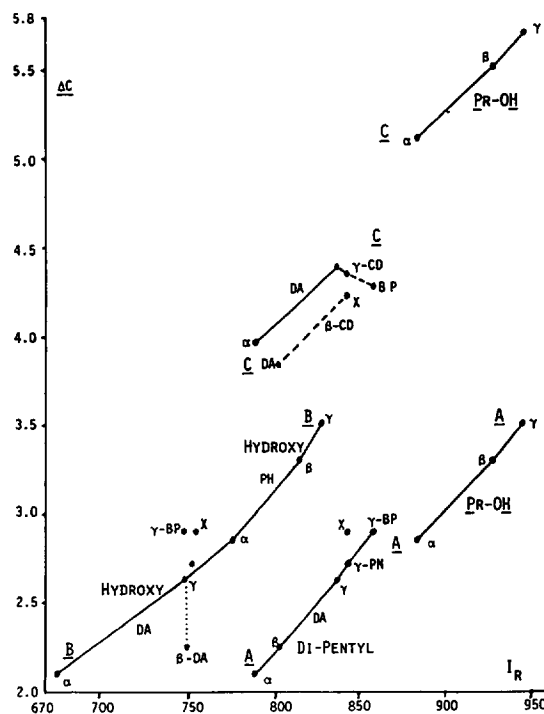


Fig. 2. Plots of $\Delta C$ values against retention index ($I_R$). A = $\Delta C$-pentanone vs. average $I_R$ of eight solutes (Table 1). B = $\Delta C$-pentanone vs. benzene $I_R$. C = $\Delta C$-butanol vs. average $I_R$. BP = butyryl ester, CD = cyclodextrin ($\alpha$-, $\beta$- or $\gamma$), DA = Chiraldex DA phases, PH = Chiraldex PH phases, PN = propionyl ester, PrOH = hydroxypropyl (dimethyl), X = Chiraldex-B (permethyl). Higher polarities are shown by higher values of $I_R$ and $\Delta C$.

as very similar by butanol-pyridine-octyne frac-
tions in Table 2 and by their plots in Fig. 1 as
well.

Using these average retention indices against
$\Delta C$-pentanone values to give plots A in Fig. 2
reveals two separated almost linear segments,
with methylated Cyclodex-B again distinctly
apart. The more polar hydroxypropyl PH phases
are away from the other five whose common
feature is dipentyl groups on each $\alpha$-glucose,
with or without esterification of the remaining
hydroxyl group. If $\Delta C$-butanol values are used
instead (plots C) the PH phases are even more
apart from the others, but the latter show less
organisation. The three dipentyl $\gamma$-CDs seem to
be linked by a reverse slope line. Plots of $\Delta C$-
butanol against just benzene indices (not shown
in Fig. 2) do not improve this.

In summary, for the two modified $\alpha$-CDs, the
various polarity parameters all show A-PH as
higher than -DA, despite an unexpected affinity
for octyne by the former.

The three $\beta$-CDs by all parameters here show
B-PH with highest polarity, and most give
Cyclodex-B between this and the lower B-DA.
B-PH may be the most polar of any modified CD
studied here. However, some parameters suggest
B-PH falls between G- and A-PH. The sequence
of low polarity values G-, B-, A-DA is also
supported by several parameters.

The four $\gamma$-CDs, by all except one parameter,
show the sequence G-PH (highest), -BP, -PN,
-DA. Whilst the first undoubtedly is the most
polar, the last two are very similar by the three-
probe fractions, with G-PN being just lower by
$\Delta C$-butanol (and G-BP lowest!).

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