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SUPRAMOLECULAR CRYSTALLINE CONSTRUCTION BASED ON A MANDELIC ACID SOURCE. HOST DESIGN, INCLUSION FORMATION AND X-RAY CRYSTAL STRUCTURES OF A METHANOL INCLUSION COMPLEX AND FREE HOST STRUCTURES IN RACEMIC AND OPTICALLY RESOLVED FORMS

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A new host compound in optically resolved and racemic forms for selective crystalline inclusion formation derived from natural mandelic acid was synthesized. Inclusion properties of the two optical species are discussed, involving comparison with a lactic acid-based host analogue. Inclusion compounds with amines, ketones and heterocyclics and specifically with small unbranched alcohols were isolated. The crystal and molecular structures of the optically resolved and racemic forms of the free host at room temperature and the methanol inclusion complex of the resolved host at 255 K were determined by x-ray analysis. Two different binding schemes characterize the packing of these structures, in which one hydroxyl group is responsible for the formation of dimers and chains while in the free host the other hydroxyl group is involved in OH···phenyl interactions. A survey of the OH···phenyl interactions based on the Cambridge Structural Data Base (October 1994 version) reveals that π-electron bonding occurs in a wide range of crystal structures. The approximation of the hydrogen appears to take place in an asymmetric way. Several calculations for the *ab initio* prediction of the crystal structures were performed.

INTRODUCTION

Optical resolution making use of the crystalline inclusion phenomenon (clathrate formation)[1] is a promising new approach to complement the classical methods of racemate solution,[2] especially in the case of non-acidic and non-basic chiral compounds.[3] Hosts having this particular feature require ready availability in optically resolved form, e.g. arising from a natural chiral source.[4]

Recently we have shown that natural lactic acid, when modified by addition of two bulky aromatic units, yields crystalline hosts that are efficient enantioselectors for guests of different compound classes either by inclusion crystallization or vapour sorption.[5] The introduction of bulky, rigid (clathratogenic) substituents tends to make the compound difficult to crystallize without a suitable guest, which is the essential point of this useful host design in addition to the clever installment of chirality.[6] Although the lactic acid-derived compounds proved very profitable,[5] more structural modifications of the host framework considering extra bulky substituents seem full of promise. A phenyl ring compared with a methyl group opens up the possibility of stacking interaction[7] and gives rise to increased host shielding, thus involving potentially improved stability and selectivity of inclusions.[1] Following this line, we became interested in natural mandelic acid as the chiral precursor, i.e. changing the methyl group of lactic acid for the phenyl group of mandelic acid.

Here we describe preparation of a host compound synthesized in optically resolved (**2a**) and racemic forms (**2b**). We discuss the properties of crystalline inclusion formation relative to the lactic acid-derived

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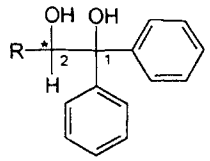
host analogue (**1a** and **b**) and report x-ray structural studies of unsolvated host compounds **2a** and **b** and of the 1:1 (host:guest) methanol inclusion complex of optically resolved **2a**. The reason for selection of this particular inclusion complex is that neither racemic **2b** nor **1a** or **b** yields an inclusion compound with methanol, suggesting specific modes of structure and supramolecular interaction for drawing conclusions.



1a R= CH_3 (2*S*)
1b R= CH_3 (2*R*,2*S*)
2a R= Ph (2*R*)
2b R= Ph (2*R*,2*S*)

RESULTS AND DISCUSSION

Synthesis

Host compounds **2a** and **b** were synthesized in a two-step process from (*S*)- and (*R*, *S*)-mandelic acid, respectively, by conversion of the acid into the methyl ester followed by reaction with lithiobenzene to give the products in good overall yields.

Inclusion properties

As mentioned above, a comparative study of the crystalline inclusion formation involving the new mandelic acid derived hosts (**2a** and **b**) and the lactic acid derived analogues (**1a** and **b**) is reasonable. The results of the present inclusion experiments, including previous data[5] for **1a** and **b**, are summarized in Table 1.

Generally, the four host species yield stoichiometric crystalline complexes with many alcohols, amines and ketones, but also with heterocyclic compounds and dipolar substances such as dimethylformamide and dimethyl sulphoxide. Nonetheless, there are significant differences between the four hosts, most obvious in the selective inclusion of alcohols. While both optical forms of the lactic acid-derived host compound **1** failed to include acyclic alcohols,[5] the optically resolved host compound **2a** was successful in forming inclusion complexes with acyclic alcohols, but the racemic analogue **2b** again failed doing so. On the other hand, hosts **2a** and **b** are less efficient in the accommodation of cyclic alcohols.

A comparison of the inclusion behaviour of the racemic hosts **1b** and **2b**, i.e. of the same optical category, also reveals an interesting result. The racemate **2b** is clearly inferior to **1b**. A similar situation applies for **2a** and **b**, where optically resolved **2a** is much more efficient. In contrast, the inclusion behaviour of optically resolved **2a** compares well with that of **1a**, except for the acyclic alcohols.

