

Configurational Studies of Complexes of Tea Catechins with Caffeine and Various Cyclodextrins

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Key words

- *ent*-gallo catechin-3-*O*-gallate
- epigallo catechin-3-*O*-gallate
- caffeine
- cyclodextrin
- NMR
- X-ray crystallography

Abstract

▼
A suspension of an equimolecular amount of *ent*-gallo catechin-3-*O*-gallate (*entGCg*) and caffeine in water afforded two kinds of crystals, which were 1:2 and 2:2 complexes of *entGCg* and caffeine. The stereochemical structures and intermolecular interactions between *entGCg* and caffeine were determined by X-ray crystallographic analysis. The crystal structure of *entGCg* was determined and compared with those of the 1:2 and 2:2 complexes. Epigallo catechin-3-*O*-gallate (EGCg) formed a 1:1 complex with β -cyclodextrin (CD),

in which the aromatic A ring and a part of the heterocyclic C ring were included from the wide secondary hydroxyl group side of the β -CD cavity in aqueous solution, while the B rings and 3-*O*-gallate groups (B' rings) were left outside the cavity. In contrast, *entGCg* formed a 1:2 complex with β -CD, in which the aromatic A and B rings of *entGCg* were included by two molecules of β -CD.

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Introduction

▼
Tea has been consumed worldwide since ancient times to maintain and improve health. Some evidence suggests that tea protects against lifestyle-related diseases such as cancer, high blood pressure, diabetes, obesity, and arteriosclerosis [3]. Tea prepared from leaves of the tea plant *Camellia sinensis* (Camelliaceae) contains various catechins and caffeine as major ingredients. Catechins are a group of polyphenols that exhibit various pharmacological activities, such as anticarcinogenic [4,5], anti-metastatic [6,7], and anti-oxidative effects [8,9]. The catechins in green tea are commonly classified into two categories, e.g., gallated- and non-gallated catechins, respectively, by the presence and absence of a galloyl group at the C3 position [1,2,10]. Generally, gallated catechins show higher activities than their non-gallated analogs [11–14].

Caffeine is an alkaloid that displays a central nervous system-stimulating effect and that forms complexes with polyphenols, especially in black tea and coffee [15–17]. Such complexes may possess a unique stereochemical structure. Thus, many researchers have been investigating the structure of such complexes. For example, Maru-

yama et al. [18] noted that some gallated catechins have a high affinity for caffeine and assumed stacking of caffeine between the aromatic B ring and the 3-*O*-gallate group (B' ring). These conclusions were based on ¹H NMR chemical shift changes of gallate complexed to caffeine. Cai et al. [19] reported that in non-gallated-type catechins, such as catechin (CA) and epicatechin (EC), the A and C rings provided a general site for caffeine association, but that in gallated-type catechins, such as *ent*-catechin-3-*O*-gallate (*entCg*) and epigallo catechin-3-*O*-gallate (EGCg), the gallate moiety is the preferred site for complexation (● Fig. 1). Furthermore, Hayashi et al. [20] reported the participation of the A ring as well as B ring or 3-*O*-gallate groups (B' ring) in the complexation with caffeine as concluded from ¹H NMR chemical shift differences, nuclear Overhauser enhancement, and exchange spectroscopy (NOESY) spectra. However, the overall structure of the complex and the detailed intermolecular interactions between catechin and caffeine have not been elucidated sufficiently.

In this study, the crystal structure of the complex between *entGCg* and caffeine was determined by X-ray crystallography, and the intermolecular in-

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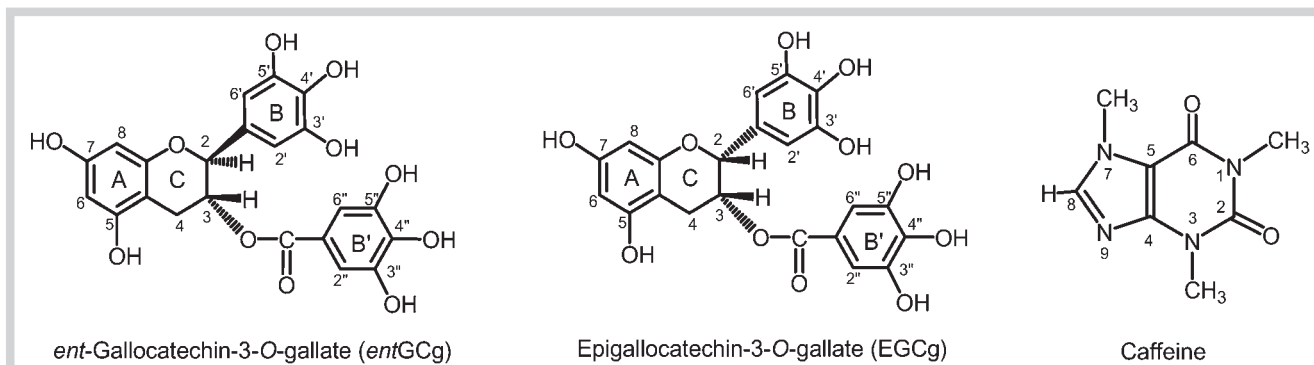


Fig. 1 *Ent*-gallocatechin-3-O-gallate (*ent*GCg), epigallocatechin-3-O-gallate (EGCg), and caffeine.

