

Hydrogen-bonding interactions in the crystalline-phase structures of cinnamic acid derivatives

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Abstract

Secondary interactions responsible for the crystalline-phase structures of various cinnamic acids and cinnamic acid esters drawn from the Cambridge Structural Database were studied with the help of the *Cerius* package implemented on an SGI workstation. Primarily hydrogen-bonding interactions were sought, but deviation from planarity was also measured. For the acids, the main structural feature is the strong hydrogen bonding between the carboxyl groups. The dimers are interconnected by C—H...O intermolecular hydrogen bonds. In most cases the C atom of the C—H unit was a member of the aromatic ring. Intramolecular (olefinic) C—H...O bonds were found to be frequent, fixing synperiplanar and antiperiplanar C=C—C=O conformations with about the same abundance in the acids and exclusively synperiplanar conformations in the esters. The carbonyl group of the ester is always involved in C—H...O hydrogen bonding. Here, the C atom of the C—H unit was either a member of the aromatic ring or the olefinic group, or was attached to the alcoholic O atom of the ester group. The β -phenyl and the carboxyl or the ester groups are almost coplanar. The crystals have a layered structure and in the most frequent parallel arrangement the phenyl groups are offset by varying amounts (but always to a small extent) in neighbouring layers. The common hydrogen bonds are mostly within a layer.

1. Introduction

The modified Perkin condensation is a convenient reaction if one intends to prepare the cinnamic acid derivative α -phenylcinnamic acid (Buckles & Bremer, 1967). The reaction is known to produce overwhelmingly the *E* isomer. Nevertheless, under mild conditions an appreciable amount of *Z* isomer is formed (Fieser & Fieser, 1955). Separation of the isomers is based on their very different acidities. Acidifying the basic solution containing the acids in the form of sodium salts to pH 6 provides the *E* isomer. Further acidification to pH 1 gives the *Z* isomer. Although this is known, a reason for two orders of magnitude difference between

the acidities has not been found. The search for an explanation led us to computer modelling of the structures of the isomers (Pálinkó, Tasi *et al.*, 1995). It turned out that *they were not* planar in spite of the extensive conjugation and there was no significant difference between their stabilities either. We also found that it was possible to approach a nearly 1:1 ratio during *E*–*Z* isomerization (Tasi *et al.*, 1997; Pálinkó *et al.*, 1996), even though the condensation gives at best a 3:1 ratio with the *E* isomer in excess. We have also been able to show that the explanation lies in their very different potential-energy surfaces. That of the *E* isomer was found to be flat and nearly any conformation was close to the global minimum. That of the *Z* isomer contained ridges of considerable energy height and some deep minima, one of which was the global minimum (Pálinkó, Tasi *et al.*, 1995; Pálinkó *et al.*, 1996).

We also studied the interactions between these molecules in solutions containing either isomer at various concentrations (Pálinkó, Török *et al.*, 1995; Pálinkó & Kiss, 1997) as well as in the solid state (Pálinkó & Kiss, 1997) by IR spectroscopy. It was found that dimerization, typical of carboxylic acids (Pauling & Brockway, 1934), was the main form of interaction in solution through O—H...O hydrogen bonds. It is general knowledge (March, 1992) that these bonds are strong (25–30 kJ mol⁻¹). Other types of hydrogen bond (*e.g.* C—H...O) were not found, although bands could also be assigned to multimers containing more than two acid molecules (Kukovecz *et al.*, 1997). In the solid state, although the main form of interaction was the formation of dimers and also multimers, indications of C—H...O bonding was also observed. These bonds kept the dimers and higher oligomers together and thus the crystalline solid was formed. This type of hydrogen bond, in spite of its relatively lower strength (~5–10 kJ mol⁻¹), is very significant in determining the crystal structures of a great variety of compounds (Desiraju, 1996; Steiner, 1997).

The two observations stressed in italics above, *i.e.* the huge deviation from planarity of the isolated molecules and the observation of C—H...O hydrogen bonds, called for a more comprehensive investigation of the crystal structures of cinnamic acid and ester derivatives. Answers to questions such as whether C—H...O bonds

are general forces in this family of compounds in making and preserving the crystalline state and which conformation prevails in the crystalline state were sought.

As further justification for undertaking a study like this, let me mention two points. First, cinnamic acid derivatives are important building blocks in crystal engineering (Desiraju, 1989). In fact, they were the models for the detailed investigations of Schmidt which lead to the discovery of the topotactic rules which govern the photochemical dimerization and oligomerization reactions of these and related compounds (Schmidt, 1971). Second, cinnamic acids and their derivatives are compounds of biological importance. They are derived from the shikimic acid metabolic pathway (Mann, 1987; Torssell, 1989) and they are important constituents in the production of lignins in higher plants.