Aside from this basic difference in inclusion behaviour, there is a more subtle distinction with regard to the stoichiometric ratios formed. Exceptional cases in this connection are the inclusion compounds of **2a** and **b** with dimethylformamide showing a high host:guest stoichiometric ratio of 1:3. Also, the stoichiometric ratios formed for the alcohol inclusions of **2a** are far from being obvious, considering the relative sizes of the molecules. This specific fact relating to the differences between the two optical species **2a** and **b** and the individuality of the alcohol inclusions of **2a** prompted us to carry out an x-ray study, i.e. the free host crystals of **2a** and **b** and the crystal of the **2a**·MeOH (1:1)

Table 1. Crystalline inclusion compounds (host:guest stoichiometric ratio)

	Host compound			
Guest solvent[a]	**1a**	**1b**	**2a**	**2b**
MeOH	—	—	1:1	—
1-PrOH	—	—	2:1	—
1-BuOH	—	—	1:1	—
t-BuOH	—	—	2:1	—
c-PentOH	1:1	1:1	1:1	1:1
c-HexOH	1:1	1:1	—	—
c-HeptOH	1:2	1:2	1:2	1:2
2-Me-*c*-HexOH	1:1	1:1	—	—
3-Me-*c*-HexOH	1:1	1:1	1:1	—
i-$BuNH_2$	2:1	2:1	2:1	—
2-$BuNH_2$	—	3:1	2:1	—
c-$PentNH_2$	1:1	1:1	1:1	—
3-Me-*c*-$HexNH_2$	1:1	1:1	2:3	—
2-Me-*c*-$HexNH_2$	1:1	1:1	1:1	—
Acetone	1:2	1:2	—	—
Cyclopentanone	2:1	—	1:1	—
Cyclohexanone	2:1	2:1	1:1	1:1
3-Methylcyclohexanone	2:1	—	1:1	1:1
Cycloheptanone	2:1	—	1:1	—
γ-Valerolactone	—[b]	—[b]	1:1	—
Dimethylformamide	2:1	2:1	1:3	1:3
Dimethyl sulphoxide	1:1	1:1	1:1	1:1
Dioxane	2:1	2:1	2:1	—
Morpholine	1:1	2:1	1:1	2:3
Piperidine	1:2	1:1	1:1	—
3-Methylpiperidine	2:1	2:1	3:2	—
Pyridine	2:1	2:1	2:1	2:1
3-Picoline	2:1	2:1	2:1	—

[a] The following solvents yielded no crystalline inclusions: EtOH, *i*-BuOH, 2-BuOH, 2-PrOH, benzaldehyde, 2-methylcyclohexanone, 4-methylcyclohexanone, β-butyrolactone, propylene oxide, tetrahydrofuran, 2-methyltetrahydrofuran, 3-methyltetrahydrofuran, acetonitrile, propionitrile, butyronitrile, nitromethane, nitroethane, toluene and xylene.
[b] Not tested.

inclusion compound were subjected to a structural determination.

Structural studies

In all compounds **2a**, **2b** and **2a**·MeOH (1:1), the OH groups are in a *gauche* conformation, except in molecule 2 of **2a**, which is *trans* [Figure 1(a)]. For all phenyl rings the *ipso* angle [C(i2)–C(i1)–C(i6); $i = 1, 2$] reflects the influence of the σ-electron-withdrawing character of the substituent[8] (Table 2). The almost coplanarity of the C(2) atom with the C(11)···C(16) phenyl ring in all compounds gives rise to angular distortion at C(1) and C(11) so that the C(2)–C(1)–C(11) and C(1)–C(11)–C(12) angles present values in the ranges 112·4(3)–113·8(3)° and 123·2(2)–124·5(3)°, respectively.

Two different binding schemes, dimers and chains, characterize the packing of these structures. In the crystal structure of the chiral host **2a** (Figure 2), the hydroxy groups bonded to the asymmetric carbon link the two independent molecules, **1** and **2**, forming chains along the *a* axis, while the remaining OH groups are involved in O–H···O and OH···Ph intramolecular interactions. In **2b**, only one of the two hydroxy groups (that which is not attached to the asymmetric carbon) is involved in O–H···O hydrogen bonds, being responsible for the formation of dimers (Figure 3), leaving the other OH group for stabilization of dimers through OH···phenyl interactions (Table 3). Compound **2a**·MeOH packs in chains parallel to the *b* axis (Figure 4), so that the methanol molecule links host molecules acting as an acceptor of two hydrogen interactions as well as a donor. In all compounds, weak phenyl···phenyl 'T-type' interactions (Table 3)join together dimers and chains forming sheets. The sheets are packed by the remaining 'herringbone' interactions, giving rise to the whole crystal.

There are substantial differences when the crystal packing of the host is compared with that of lactic acid.[9] The resolved molecules present completely different arrangements and in the racemic structures only the hydrogen-bonded dimers are equivalent for both compounds. However, the packing of the MeOH inclusion compound can be related to that of the resolved lactic acid host. The lattice has been expanded along the *c* axis to accommodate the C(31)–C(36) phenyl ring and the methanol moiety [cell dimensions of lactic acid: 12·3277(6), 6·5165(3), 8·1958(3) Å and 108·831(3)° and same space group].

The OH-π hydrogen bond to an aromatic ring has been subject of several experimental and theoretical studies.[10] In recent years there has been increasing interest in the study of these interactions because of their importance in biological systems (interaction of water with aromatic moieties) or because they can be associated with anomalous reactivity.