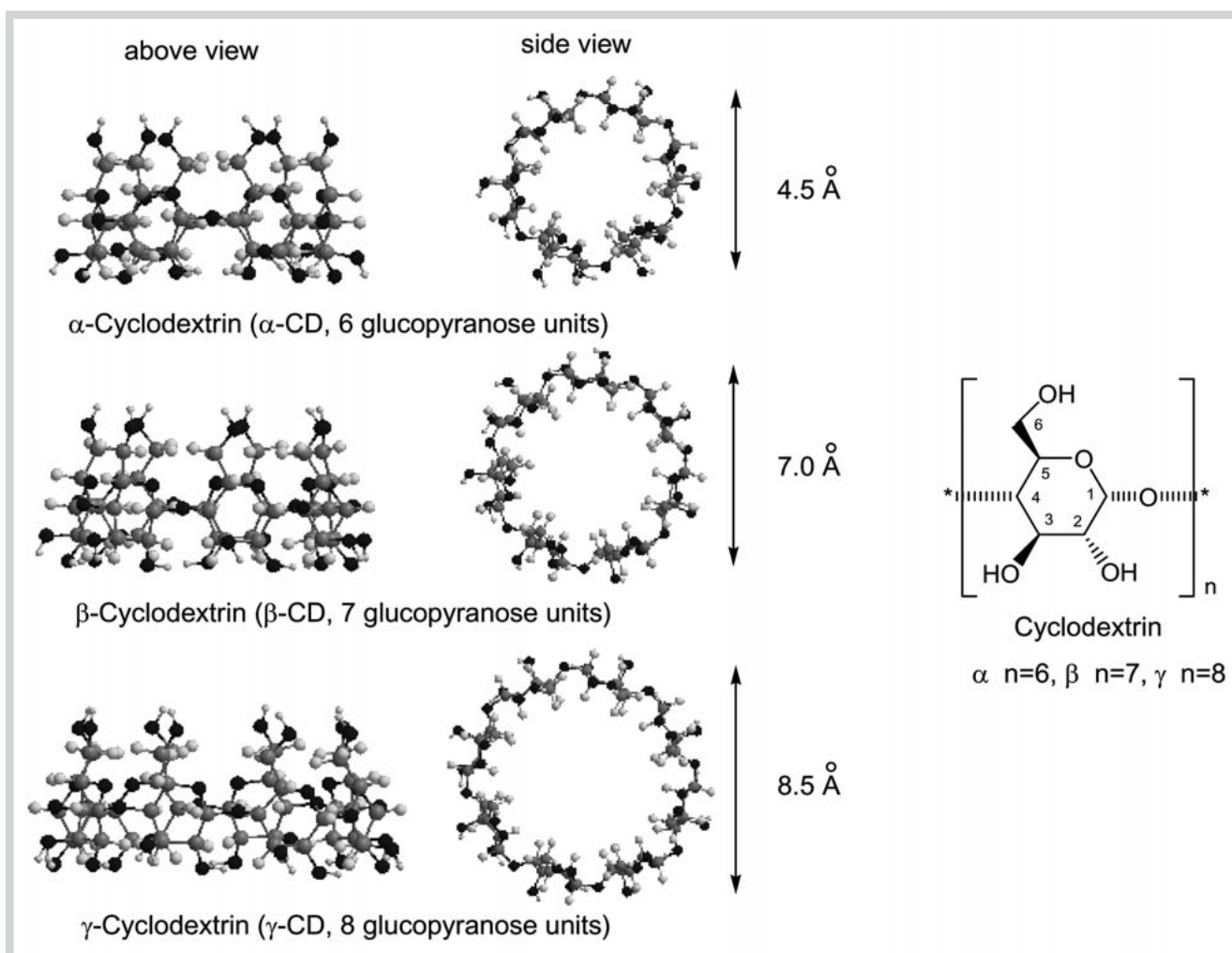


Fig. 2 Various cyclodextrins.

teractions between *ent*GCg and caffeine moieties were also elucidated [21–23].

A further study focused on the inclusion complexes comprising cyclodextrins and catechins. Cyclodextrins (CDs) are cyclic oligosaccharides which have six, seven, and eight D-(+)-glucopyranose units for α -, β -, and γ -CDs, respectively (● Fig. 2). CDs incorporate compounds in their hydrophobic cavities depending on the cavity size. The inclusion complexes alter the physical, chem-

ical, and biological properties of the guest molecule and may yield complexes that have considerable medicinal potential [24]. Special interest has been paid to EGCg, a major green tea component with a broad spectrum of bioactivities. However, catechin powders are bitter, brown and are easily oxidized, making them difficult to use as a medicine or natural food additive. In order to overcome these problems, we investigated the fundamental properties of the inclusion complexes of α -, β -, and γ -CDs with

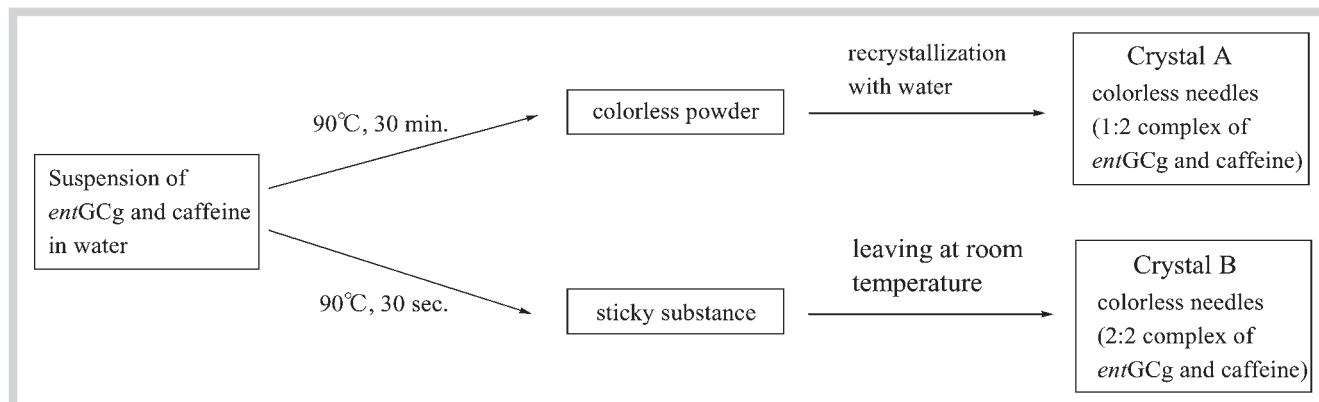


Fig. 3 Preparation of two kinds of crystal of complexes of *entGCg* and caffeine.

entGCg and EGCg in aqueous solution using a combination of NMR techniques and theoretical approaches [25–27]. *EntGCg* is a diastereomer of EGCg, differing in the configuration at C2. The difference between the inclusion complexes is discussed in relation to their conformations in aqueous solution.

The Two Complexes of *entGCg* and Caffeine [21–23]

An aqueous suspension containing an equimolar amount of *entGCg* and caffeine in water was heated at 90 °C for 30 min. The solution gave a colorless powder (● Fig. 3), which was recrystallized from water to give colorless needles (crystal A, mp 160–162 °C). The crystals represented a complex of *entGCg* and caffeine in a molar ratio of 1 : 2 based on the measurement of the integral area of ¹H NMR signals. When the same suspension was heated at 90 °C for 30 s and left at room temperature, a sticky substance was obtained (● Fig. 3), comprising a complex of *entGCg*, caffeine, and water in a molar ratio of 1 : 1 : 22 as evident from the integrals of ¹H NMR signals. The sticky material crystallized slowly over a period of ca. three months at room temperature to give colorless needles (crystal B, mp 155–157 °C) which contained complexes of *entGCg* and caffeine in a molar ratio of 1 : 1 based on measurement of the integral area of ¹H NMR signals. However, it was actually a 2 : 2 complex of *entGCg* and caffeine based on evidence from X-ray crystallography [22]. Interestingly, when the sticky substance was heated at 90 °C for 30 min, the product contained *entGCg* and caffeine in a molar ratio of 1 : 2 and was recrystallized from water to give colorless needles (crystal A). It was concluded that the complex formation energy of the 1 : 2 complex was higher than that of the 2 : 2 complex. Crystallizations of EGCg and caffeine have been also attempted, but they did not yet succeed.

An ORTEP drawing and a one unit cell of the 1 : 2 complex of *entGCg* and caffeine (● Fig. 4a) show that two caffeine molecules were located above the aromatic A ring and the 3-O-gallate group (B' ring) of an *entGCg* molecule. In one unit cell, four 1 : 2 complex entities and twelve water molecules as the crystal solvent were present. In a unit of the merohedral twinned structure [28] of crystal B with 2 : 2 complexes, the A and C rings of the two *entGCg* molecules faced each other, and their aromatic B rings and 3-O-gallate groups (B' rings) faced the two caffeine molecules (● Fig. 4b). One unit cell contained eight units consisting of the