Obviously, the present study is not the first work concerning hydrogen-bonding interactions and packing in carboxylic acid crystals. Two of the most important papers (Leiserowitz, 1976; Berkovitch-Yellin & Leiserowitz, 1984) are wider in scope, since they deal with carboxylic acids and their derivatives in general. As a consequence, they are less detailed when they discuss α,β -unsaturated acids, particularly cinnamic acids and their derivatives. In this work I give numeric data for bond distances and bond angles, distinguish between C—H \cdots O hydrogen bonds according to the type of C and O atom in the molecules, and point out peculiarities typical of this class of compounds. One of them is the conformational enforcing power of the intramolecular C—H \cdots O hydrogen bond, rendering synperiplanar and antiperiplanar C=C—C=O arrangements equally possible in the acids, but making exclusively a synperiplanar conformation in the esters.

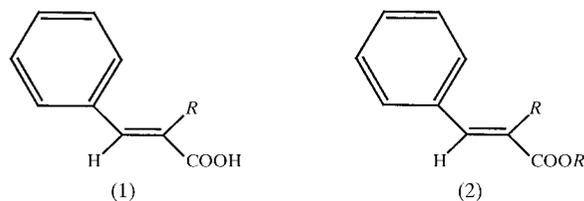


Fig. 1. General structural formulae of *E* cinnamic acids, (1), and *E* cinnamic acid esters, (2). $R = \text{H}, \text{CH}_3$.

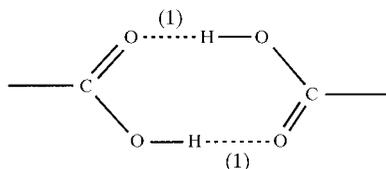


Fig. 2. Schematic representation of O—H \cdots O intermolecular hydrogen bonds in cinnamic acids [mean values calculated from relevant distances or angles with s.u. of the mean values in parentheses: (1) O \cdots O 2.64 (2), H \cdots O 1.63 (19) Å, O—H \cdots O 171 (7) $^\circ$].

2. Methodology

Crystal structures of various cinnamic acids and esters were drawn from the Cambridge Structural Database (CSD, April 1996 release; Allen *et al.*, 1991). Ordered and error-free crystals with *R* values less than 0.06 were selected and mixed crystals were not considered. Structures in which H-atom positions were not determined were not taken into account in bond-distance and bond-angle evaluations but were used in conformation studies (they are marked with asterisk). The structures included were acids: BEJVOB, CEMJIN, CINAMA10, CINAMB10, CINAMC10, CINAMD10*, CINMAC03, CINMAC, COWRIP, FESNOG, FOFCAE*, GASVOL, GEYPIJ, JADVUF, KODHUG, KODJAO, MACINA10, MXCINN*, PCTCINN*, VIBKEW, VIBKIA, ZZZFKS01; esters: CEGWIU*, CEGWOA*, CEGWUG*, CVCYCA, ECPRPR01, JERKIA10, MBRCIN*, MECINT*, MHNTCN, MPDACL, PPDACR, PPDACS, SEDMOD, SEVLOU*, VOJDIH.†

The interactions within the crystals were studied by measuring geometric parameters with the help of the *Cerius* package (Molecular Simulations Inc., 1993) running on a Silicon Graphics workstation. Bond lengths and bond angles were calculated from atomic coordinates retrieved from CSD files. For bond lengths the sum of the van der Waals radii (Bondi, 1964) of the non-H atoms were used as a cut-off distance and 90 $^\circ$ as a cut-off angle. Data are given as averages (mean values) with standard uncertainties (s.u.'s).

As an aid to understanding, the general structural formulae of the acids and esters are given in Fig. 1. It should also be pointed out that only the *E* isomers were treated in this study, since only one structure corresponding to the *Z* configuration was found and it did not meet the selection criteria described above.