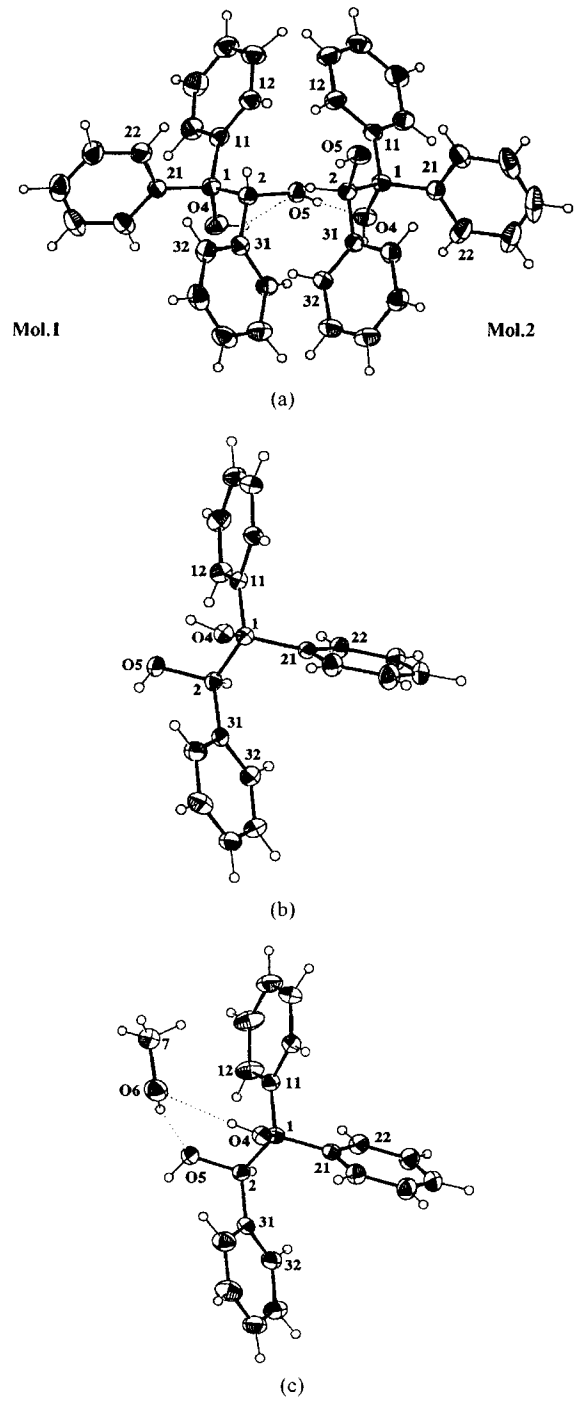


Figure 1. Molecular structures of (a) **2a**, (b) **2b** and (c) **2a**·MeOH showing the numbering system. Displacement ellipsoids were drawn at the 30% probability level. Dotted lines indicate hydrogen bonds

Table 2. Selected geometrical parameters (bond lengths in Å, angles in degrees)

Bonds	**2a**		**2b**	**2a**·MeOH
C(1)—C(2)	1·550(4)	1·552(4)	1·557(2)	1·542(5)
C(1)—O(4)	1·424(4)	1·442(4)	1·430(2)	1·432(4)
C(1)—C(11)	1·536(4)	1·538(4)	1·535(2)	1·537(5)
C(1)—C(21)	1·533(5)	1·521(5)	1·528(2)	1·530(4)
C(2)—C(31)	1·521(4)	1·530(4)	1·513(2)	1·528(5)
C(2)—O(5)	1·426(4)	1·407(4)	1·434(2)	1·427(4)
C(12)—C(11)—C(16)	118·7(3)	119·4(3)	118·6(1)	118·7(3)
C(22)—C(21)—C(26)	119·2(3)	119·2(4)	119·0(1)	118·8(3)
C(32)—C(31)—C(36)	118·7(3)	119·4(3)	118·3(2)	119·0(3)
C(2)—C(1)—C(11)	113·5(3)	113·8(3)	112·9(1)	112·4(3)
C(1)—C(11)—C(12)	124·5(3)	123·0(3)	124·3(1)	124·2(3)
C(2)—C(1)—C(21)	109·8(3)	110·0(3)	109·3(1)	109·2(3)
C(1)—C(21)—C(22)	119·3(3)	120·9(3)	119·7(1)	119·8(3)
O(4)—C(1)—C(2)—O(5)	64·2(3)	−174·7(2)	65·2(1)	62·3(3)
C(21)—C(1)—C(2)—C(3)	60·5(3)	−58·6(3)	57·3(2)	56·7(4)
C(11)—C(1)—C(2)—C(3)	−178·4(3)	176·8(3)	178·1(1)	178·0(3)
C(1)—C(2)—C(31)—C(32)	−88·6(4)	−91·5(4)	−111·4(2)	−107·5(4)
C(2)—C(1)—C(11)—C(12)	−10·1(5)	−6·7(5)	−17·2(2)	−15·5(5)
C(2)—C(1)—C(21)—C(22)	65·1(4)	108·0(4)	70·7(2)	76·0(4)

