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Boronic Acid Fluorophore/β-Cyclodextrin Complex Sensors for Selective Sugar Recognition in Water

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A novel boronic acid fluorophore 1/β-cyclodextrin (β-CyD) complex sensor for sugar recognition in water has been designed. The probe 1 bearing pyrene moiety as a fluorescent signal transducer exhibits no fluorescence emission, due to its aggregation in water containing 2% DMSO; however, the addition of β-CyD to this solution largely changes UV−vis and fluorescence spectra of 1 by forming an inclusion complex with β-CyD, and an efficient fluorescence emission response of 1/β-CyD complex upon sugar binding is found to be obtained at pH 7.5. The pH-fluorescence profile of the 1/β-CyD complex reveals that the boronate ester formation with fructose induces the apparent pK_a shift from 7.95 ± 0.03 in the absence of fructose to 6.06 ± 0.03 in the presence of 30 mM fructose, resulting in the fluorescence emission response under the neutral condition. The spectral properties of 1 in 95% methanol:5% water (v/v), as well as the fluorescence quenching study of 1-methylpyrene with 4-methoxycarbonylphenyl-boronic acid 2, demonstrate that the response mechanism is based on the photoinduced electron transfer (PET) from the pyrene donor to the acid form of phenylboronic acid acceptor in 1, and thus, the proton dissociation of phenylboronic acid induced by sugar binding inhibits the PET system while increasing the fluorescence intensity of the pyrene moiety. To evaluate the binding ability and selectivity of the 1/β-CyD complex for monosaccharides in water, the response equilibria have been derived. The 1:1 binding constants of the 1/β-CyD complex obtained from the equilibrium analysis are in the order: D-fructose (2515 ± 134 M^{-1}) ≫ L-arabinose (269 ± 28 M^{-1}) > D-galactose (197 ± 28 M^{-1}) > D-glucose (79 ± 33 M^{-1}), which is consistent with the binding selectivity of phenylboronic acid.

Sugars are important biological molecules that are essential in processes such as nutrition, metabolism, and cell structure.[1] Sugars are also physiologically active substances, and they play fundamental roles in controlling an individual's birth, differentiation and immunity. Because of these important properties, there is a need to develop methods for in-situ sugar sensing in aqueous solution.[1] One approach that has recently attracted strong interest is the use of boronic acid derivatives as fluorescent sugar sensors.[2−10] For example, Czarnik and co-workers reported the properties of anthrylboronic acid **3**, which senses sugars in neutral aqueous solution via a fluorescence quenching process.[2] Similarly, Aoyama and co-workers synthesized indolylboronic acid **4**, which recognizes fructose and oligosaccharides at pH 9 with chain length selectivity due to the CH-π interaction in addition to boronate ester formation.[3] A major design effort has been made by Shinkai et al. to develop sensors for precise and selective sugar recognition.[5] A notable design uses a boronic acid unit connected to a fluorescent tertiary amine, as shown in **5**.[6−10] Sugar binding results in fluorescence enhancement due to a strengthening of the boron−nitrogen Lewis acid−base interaction which suppresses electron-transfer quenching. This photoinduced electron transfer (PET) system senses sugars in neutral aqueous methanol solution with fluorescence intensity increases.

Molecular recognition by multicomponent assemblies of host molecules appears to be another promising way to construct novel molecular sensors.[11] Self-assembled systems often exhibit different recognition properties as compared to the original host molecule.[12]

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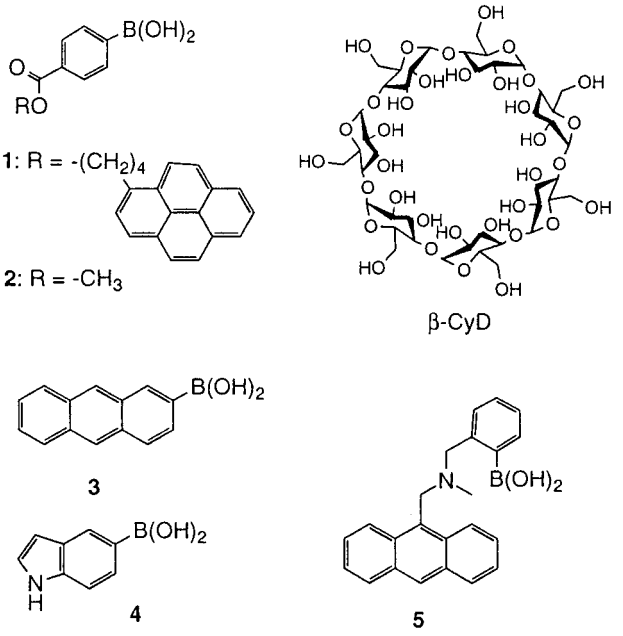
For example, we recently used a crown ether fluorophore/γ-cyclodextrin (γ-CyD) complex to selectively sense potassium ions in water.[13] Dimerization of the probe inside the γ-CyD provides a highly selective binding site for the potassium ion. This finding has led us to design additional multicomponent probe/CyD complex sensors for ion and molecule recognition in water.