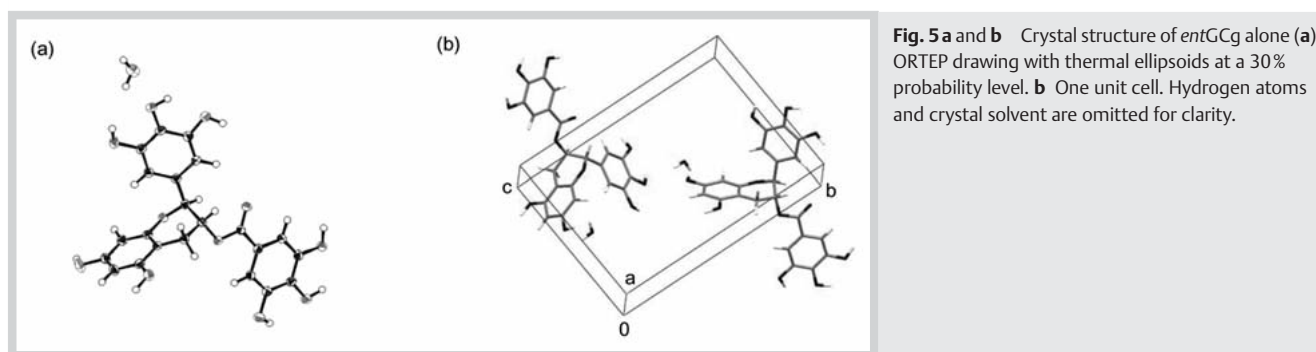
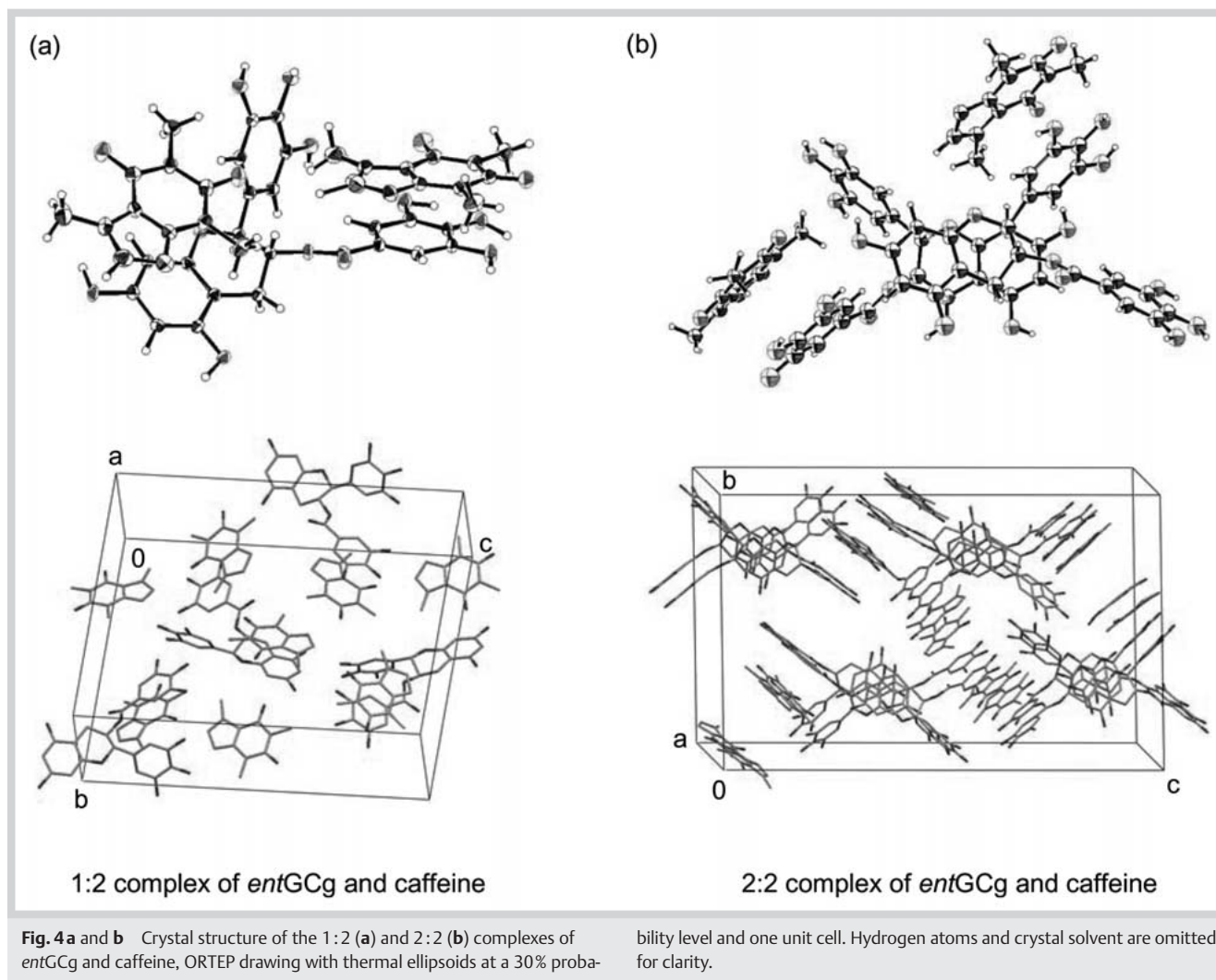
2 : 2 complex and ninety-six water molecules as the crystal solvent.

To compare the crystal structures of the 1 : 2 and 2 : 2 complexes, we carried out X-ray analysis of *entGCg* alone, which was crystallized using the different solubility between *entGCg* and EGCg in water. A solution containing an equimolar amount of *entGCg* and EGCg was left at room temperature for a few days to afford a colorless block-shaped single crystal of only *entGCg*, while EGCg as well as some *entGCg* were still soluble in the solution. The single crystal of *entGCg* was determined by X-ray crystallographic analysis [21]. One unit cell contains two *entGCg* molecules and two water molecules (● Fig. 5).

The dihedral angles of C1'–C2–C3–O and H2–C2–C3–H3 of the *entGCg* moiety of the 1 : 2 complex are 55.93° and 173.18°, respectively, indicating that the B ring and the 3-O-gallate group (B' ring) both adopt equatorial positions (● Fig. 6; ● Table 1). This also holds true for the 2 : 2 complex, whereas the corresponding aromatic rings of *entGCg* crystals alone adopt axial and pseudoaxial positions, respectively (● Fig. 6; ● Table 1). These findings suggested a conformational change of *entGCg* upon conversion of 1 : 2 to 2 : 2 complexes, facilitated by the conformational flexibility of *entGCg* molecules owing to puckering of the pyran C ring. On the other hand, the caffeine molecule has a planar and rigid xanthine skeleton.

For complex formation of compounds with aromatic rings, three kinds of interactions are important, namely face-to-face π – π interaction between the planes of two aromatic rings, offset π – π interaction between the planes of two slightly shifted aromatic rings, and CH– π interaction (● Fig. 7).

A marked difference in the layer structure between the crystal structures of the 1 : 2 and 2 : 2 complexes and *entGCg* alone was observed (● Figs. 8–11). As shown in ● Fig. 8, units of the former piled up in parallel in the same direction as the a-axis. The distances between the aromatic A rings and the 3-O-gallate groups (B' rings) of two *entGCg* molecules were 6.866 and 6.767 Å, respectively. Two caffeine molecules were located almost in the middle of the A ring and 3-O-gallate group (B' ring) of *entGCg*s in a sandwich-like manner. This allows for face-to-face π – π interactions between the A ring and the 3-O-gallate group (B' ring) of the upper *entGCg* and the six-membered ring of caffeine, and offset π – π interactions between the same structural elements involving the lower *entGCg*. Also, a CH– π interaction was formed between the B ring of the lower *entGCg* and the methyl group at N7 of caffeine (distance 3.281 Å). As shown in ● Table 2, three in-



termolecular hydrogen bonds between *entGCg* and caffeine, and *entGCg*s were observed in the 1:2 complex.

In **Fig. 9**, packing of the 2:2 complex of *entGCg* and caffeine in the cell down the *a*-axis is shown. Each caffeine molecule and the aromatic B ring and 3-*O*-gallate group (B' ring) of the *entGCg* molecules were arrayed regularly in the following order: 3-*O*-gallate group (B' ring), caffeine, 3-*O*-gallate group (B' ring), caffeine, and B ring. The average distances between each ring were ca. 3.2 Å, ca. 3.3 Å, ca. 3.3 Å, and ca. 3.4 Å, respectively. Furthermore, these caffeine molecules were surrounded on four sides by the

aromatic B rings and the 3-*O*-gallate groups (B' rings) of two *entGCg* molecules.