3. Results and discussion

3.1. Intermolecular hydrogen bonding

As can be expected, in the acids the main structural feature is the strong hydrogen bonding between the carboxyl groups (Fig. 2). Dimers were observed exclusively; chain-type structures (catemer motif; Leiserowitz, 1976) were not found. The dimers are connected by O—H \cdots O bonds. The O \cdots O or H \cdots O distances are short and the spatial arrangement is close to linear (Table 1, first row). Besides the strong O—H \cdots O hydrogen bonds, appreciably longer (that is, weaker) C—H \cdots O bonds also exist. They are mostly of two types (Fig. 3) in which the C atom is a member of an aromatic ring, while the O atom is either a carbonyl or an alcoholic O atom (see Table 1, second and third rows,

† Supplementary data for this paper are available from the IUCr electronic archives (Reference: KA0041). Services for accessing these data are described at the back of the journal.

Table 1. Characteristic data for intermolecular O—H···O hydrogen bonds in cinnamic acids and C—H···O hydrogen bonds in cinnamic acids and esters

Mean values calculated from relevant distances or angles of acids and esters are followed by the s.u. of the mean values in parentheses. ol indicates olefinic, al indicates alcoholic (H—C—O—) and ar indicates aromatic.

	C(O)···O (Å)	H···O (Å)	C—H···O (°)
Acids			
O—H···O	2.64 (2)	1.63 (19)	171 (7)
C—H···O (carbonyl)	3.50 (17)	2.65 (6)	146 (19)
C—H···O (alcoholic)	3.45 (9)	2.60 (10)	144 (16)
(olefinic) C—H···O	3.38 (10)	2.55 (5)	148 (17)
Esters			
C(ol)—H···O	3.47 (10)	2.55 (15)	157 (5)
C(al)—H···O	3.28 (24)	2.55 (3)	137 (23)
C(ar)—H···O	3.41 (11)	2.51 (12)	156 (9)

respectively, and Fig. 4). It should be noted that (olefinic) C—H···O bonds were found to be rare. They only occur when the β -phenyl ring is substituted by a group or groups containing a strong proton acceptor (an O atom). The presence of oxygen in the substituent seems to be a necessary but not sufficient condition for the interaction to take place. Relevant data are given in the fourth row of Table 1. The C···O (H···O) distances and C—H···O bond angles are comparable and the bonds are mainly responsible for interconnecting the dimers, *i.e.* keeping the layers of the crystals together.

O—H···O bonds do not exist in the esters. Instead, the carbonyl O atom is hydrogen-bonded to the H atom of a C—H unit. Three types of C—H units can be distinguished (Fig. 5): the C atom in the unit is a member of either (i) an aromatic ring or (ii) an olefinic bond, or (iii) it is bonded to the alcoholic O atom of the ester group. These types of C atom are marked in Fig. 5 and in Table 1 as (ar), (ol) and (al), respectively. Note that the (olefinic) C—H···O bond is different here than in the acids. Here, the acceptor is the O atom in the ester group

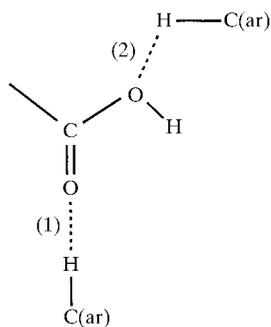
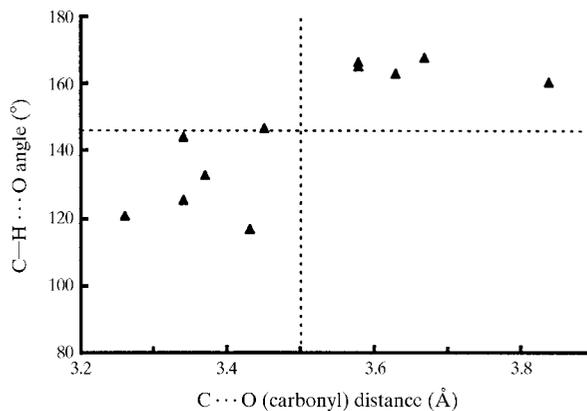
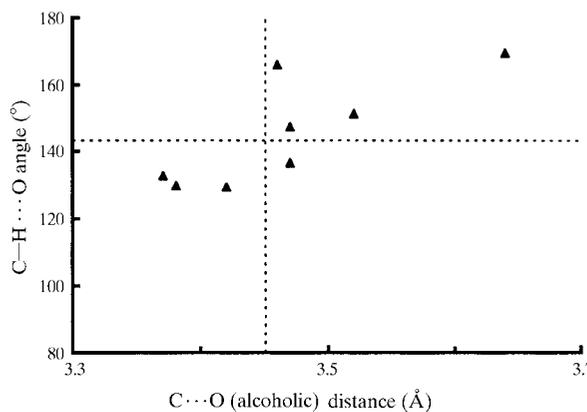