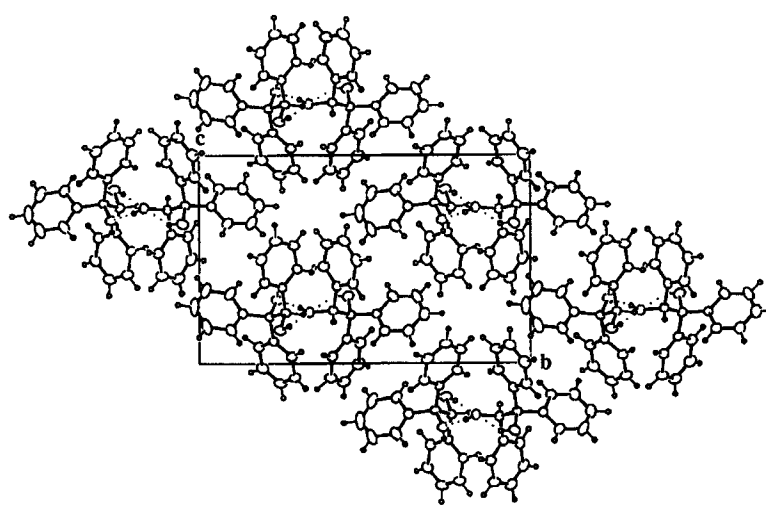


Figure 2. Crystal packing of **2a** projected along the *a* axis

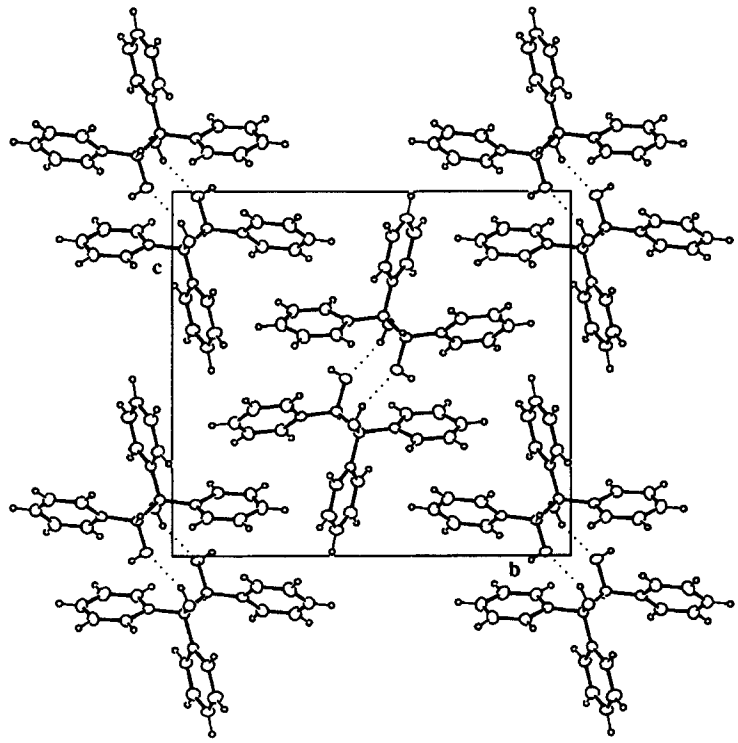


Figure 3. Crystal packing of **2b** projected along the *a* axis

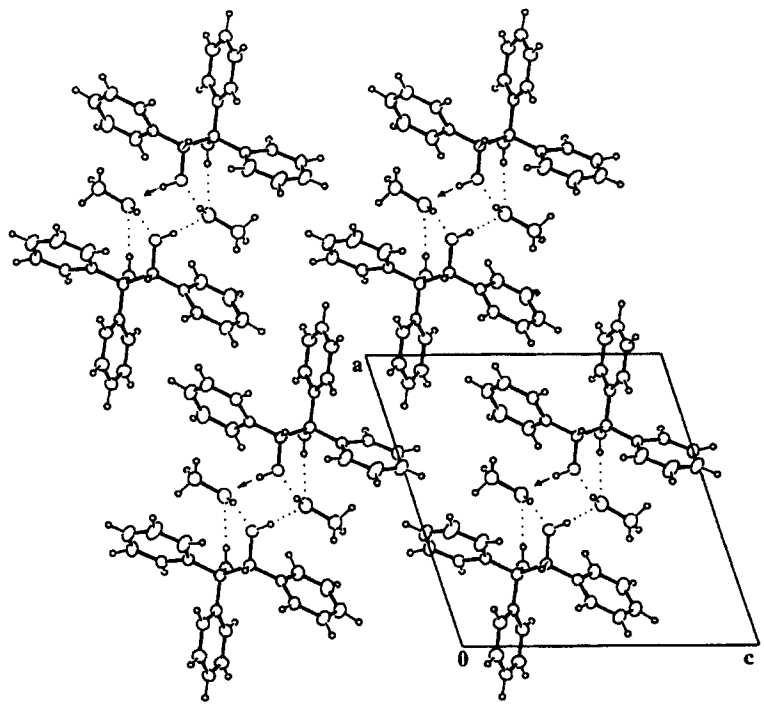


Figure 4. Crystal packing of **2a**·MeOH projected along the *b* axis

Table 3. Hydrogen bond interactions (bond length in Å, angles in degrees)[a]