In the layer structure, units of the 2:2 complex of *entGCg* and caffeine piled up in parallel to the *a*-axis, and the A and A rings of *entGCg*s faced each other by face-to-face π - π interactions (**Fig. 10**). All caffeine molecules were sandwiched between the aromatic B ring and the 3-*O*-gallate group (B' ring) or the 3-*O*-gallate groups (B' rings) of *entGCg* molecules by face-to-face π - π interactions. Also, CH- π interactions occurred between the B rings of *entGCg* and both the methyl groups at N3 (average dis-

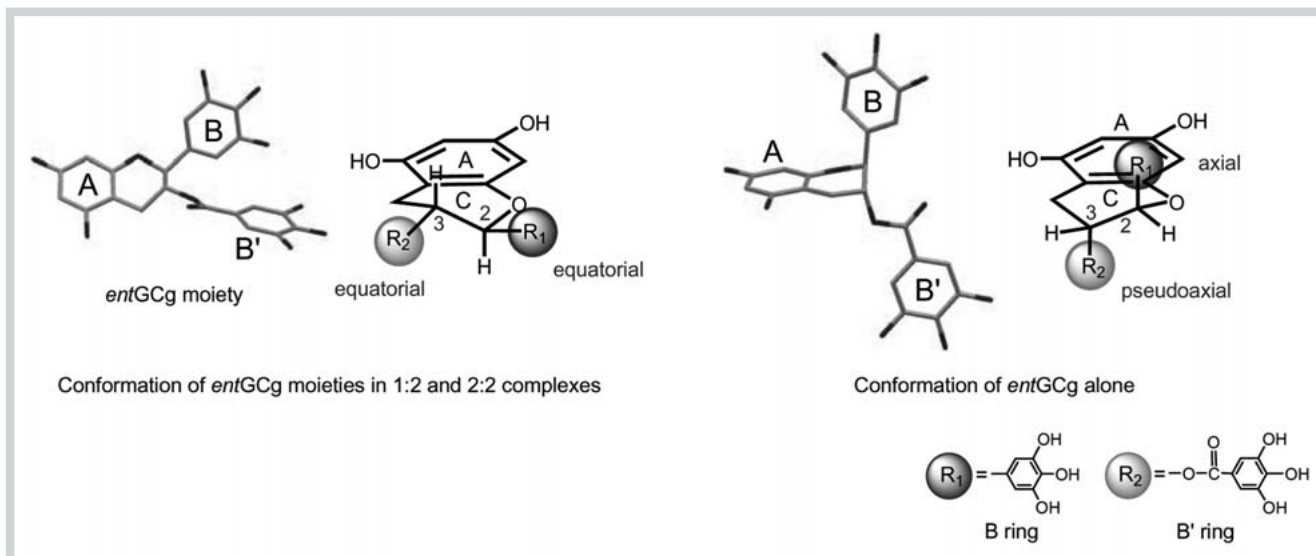


Fig. 6 Conformation of *entGCg* moieties in the 1:2 and 2:2 complexes, and *entGCg* alone in crystal state.

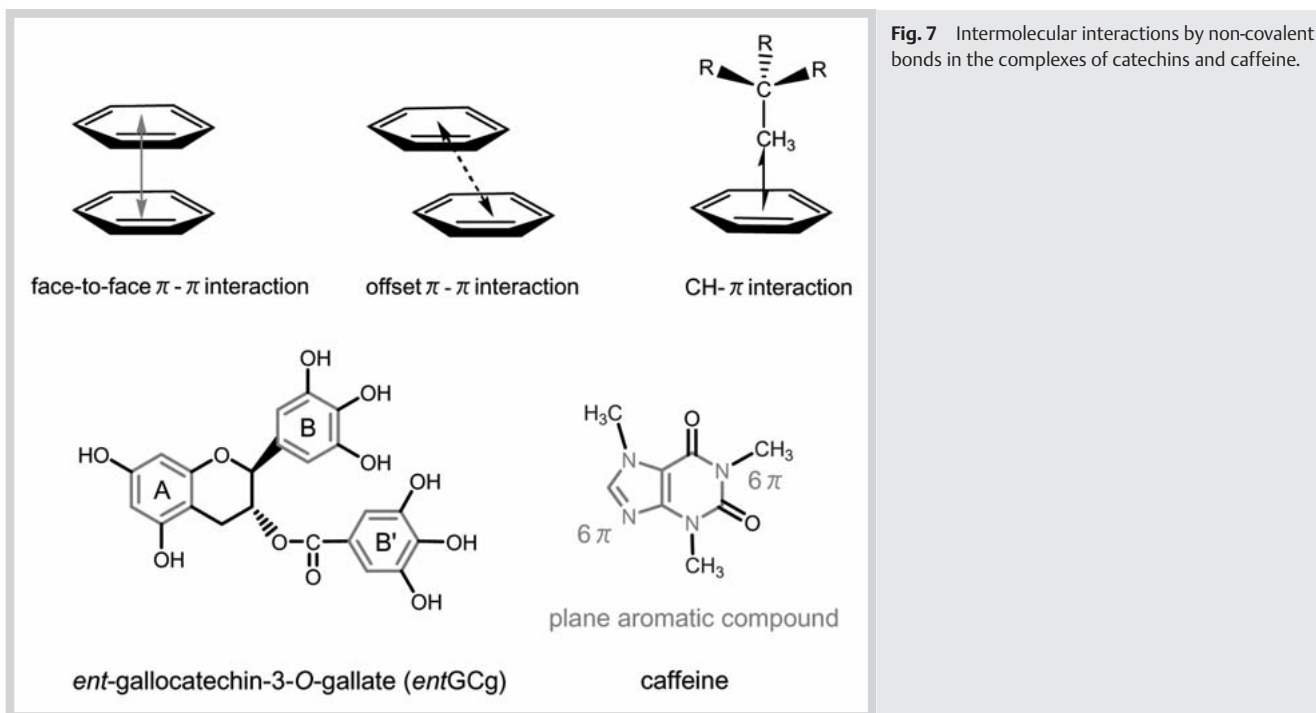


Fig. 7 Intermolecular interactions by non-covalent bonds in the complexes of catechins and caffeine.

	Torsion angle (C1'-C2-C3-O)	Torsion angle (H2-C2-C3-H3)
1:2 Complex of <i>entGCg</i> and caffeine	55.93°	173.18°
2:2 Complex of <i>entGCg</i> and caffeine	61.05° (average)	176.94° (average)
<i>entGCg</i> alone	159.03°	72.80°

Table 1 Torsion angle in *entGCg* in the 1:2 and 2:2 complexes and *entGCg* alone.

tance ca. 3.0 Å) and N7 of caffeine (average distance ca. 2.8 Å). As shown in Table 3, eight intermolecular hydrogen bonds between *entGCg*s, *entGCg* and caffeine were observed in this case. In the layer structure, *entGCg* faced in the same direction and accumulated parallel to the a-axis (Fig. 11). Offset π - π interactions formed between A and A rings, B and B rings and 3-O-gal-

late groups (B' rings) of *entGCg* molecules. However, no face-to-face π - π interaction was observed in the layer of *entGCg*. Furthermore, five hydrogen bonds were observed between *entGCg*s, *entGCg* and water and, as a result, a network of hydrogen bonds was formed in the crystal structure of *entGCg* (Table 4). Generally speaking, the equatorial position of a bulky group is kineti-