Fig. 3. Schematic representation of C(ar)—H···O (ar = aromatic) intermolecular hydrogen bonds in cinnamic acids [mean values calculated from relevant distances or angles with s.u. of the mean values in parentheses: (1) C(ar)···O 3.50 (17), H···O 2.65 (6) Å, C(ar)—H···O 146 (19)°; (2) C(ar)···O 3.45 (9), H···O 2.60 (10) Å, C(ar)—H···O 144 (16)°].

and it is not part of the substituent on the β -phenyl group. These bonds are significantly weaker, *i.e.* they are longer than the O—H···O bonds (compare with Table



(a)



(b)

Fig. 4. Scatter plots of C—H···O angles versus C···O distances in intermolecular C—H···O contacts in cinnamic acids: (a) C—H···O (carbonyl), (b) C—H···O (alcoholic) hydrogen bonds (mean values are shown by dashed lines).

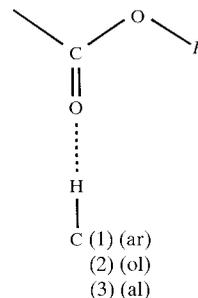


Fig. 5. Schematic representation of C—H···O intermolecular hydrogen bonds in cinnamic esters [mean values calculated from relevant distances or angles with s.u. of the mean values in parentheses: (1) C(ar)···O 3.41 (11), H···O 2.51 (12) Å, C(ar)—H···O 156 (9)°; (2) C(ol)···O 3.47 (10), H···O 2.55 (15) Å, C(ol)—H···O 157 (5)°; (3) C(al)···O 3.28 (24), H···O 2.55 (3) Å, C(al)—H···O 137 (23)°] [ar = aromatic, ol = olefinic, al = alcoholic (H—C—O—)].

1, first row). Nevertheless, they do represent important interactions. Other types of intermolecular hydrogen-bonding interactions were not found in the esters. Scatter plots for $C(ol)-H\cdots O$ and $C(ar)-H\cdots O$ interactions are shown in Fig. 6. The $C(al)-H\cdots O$ interaction may be considered as the replacement of the $O-H\cdots O$ hydrogen bonds. Dimers, however, cannot be distinguished; instead, the layers are formed and kept together with the participation of the three bond types. The vast majority of these hydrogen bonds are to be found in the layers.

3.2. Interactions between the layers

As far as the geometry in the crystalline state is concerned, it was found that the molecules in the layers were very close to being planar. In the acids, deviation from the plane of the olefinic bond is $4.1 (35)^\circ$ for the β -phenyl group and $3.2 (26)^\circ$ for the carboxyl group. These values are somewhat but not significantly larger for the

esters [$7.1 (55)^\circ$ for the β -phenyl and $4.2 (30)^\circ$ for the ester group]. The layers were found to be parallel. In most instances the molecules in the crystal structures lie parallel to each other (β or γ forms). In these structures the aromatic rings in neighbouring layers are somewhat (but always to a small extent) offset with respect to each other. Since the common hydrogen bonds are mostly within the layers, this means that the layers are kept together by other forces, such as $\pi-\pi$ and $C-H\cdots\pi$ interactions. These interactions were not investigated since clear cut-off criteria could not be identified.

Although examples exist in which the layer is puckered, such that deviation from planarity is appreciable, they are rare. They can be found when the α C atom of the olefinic bond is substituted by a methyl group (Desiraju & Sharma, 1991) (and possibly this would be the case if a bulkier substituent was applied) or when there is no α substitution but the β -phenyl group contains more than one substituent capable of strong hydrogen bonding (Bryan & White, 1982). Even in these instances the hydrogen bonds are within the layer.