Compound	Parameter	X—H	X···Y	H···Y	X—H···Y
2a	O(4)—H(4)Mol.1···O(5)Mol.1	0·79(5)	2·792(3)	2·43(6)	109(5)
	O(5)—H(5)Mol.1···O(4)Mol.2	0·93(4)	2·784(3)	1·86(4)	173(4)
	O(5)—H(5)Mol.2···O(5)Mol.1$_1$	0·98(5)	2·841(3)	1·89(4)	165(5)
	O(4)—H(4)Mol.2···C(31–36,Mol.2)	0·84(5)	3·859(2)	3·08(5)	155(6)
	C(36)—H(36)Mol.1···C(31–36,Mol.2)$_2$	0·91(3)	3·743(4)	2·85(4)	169(3)
	C(23)—H(23)Mol.1···C(11–16,Mol.2)$_3$	1·11(5)	3·802(5)	2·79(5)	152(3)
	C(15)—H(15)Mol.1···C(21–26,Mol.2)$_4$	1·03(5)	3·994(4)	3·31(4)	126(4)
	C(23)—H(23)Mol.2···C(31–36,Mol.1)$_5$	0·94(9)	3·801(7)	2·99(9)	146(5)
	C(12)—H(12)Mol.2···C(11–16,Mol.1)$_1$	1·01(4)	3·995(4)	3·07(4)	147(3)
	C(15)—H(15)Mol.2···C(21–26,Mol.1)$_6$	1·03(4)	3·950(4)	3·08(4)	143(3)
	1: $1+x, y, z$	2: $-1+x, y, z$			3: $1-x, \frac{1}{2}+y, -z$
	4: $-x, \frac{1}{2}+y, -z$	5: $1-x, -\frac{1}{2}+y, 1-z$			6: $-x, -\frac{1}{2}+y, -z$
2b	O(4)—H(4)···O(5)$_1$	0·86(3)	2·921(1)	2·10(3)	160(3)
	O(5)—H(5)···C(11–16)$_1$	0·79(3)	3·531(1)	2·85(3)	145(3)
	C(33)—H(33)···C(11–16)$_2$	0·97(3)	3·634(2)	2·92(3)	131(2)
	1: $1-x, 1-y, 1-z$	2: $-x, -\frac{1}{2}+y, \frac{1}{2}-z$			
2a·MeOH	O(4)—H(4)···O(6)	0·85(5)	3·041(4)	2·22(5)	163(5)
	O(5)—H(5)···O(6)$_1$	0·85(6)	2·670(4)	1·83(5)	171(6)
	O(6)—H(6)···O(5)	0·96(8)	2·650(5)	1·77(8)	152(6)
	C(7)—H(72)···C(31–36)$_2$	1·02(7)	3·753(5)	3·18(5)	117(3)
	C(23)—H(23)···C(21–26)$_3$	0·96(6)	3·794(4)	3·19(5)	123(4)
	1: $1-x, \frac{1}{2}+y, 1-z$	2: $1-x, -\frac{1}{2}+y, 1-z$			3: $-x, \frac{1}{2}+y, -z$

[a] C(11–16), C(21–26) and C(31–36) stand for the centroids of the corresponding rings

In order to characterize geometrically the OH···phenyl inter- and intramolecular interactions, a survey of these contacts in monosubstituted phenyl rings was carried out using the Cambridge Structural Data Base.[11] Only structures with $R < 0{\cdot}050$ and without any kind of disorder were retained. Inter- and intramolecular contacts were present in 114 and 14 structures, respectively. Among the former, 23 correspond to hydrates and were analysed independently. The total number of interactions is distributed as follows: 112 alcohols, 33 hydrates and 19 intramolecular. The H···centroid distance is not significantly different between groups in terms of the dispersion and it ranges from 2·39 to 4·00 Å. The interaction occurs in an asymmetric way, so that the H···C-aryl distance ranges from 2·271 to 5·251 Å, the minimum being lower than the estimated van der Waals distance[12] of 2·8 Å. The mean OH bond value and the standard deviation of the sample is 0·91(14) Å. The histograms of H···centroid distance and the O–H···centroid angle are represented in Figures 5 and 6. The scatter plots of O–H···Ph angle vs H···centroid distance and the H···centroid distance vs the angle of the H-centroid and the normal to the phenyl plane are shown in Figures 7 and 8. The O–H···centroid angle distribution is bimodal and the most probable angle is 117°, showing that these interactions are not linear. Figure 7 shows that the more linear interactions correspond to the shorter distances and an almost spherical distribution for distances near to 4 Å can also be observed. Only 11, 4 and 3 fragments corresponding to the three groups already mentioned, present H···C values less than the sum of van der Waals radii and the deviation from the perpendicular to the phenyl ring is 22, 23 and 32°, respectively. Figure 8 shows the relationship between the direction in which the interaction takes place and the H···centroid distance. The symmetry of the plot indicates the ambiguity between the two faces of the ring. There is no correlation between the H···C(phenyl) and the C–C distances in the phenyl ring, which present the expected C_{2v} symmetry for the monosubstituted rings in terms of bond distances and angles. In conclusion, there is a large number of well refined structures in which the proton of the OH group is directed to the electronic π cloud of the phenyl ring, but just a few number of them present short H···C distances, up to 0·6 Å less than the sum of the van der Waals radii. The interactions are, in general, not linear and there is no