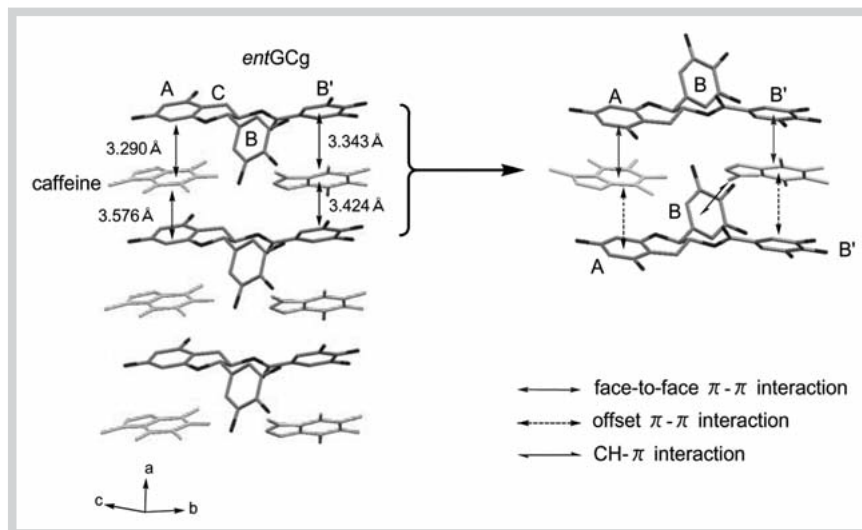


Fig. 8 The layer structure and intermolecular interactions of the 1:2 complex of *entGCg* and caffeine.

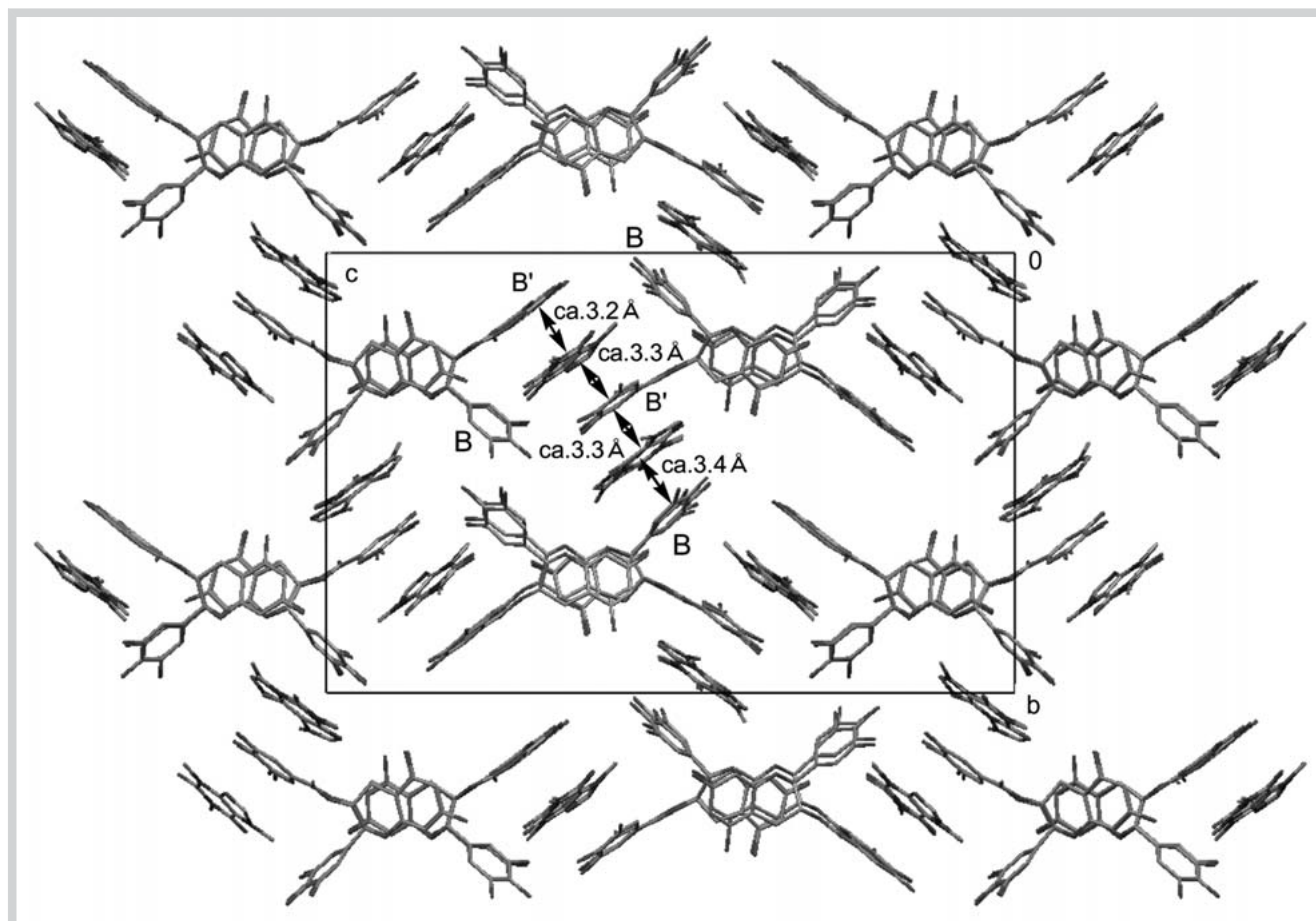


Fig. 9 Packing of the 2:2 complex of *entGCg* and caffeine in the cell down the *a*-axis.

D-H	A	D...A	D-H	H...A	∠D-H...A
C(4)-OH(20)	O(14)	2.727	1.108	1.656	160.81
C(6)-OH(30)	O(7)	2.880	1.045	1.710	157.97
C(20)-OH(100)	O(5)	2.894	1.059	1.870	161.49

Table 2 Intermolecular hydrogen bonds in the 1:2 complex.

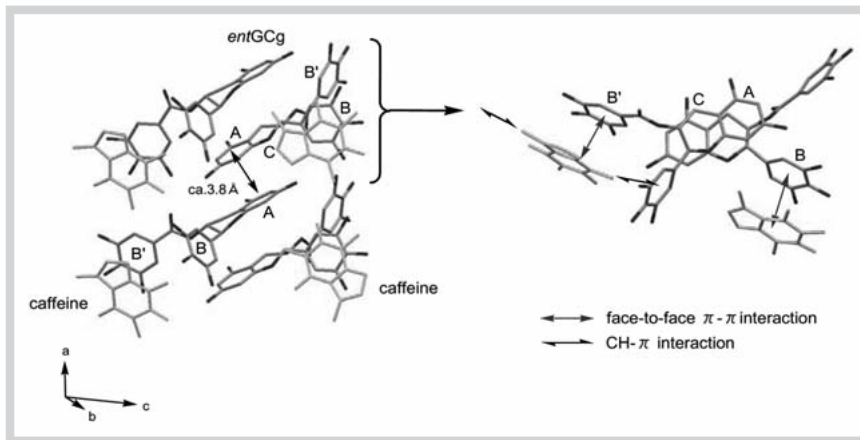


Fig. 10 The layer structure and intermolecular interactions of the 2:2 complex of *entGCg* and caffeine.