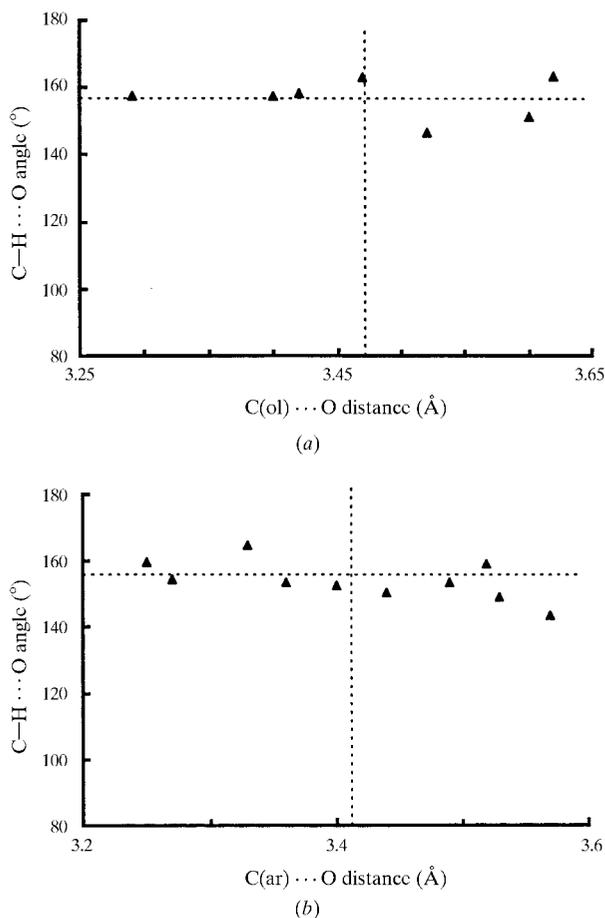


Fig. 6. Scatter plots of $C-H\cdots O$ angles versus $C\cdots O$ distances in intermolecular $C-H\cdots O$ contacts in cinnamic esters: (a) $C(ol)-H\cdots O$, (b) $C(ar)-H\cdots O$ hydrogen bonds (mean values are shown by dashed lines, ol = olefinic, ar = aromatic).

3.3. Intramolecular hydrogen bonds

These types of bonds could be found both in the acids and the esters (Fig. 7). They were of the (olefinic) $C-H\cdots O$ type. The C atom in the $C-H$ unit was always the olefinic C atom, while the O atom was either a carbonyl (1) or alcoholic O atom (2) in the acids or a carbonyl O atom (1) in the esters. Type (1) results in a synperiplanar conformation, while type (2) enforces an antiperiplanar conformation. Both conformations are equally abundant in the acids; however, synperiplanar conformation

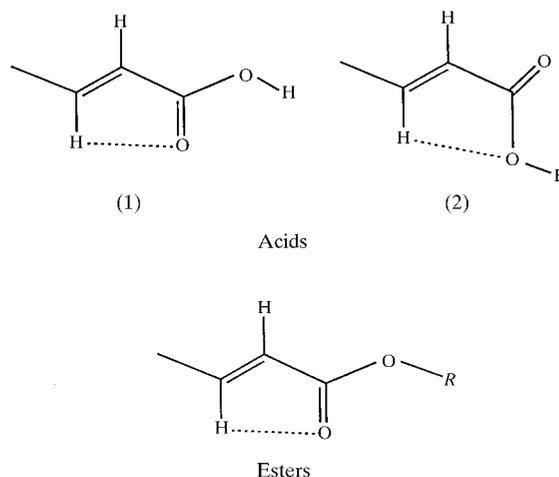


Fig. 7. Schematic representation of intramolecular $C-H\cdots O$ hydrogen bonds in cinnamic acids [mean values calculated from relevant distances or angles with s.u. of the mean values in parentheses: (1) $H\cdots O$ 2.50 (7) Å, $C-H\cdots O$ 99 (4)°; (2) $H\cdots O$ 2.46 (6) Å, $C-H\cdots O$ 100 (3)°] and in the esters [mean values calculated from relevant distances or angles with s.u. of the mean values in parentheses: $H\cdots O$ 2.51 (7) Å, $C-H\cdots O$ 99 (4)°].

Table 2. *Characteristic data for intramolecular (olefinic) C—H...O bonds in cinnamic acids and esters*

Mean values calculated from relevant distances or angles of acids and esters are followed by the s.u. of the mean values in parentheses.

	H...O (Å)	C—H...O (°)
Acids		
C—H...O (carbonyl)	2.50 (7)	99 (4)
C—H...O (alcoholic)	2.46 (6)	100 (3)
Esters		
C—H...O (carbonyl)	2.51 (7)	99 (4)

is exclusive in the esters. Hydrogen-bond length and angle data are summarized in Table 2.

4. Conclusions

The crystal-building and structure-determining forces in crystals of cinnamic acids and their derivatives are inter- and intramolecular hydrogen bonds of various kinds and strengths (O—H...O and C—H...O) within the layers and π - π or C—H... π interactions between the layers. The layers are mostly planar and when they are puckered the common hydrogen bonds are still present within the layers.

The *Cerius*² package (Molecular Simulations Inc., 1993) was licensed to Professor K. R. Seddon, The Queen's University of Belfast. Permission to use it was highly appreciated.

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