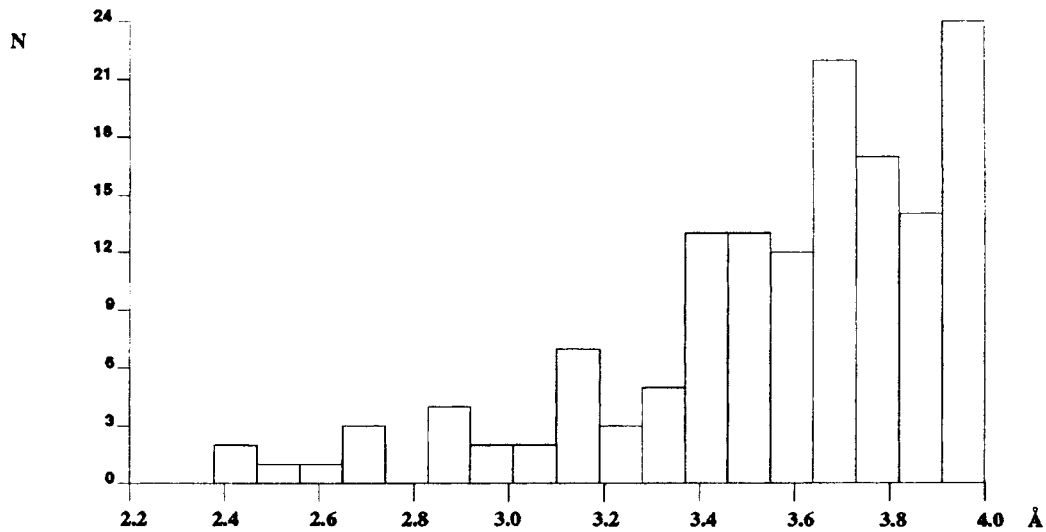


Figure 5. Histogram of the H···centroid of the phenyl ring distance corresponding to the OH···phenyl interactions study

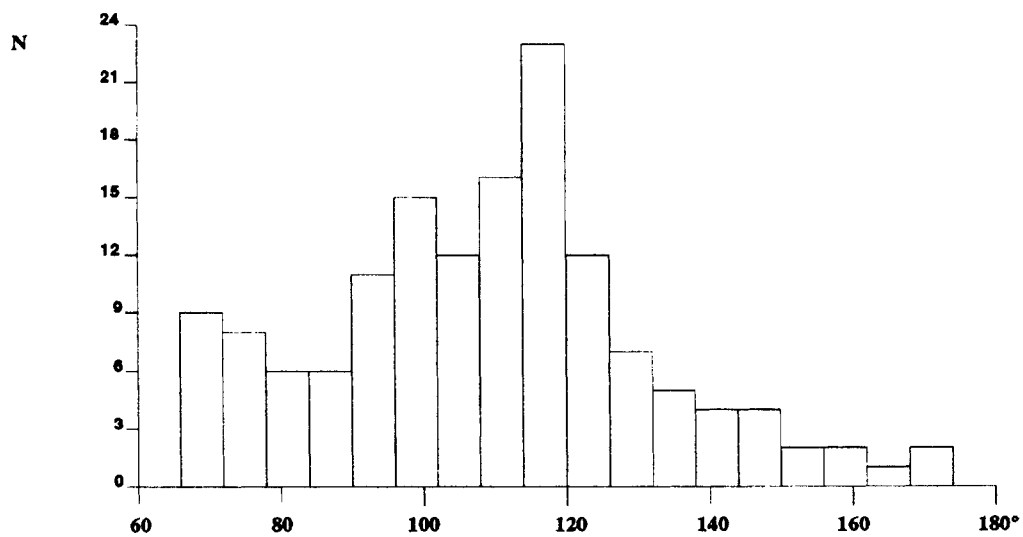


Figure 6. Histogram of the O–H···centroid of the phenyl ring angle corresponding to the OH···phenyl interactions study

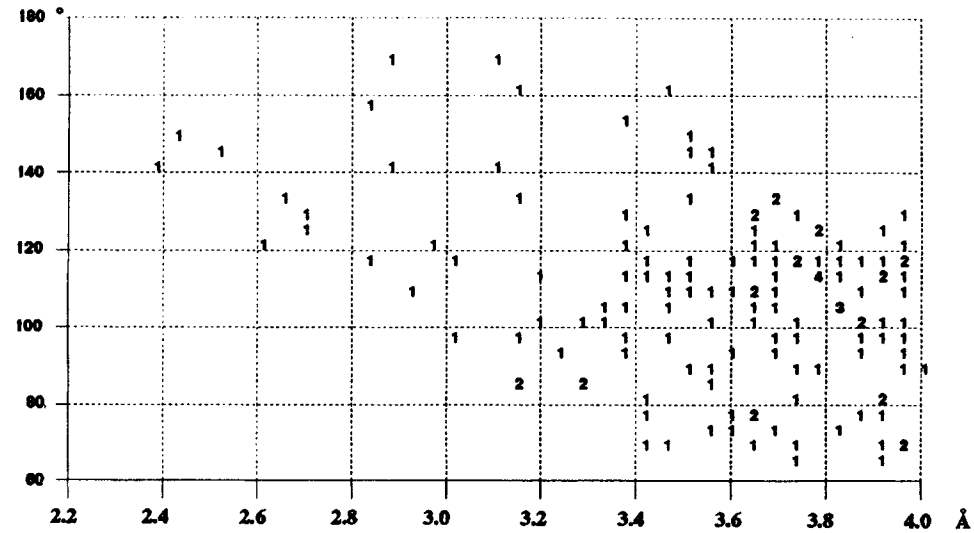


Figure 7. Scatter plot of the O–H···centroid of the phenyl ring angle vs H···centroid distance corresponding to the OH···phenyl interactions study