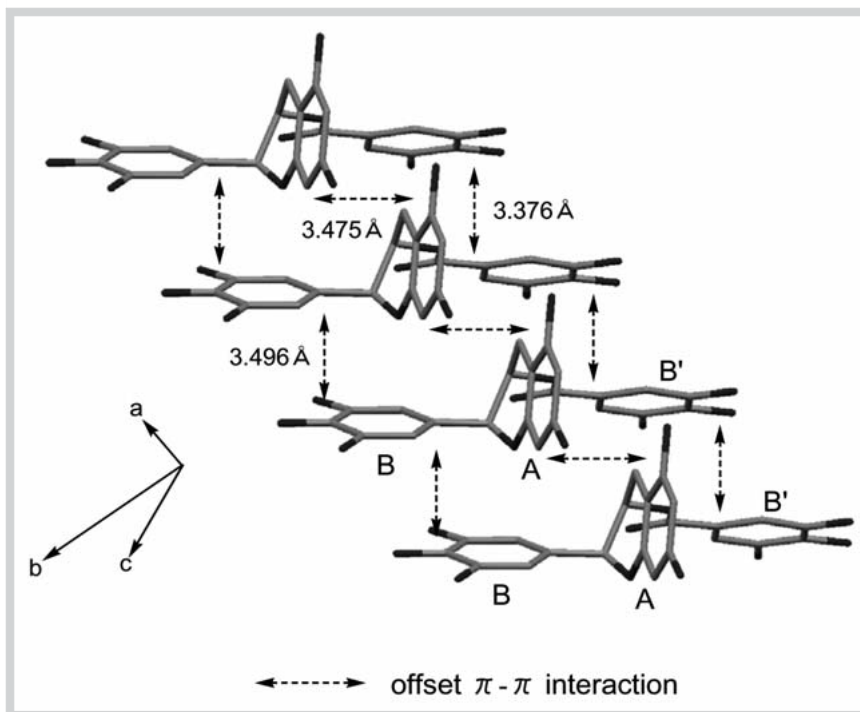


Fig. 11 The layer structure and intermolecular interaction of *entGCg* alone.

D-H	A	D...A	D-H	H...A	∠ D-H...A
C(36)-OH(16)	N(27)	2.729	0.841	1.891	174.83
C(42)-OH(18)	O(78)	2.660	0.840	1.830	169.96
C(96)-OH(42)	O(13)	2.657	0.839	1.818	177.62
C(104)-OH(46)	O(39)	2.513	0.840	1.705	160.36
C(109)-OH(48)	O(3)	2.816	0.839	2.058	149.88
C(186)-OH(81)	O(52)	2.621	0.840	1.781	177.90
C(194)-OH(85)	O(26)	2.657	0.841	1.820	173.58
C(224)-OH(98)	O(65)	2.570	0.842	1.740	168.46

Table 3 Intermolecular hydrogen bonds in the 2:2 complex.

D-H	A	D...A	D-H	H...A	∠ D-H...A
C(7)-OH(7)	O(8)	2.728	1.014	1.750	160.77
C(15)-OH(12)	O(4)	2.801	0.919	1.933	156.53
C(19)-OH(15)	O(11)	2.694	0.972	1.746	164.30
C(20)-OH(16)	O(5)	2.734	0.953	1.810	162.29

Table 4 Intermolecular hydrogen bonds in *entGCg* alone.

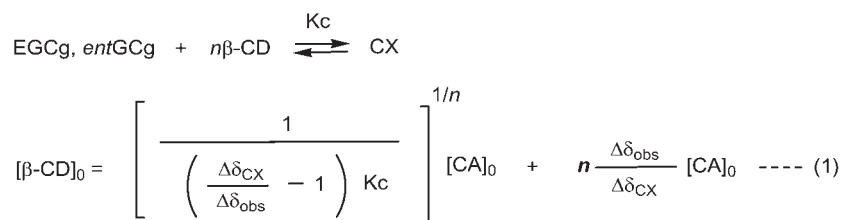


Fig. 12 Equation for the formation of the inclusion complex of β -CD with EGCg and *entGCg*. $[\beta\text{-CD}]_0$: initial concentration of β -CD (mM); $[\text{CA}]_0$: initial concentration of EGCg, *entGCg* (mM); Kc : binding constant (mM^{-1}). δ_{CA} , δ_{CX} and δ_{obs} represent the chemical shift (ppm) of the H₈ proton signal of EGCg and the H_{2'',6''} proton signal of *entGCg* in a free state, the inclusion complex of β -CD and EGCg, *entGCg*, and the mixture of β -CD and EGCg, *entGCg* in ¹H NMR spectra, respectively. $\Delta\delta_{\text{CX}}$ and $\Delta\delta_{\text{obs}}$ represent $(\delta_{\text{CA}} - \delta_{\text{obs}})$ and $(\delta_{\text{CA}} - \delta_{\text{CX}})$, respectively.

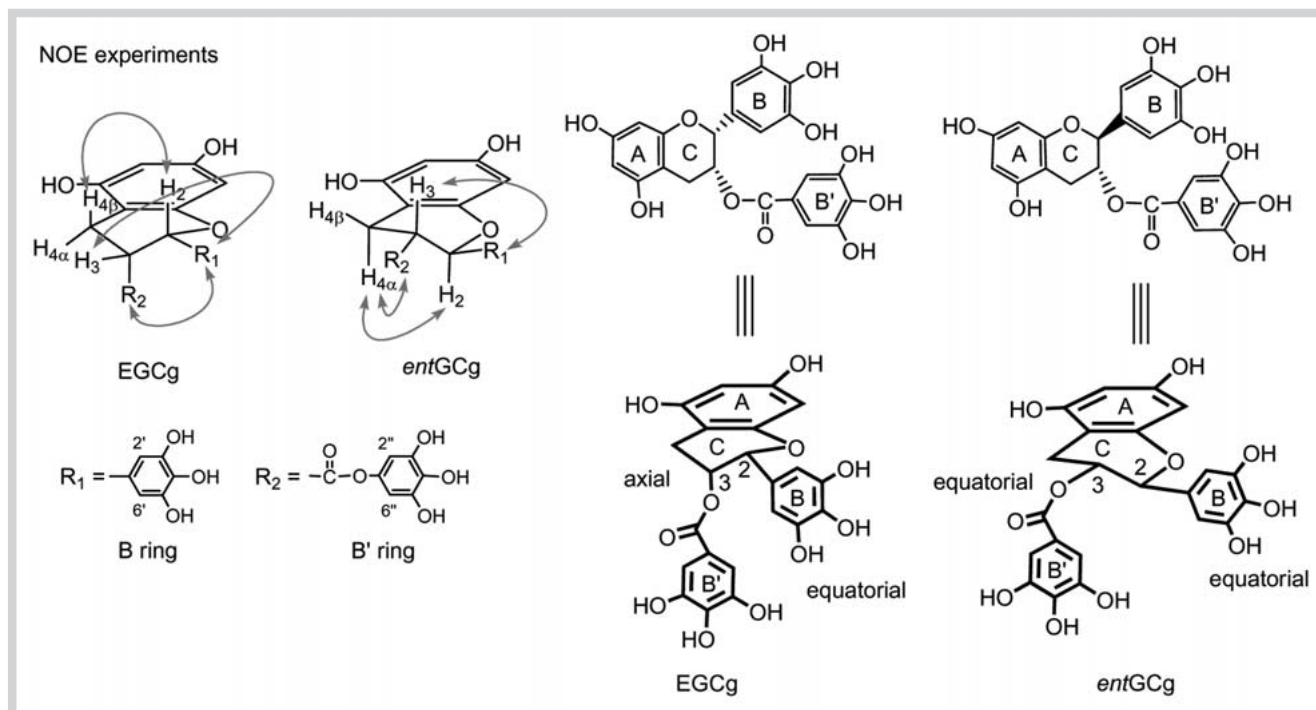


Fig. 13 Conformation of EGCg and *entGCg* in aqueous solution. Measurement temperature of NOE experiments was 35 °C.

cally more stable than the axial position, but it is thought that the cooperative effect of these interactions permits axial and pseudoaxial positions of the B ring and the 3-O-gallate group (B' ring).