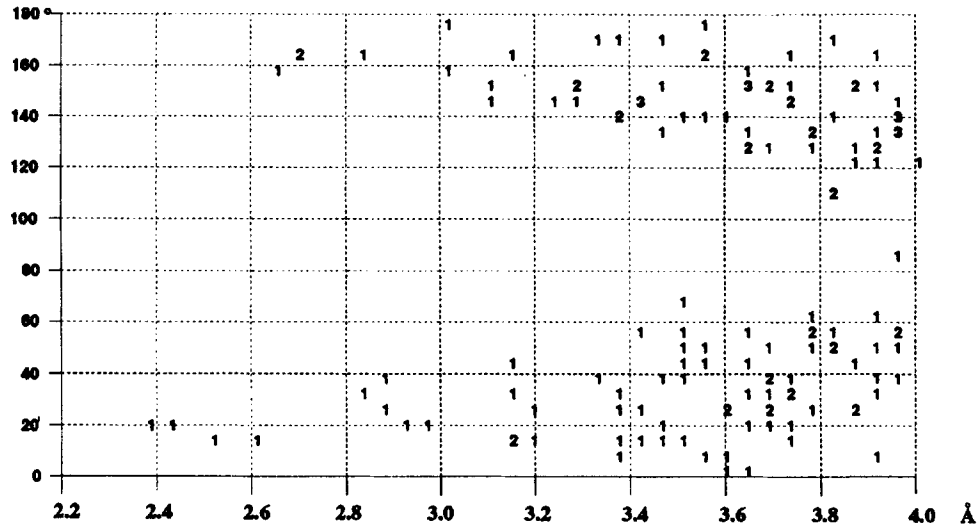


Figure 8. Scatter plot of the H···centroid distance vs the angle of the H···centroid and the normal to the phenyl plane corresponding to the OH···phenyl interactions study

difference if the donor correspond to an OH group or a water molecule.

The location and characterization of cavities in the crystals were carried out using a model of interpenetrating spheres of van der Waals radii. The resulting surface was smoothed by rolling a sphere of 1·4 Å radius.[13] The highest total packing coefficient ($C_k^{all} = (V_{host} + V_{guest})$/unit cell volume = 0·69) is shown by **2b** and therefore with efficient crystal packing and high molecular density (0·67 and 0·66 for the remaining compounds). The guest molecule in **2a**·MeOH was located in cavities (almost channels) elongated along the *a* axis. The local packing coefficient ($C_k^l = V_{guest}/V_{hole}$) was 0·56. The shape of the cavities and guests were estimated by means of the ratios (Q_{ij}^2) of the planar specific inertial moments of volume (i_{ij}^v) to the superficial ones (i_{ij}^s) with respect to the eigensystems,[13] oblate spheroid for the cavity and prolate for the methanol molecule.

Using the results for the molecular structure and according to the paper by Holden *et al.*,[14] an *ab initio* study of the crystal packing was undertaken. All the coordination spheres available for the space groups $P2_1/c$ and $P2_1$ (compounds **2b** and **2a**·MeOH) were considered. The program failed for structure **2a**, which contains two molecules in the crystallographic asymmetric unit. Although in all crystal structures the hydrogen bonds play an important role, the correct packing arrangements correspond to the lowest lattice energy. The calculated cell dimensions and the labels for the category of the coordination spheres[14] are 5·795, 16·493, 16·022 Å, 99·12° and AM; and 13·368, 5·830, 11·727 Å, 106·82° and AF.

CONCLUSION

Exchange of the methyl group of an existing lactic acid-derived host molecule available in two optical species, **1a** (resolved) and **1b** (racemic), for a phenyl ring to give the mandelic acid analogues **2a** and **b** involves distinct alteration of the lattice inclusion behaviour. Compound **2a**, the optically resolved species, yields an improvement in the formation of crystalline complexes relative to **1a** with regard to acyclic alcohols as guests. With reference to the racemic compounds, **1b** is clearly superior to **2b**. Hence, resolved **2a** and racemic **2b** are very different in their host efficiency.

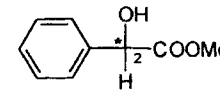
In summary, the design of new and improved inclusion hosts based on an iterative structural modification of a given molecular framework proved useful. In this context, a future challenge would be the addition of extra substituents to the phenyl rings or the use of the phenyl ring of mandelic acid for coupling the two moieties in order to obtain asymmetric, more extended host structures.

EXPERIMENTAL

Synthesis. Melting points were taken with a Koffler hot-stage apparatus. ^{1}H NMR spectra were recorded on a Varian TS 60 instrument, using TMS as internal reference.

Compounds **1a** and **b** were prepared as described previously.[5]

Methyl mandelates **3a** and **3b**: to a solution of optically resolved or racemic mandelic acid (25 g, 0·16 mol) in methanol (75 ml), concentrated sulphuric acid (2·5 ml) was added and the mixture was heated under reflux for 5 h. Work-up including addition of water (125 ml), neutralization with solid potassium carbonate, removal of the methanol under reduced pressure, extraction with chloroform, drying and evaporation of the solvent under reduced pressure yielded an oil, which was recrystallized from benzene–hexane (1:1). **3a**: Colourless crystals, yield 90%, m.p. 56 °C (lit.[15] m.p. 58 °C). **3b**: Colourless crystals, yield 92%, m.p. 54 °C (lit.[15] m.p. 55 °C).



3a (2*R*)
3b (2*R*, 2*S*)

Host compounds **2a** and **b**: the organolithio reagent was prepared from bromobenzene (21 ml, 0·2 mol) in dry diethyl ether (100 ml) by dropwise addition of butyllithium (1·6 M in hexane; 140 ml, 0·224 mol) at −15 °C. After stirring for about 1 h, a solution of methyl mandelate **3a** or **b** (8·3 g, 0·05 mol) in dry diethyl ether (100 ml) was added slowly. The mixture was heated under reflux for another 1·5 h. Work-up included hydrolysis (saturated NH_4Cl), separation of the phases, extraction with diethyl ether, washing (water), drying (sodium sulphate), evaporation of the solvent under reduced pressure and recrystallization. **2a**: Colourless crystals, on recrystallization from benzene–hexane (1:1), yield 72%, m.p. 126 °C (lit.[15] m.p. 129 °C); $[\alpha]_D^{21} + 169$ (*c*1 in $CHCl_3$) {lit.[15] $[\alpha]_D^{25} + 213{\cdot}8$ (*c*1 in EtOH)}; δ_H (60 MHz; $CDCl_3$) 7·0 (15H, m, Ar), 5·5 (1H, s, CH), 3·1 (1H, s, OH), 2·3 (1H, s, OH). **2b**: Colourless crystals, on recrystallization from dichloromethane, yield 67%, m.p. 172 °C (lit.[16] m.p. 170 °C); found, C 82·83, H 5·96; $C_{20}H_{18}O_2$ requires C 82·73, H 6·25%; δ_H (60 MHz; $CDCl_3$) 7·0 (15H, m, Ar), 5·5 (1H, s, CH), 3·1 (1H, s, OH), 2·3 (1H, s, OH); δ_C (62·5 MHz, $CDCl_3$) 145·7, 145·8, 140·0, 79·5 (C), 126·7–125·1 (Ar-CH), 76·5 (CH), 14 signals.

Crystalline inclusion compounds. General procedure. These were obtained by recrystallization of the corresponding host compound from a minimum amount

of the respective guest solvent. The crystals formed were collected by suction filtration, washed with an inert solvent (hexane) and dried (1 h, 15 Torr, room temperature). The host–guest stoichiometric ratio was determined by ^{1}H NMR integration. Data for each compound are given in Table 1.

Crystallography. Sample preparation. Suitable crystals for x-ray diffraction were prepared by slow cooling of a solution of the corresponding host compound in the guest solvent (methanol). Single crystals of the free hosts were obtained from ethanol.

X-ray structure determination. A summary of crystal data, experimental details and refinement parameters is displayed in Table 4. All crystal structures were solved by direct methods, SIR92.[17] The refinement was performed by least-squares fitting on F. The hydrogen atoms were located in the corresponding difference Fourier maps and were included isotropically in the last cycles of refinement. Most of the calculations were carried out with the XRAY80 System[18] on a Vax 6410 computer. The atomic scattering factors were taken from the *International Tables for X-Ray Crystallography*.[19]

SUPPLEMENTARY MATERIAL

Lists of the structure factors, atomic coordinates and thermal components for the non-hydrogen atoms and hydrogen atom parameters are available from C.F.-F. on request.

Table 4. Crystal analysis parameters

Parameter	**2a**	**2b**	**2a**·MeOH
Crystal data			
Formula	$C_{20}H_{18}O_2$	$C_{20}H_{18}O_2$	$C_{20}H_{18}O_2{\cdot}CH_3O$
Crystal habit	Colourless prism	Colourless prism	Colourless prism
Crystal size (mm)	0·50 × 0·50 × 0·50	0·43 × 0·50 × 0·67	0·20 × 0·20 × 0·40
Symmetry	Monoclinic, $P2_1$	Monoclinic, $P2_1/c$	Monoclinic, $P2_1$
Unit cell determination:	Least-squares fit from 85 reflections ($\theta<45°$)	Least-squares fit from 57 reflections ($\theta<45°$)	Least-squares fit from 57 reflections ($\theta<45°$)
Unit cell dimensions (Å, °)	a = 7·2840(3)	a = 5·9565(2)	a = 13·0398(8)
	b = 18·3188(18)	b = 16·5149(12)	b = 5·8807(2)
	c = 12·1577(9)	c = 15·7004(12)	c = 12·2663(6)
	90, 106·025(4), 90	90, 99·355(5), 90	90, 107·937(5), 90
Packing: V (Å^3), Z	1559·2(2), 4	1523·9(2), 4	894·9(1), 2
D_c (g/cm^3), M, F(000)	1·237, 290·36, 616	1·266, 290·36, 616	1·200, 322·40, 344
μ (cm^{-1})	5·85	5·99	5·95
T (K)	295	295	225
Experimental data			
Technique	Four-circle diffractometer: Philips PW1100, bisecting geometry Graphite monochromator: Cu Kα, $\omega/2\theta$ scans Detector apertures 1 × 1°. θ_{max} = 65°		
Scan width (°)	1·6	1·6	1·5
Scan speed (per reflection) (min)	1	1	0·5
Number of reflections:			
Independent	2633	2537	1662
Observed	2579 (3σ(I) criterion)	2390 (3σ(I) criterion)	1561 (3σ(I) criterion)
Standard reflections	2 reflections every 90 minutes. No variation		
Solution and refinement:			
Solution	Direct methods: SIR92		
Refinement: least-squares on F_o	Two block	Full matrix	Full matrix
Parameters:			
Number of variables	540	271	304
Degrees of freedom	2039	2119	1257
Ratio of freedom	4·8	8·8	5·1
H atoms	From difference synthesis		
Weighting scheme	Empirical so as to give no trends in $\langle\omega\Delta^2F\rangle$ vs $\langle\lvert F_{obs}\rvert\rangle$ and $\langle\sin\theta/\lambda\rangle$		
Max. thermal value (Å^2)	U33 [C(24)Mol.2] = 0·179(6)	U11 [C(34)] = 0·091(1)	U22 [C(7)] = 0·109(4)
Final $\Delta\rho$ peaks (e Å^{-3})	±0·16	±0·37	±0·30
Final R and R_w	0·045, 0·055	0·045, 0·050	0·051, 0·068

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