Inclusion Complexes of Various Cyclodextrins with EGCg and *entGCg* [26–28]

Equation (1) for the formation of the inclusion complex of β -CD with EGCg and *entGCg* was constructed to calculate the respective n values (Fig. 12), which were 1.20 and 1.90 for EGCg and *entGCg* at 35 °C, respectively. This suggested that the stoichiometry of the formation of the inclusion complex of β -CD with EGCg was mainly 1 : 1, a conclusion that was supported by Job's Plot experiments [29]. In contrast, the stoichiometric composition of the inclusion complex of β -CD with *entGCg* was mainly 1 : 2.

The conformation of EGCg and *entGCg* in aqueous solution were investigated. In the ¹H NMR spectrum of EGCg, the signal for H₂ appeared as a broad singlet, indicating that the coupling constant $J_{2,3}$ was ca. 0 Hz. The dihedral angle $\angle\text{H}_2\text{-C}_2\text{-C}_3\text{-H}_3$ was expected to be approximately 90° as judged from the Karplus equation

[30]. Fig. 13 shows the results of the nuclear Overhauser effect (NOE) differential analysis of EGCg and *entGCg* in D₂O at 35 °C. NOEs between H₂ and H_{4 β} , H₃ and H_{2'',6''}, and between H_{2'',6''} and H_{2'',6''} of EGCg suggested that the aromatic B ring and the 3-O-gallate groups (B' rings) of EGCg adopt equatorial and axial positions, respectively.

In the ¹H NMR spectrum of *entGCg*, the H₂ signal appeared as a doublet ($J_{2,3} = 6.5$ Hz). As shown in Fig. 13, NOEs between H₂ and H_{4 α} , H_{4 α} and H_{2'',6''}, and between H₃ and H_{2'',6''} suggested that the aromatic B ring and 3-O-gallate groups (B' rings) were both in equatorial positions and therefore much more distant when compared with EGCg.

To determine the structure of the 1 : 1 inclusion complex of EGCg and β -CD, rotating frame nuclear Overhauser effect spectroscopy (ROESY) of a solution containing equimolar amounts of β -CD and EGCg in D₂O was measured. Strong intermolecular ROE correlations between the H₈ of EGCg and the H₃, H₅, and H₆ being on the inner surface of β -CD suggested that the A ring of EGCg was included in the β -CD cavity. Furthermore, intermolecular ROE correlations between H_{2'',6''} of EGCg and each β -CD proton were detected. Based on the results of the ROESY spectrum and the ¹H

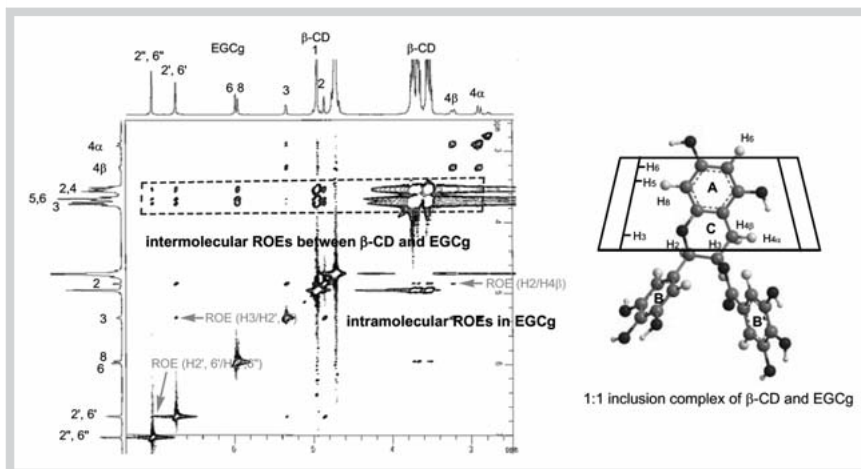


Fig. 14 ROESY spectrum of a solution containing an equimolar amount of β -CD and EGCg in D_2O at $35^\circ C$, and possible structure of 1:1 inclusion complex of β -CD and EGCg.

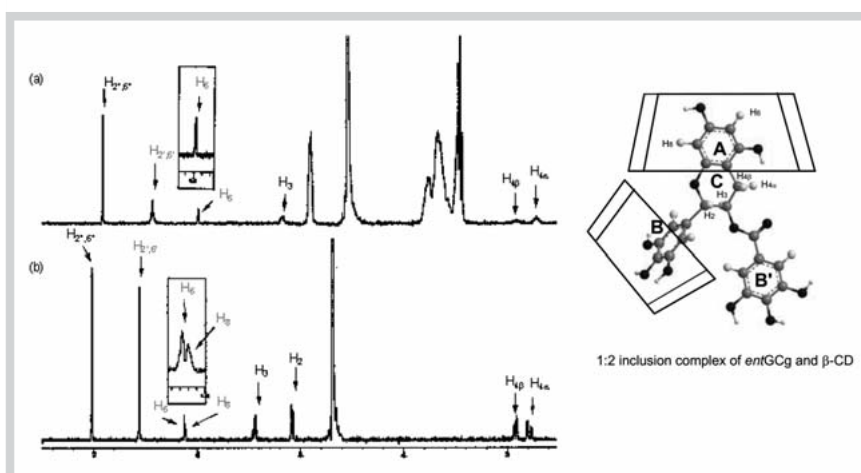


Fig. 15a and b 1H NMR spectra of solutions containing (a) *entGCg* and twice the amount of β -CD, and (b) *entGCg* alone in D_2O at $35^\circ C$, and possible structure of 1:2 inclusion complex of β -CD and *entGCg*.

NMR chemical shift changes [24], it was concluded that the A ring and a part of the C ring of EGCg were included in the wide secondary hydroxyl group side of the β -CD cavity, and that the aromatic B ring and 3-O-gallate group (B' ring) were left outside the cavity (● Fig. 14). Also, EGCg intramolecular associations between H_2 and $H_{4\beta}$, H_3 and $H_{2',6'}$, as well as $H_{2',6'}$ and $H_{2'',6''}$ indicated that the conformation in which the B ring and 3-O-gallate group (B' ring) of EGCg adopted equatorial and axial positions, respectively, were still maintained upon the formation of the inclusion complex.

In the ROESY spectrum of a solution containing *entGCg* and β -CD (ratio 1:2) in D_2O , strong intermolecular ROE correlations between the H_8 of *entGCg* and the H_5 and H_6 of β -CD were observed, suggesting that the A ring of *entGCg* was included in the β -CD cavity [25]. Upon the formation of the 1:2 inclusion complex of *entGCg* and β -CD, all proton signals of *entGCg* were shifted upfield due to C-C bond anisotropy by the two molecules of β -CD. The proton signals of *entGCg* were broadened, except those for H_6 and $H_{2'',6''}$ (● Fig. 15). A plausible explanation of the observed signal broadening may be due to the restricted motion of these protons by the two molecules of β -CD. Notably, the signal for the $H_{2',6'}$ protons was markedly broadened, while that for the $H_{2'',6''}$ protons appeared sharp. These findings suggested that the B ring of *entGCg* was localized in the cavity of β -CD, while the 3-O-gallate group (B' ring) was outside the cavity. Furthermore, the H_8 signal almost disappeared on formation of the inclusion complex

with β -CD, whereas the H_6 signal was still sharp. The disappearance of the H_8 signal may be explained by the close proximity with the hydrogens on the inner surface of β -CD. On the other hand, the motion of the H_6 proton might not be restricted due to its position in the vicinity of the rim of the narrow primary hydroxyl group side of β -CD. It is therefore concluded that *entGCg* is enclosed in the two β -CD molecules in the manner illustrated in ● Fig. 15.

To confirm the structure of the 1:2 inclusion complex of *entGCg* and β -CD deduced from NMR experiments, the energies and structure of the 1:1 and 1:2 inclusion complexes were calculated using the PM5 MO method [31]. The 1:2 complex including the aromatic A and B rings of *entGCg* is ca. 3 kcal/mol more stable than that including the A ring and 3-O-gallate group (B' ring) in the PM5 calculation (● Fig. 16).

EGCg and *entGCg* afforded no inclusion complex with α -CD because the cavity of α -CD is not large enough to include these molecules. While EGCg yielded a 1:1 inclusion complex with β -CD, *entGCg* formed a 1:2 inclusion complex with β -CD, resulting from the different spacing between the B rings and the 3-O-gallate groups (B' rings) in aqueous solution. EGCg failed to form an inclusion complex with γ -CD, whereas *entGCg* did form a 1:1 inclusion complex with γ -CD due to the large cavity of γ -CD.

The difference in stereochemistry between EGCg and *entGCg* is only the configuration at the 2 position, but for the two mole-

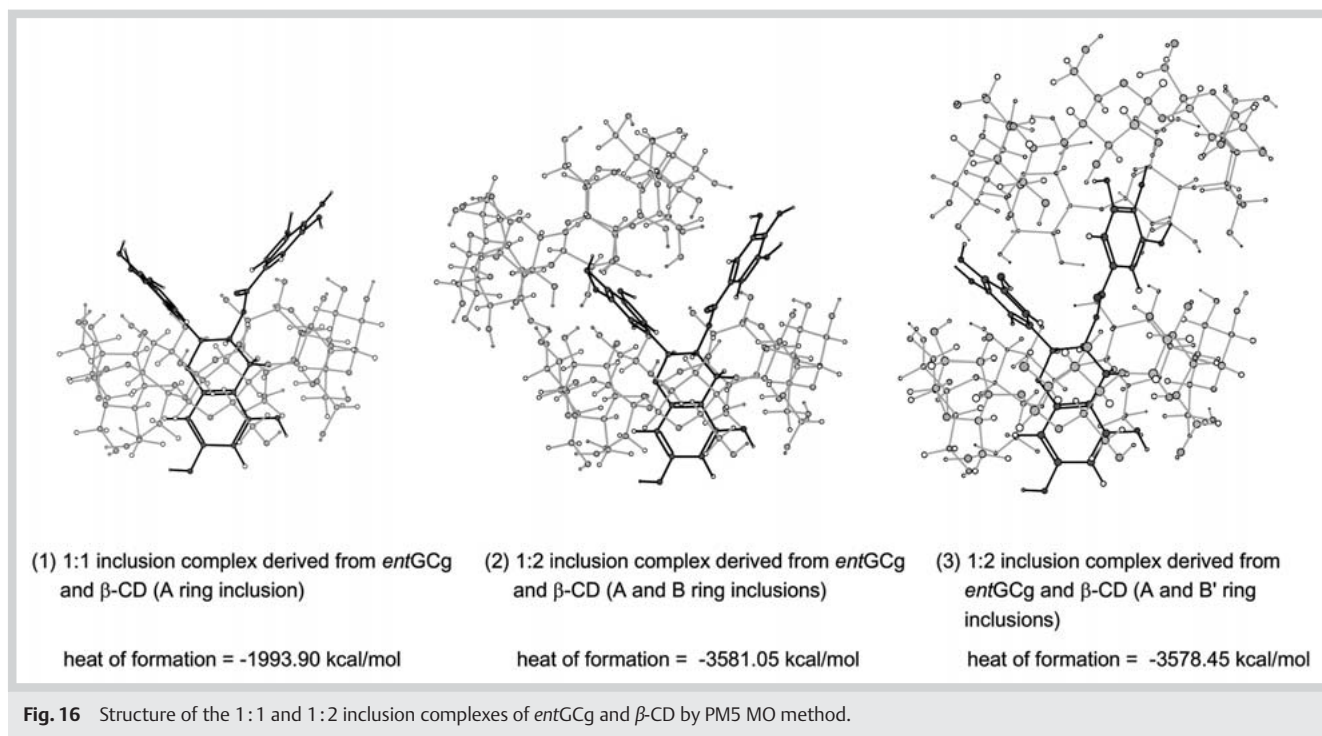


Fig. 16 Structure of the 1:1 and 1:2 inclusion complexes of *entGCg* and β -CD by PM5 MO method.

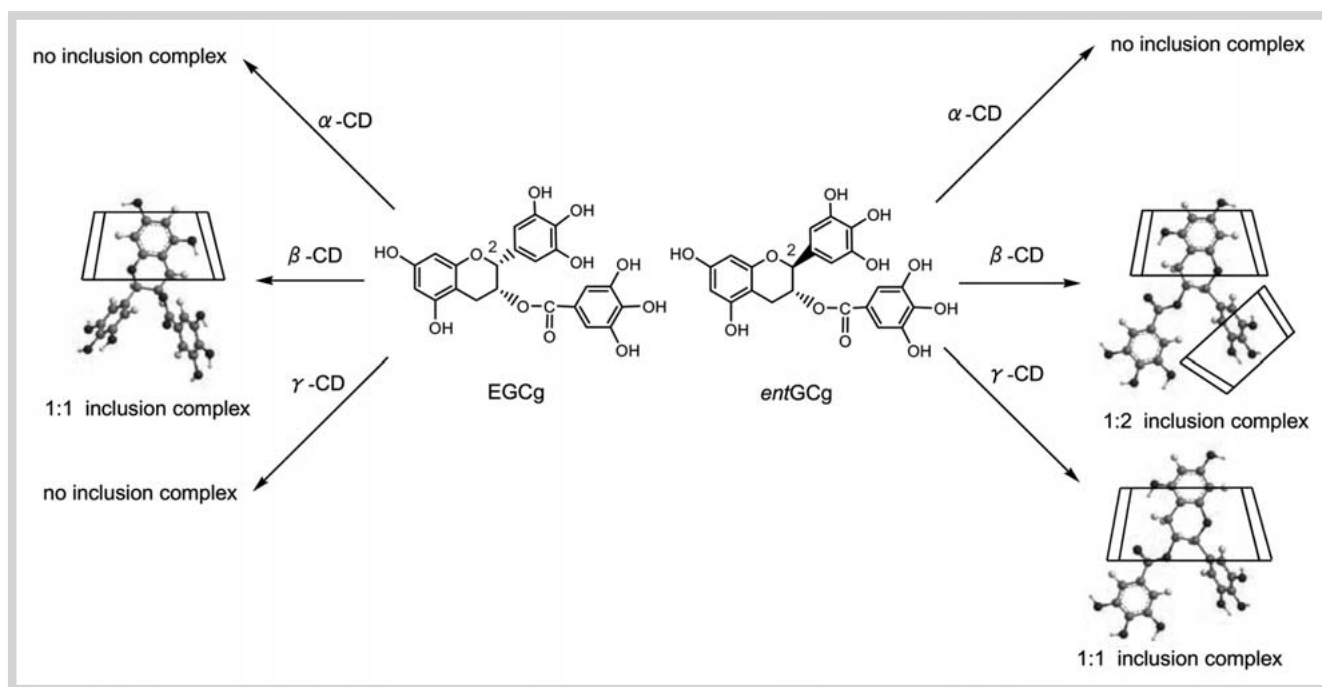


Fig. 17 Inclusion modes of EGCg and *entGCg* with α , β , and γ -CDs.

cules the inclusion modes with various cyclodextrins vary considerably and are summarized in **Fig. 17**.

Supporting information

X-ray data of the 1:2 and 2:2 complexes of *entGCg* and caffeine and *entGCg* alone, NMR experiments and calculation methods for the inclusion complexes of *entGCg* and β -CD are available as Supporting Information.

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