The objective of this study is to develop a highly sensitive and selective recognition system for sugars in aqueous solution by using the inclusion complex of newly designed fluorescent probe, **1**, with β-CyD. Probe **1** contains a fluorescent pyrenyl group and a sugar-binding arylboronic acid moiety.[14] The hydrophobic cavity of β-CyD can incorporate probe **1** and the assembled probe **1**/β-CyD complex acts as a sugar sensor. We find that the **1**/β-CyD complex exhibits an increased fluorescence emission response upon sugar binding in water.



EXPERIMENTAL SECTION

Apparatus. Fluorescence spectra were measured with a JASCO FP-770 spectrofluorometer at 25 °C; the excitation and emission bandwidths were 5.0 and 3.0 nm, respectively. The scan speed was 50.0 nm/min. All fluorescence spectra were recorded under an aerated condition. UV−vis spectra were measured by a Hitachi U-3000 UV−vis spectrophotometer (Hitachi Ltd.) by using a 5-cm quartz cell at 25 °C. ^{1}H NMR spectra were obtained using a JEOL-GSX270 (270 MHz; JEOL DATUM).

Reagents. L(+)-Arabinose, D(−)-fructose, D(+)-galactose, and D(+)-glucose were special grade reagents obtained from Wako Pure Chemical Industries, Ltd. The first reagent grade of β-CyD (Wako Pure Chemical Industries, Ltd) was recrystallized twice from water. 2-(4-Carboxyphenyl)-1,3,2-dioxaborinane was prepared by a slightly modified procedure;[15] benzene (reaction time, 12 h) was used instead of toluene (reaction time, 2 h). Water was doubly distilled and deionized by a Milli-Q Labo system (Millipore) before use. Other chemicals used were of reagent grade and were used as received.

Synthesis of 4-(4-(1-Pyrenyl)butoxy)carbonylphenylboronic Acid (1). To a mixture of 4-(1-pyrenyl)butanol (80 mg, 0.29 mmol), 2-(4-carboxyphenyl)-1,3,2-dioxaborinane (60 mg, 0.29 mmol), and 4-(dimethylamino)pyridine (18 mg, 0.15 mmol) in dry CH_2Cl_2/DMF (10:1 v/v, 15 mL) was slowly added a solution of 1-(3-dimethylamino)propyl-3-ethylcarbodiimide hydrochloride (87 mg, 0.44 mmol) in dry CH_2Cl_2/DMF (10:1 v/v, 2 mL) at 0 °C. The reaction mixture was stirred at 0 °C for 2 h and at room temperature for 2 days. The solvent was evaporated in vacuo and the residue was taken up with CH_2Cl_2 (20 mL). The organic solution was washed with 10% aqueous HCl (20 mL), water (20 mL), 4% aqueous Na_2CO_3 (20 mL), 5% aqueous HCl (20 mL), and water (20 mL), was dried over $MgSO_4$, and was evaporated in vacuo. The residue was chromatographed on silica gel sequentially with EtOAc/hexane (3:1, v/v) and MeOH/$CHCl_3$ (1:1, v/v) as eluents to give 73 mg (60%) of the desired product as a white solid. mp 194−197 °C. MS (+ FAB in glycerol) m/z 478 for boronic acid/glycerol adduct. ^{1}H NMR (300 MHz; DMSO-d_6) δ 1.9 (m), 3.38 (peak + water impurity), 4.36 (t), 7.88 (d), 7.97 (d), 8.04 (t), 8.12 (d), 8.19 (t), 8.23−8.25 (m), 8.27−8.28 (m), 8.37 (d). ^{13}C NMR (75 MHz; DMSO-d_6) δ 27.97, 28.25, 32.24, 64.23, 123.55, 124.23, 124.34, 124.90, 125.06, 126.27, 126.61, 127.31, 127.56, 127.61, 128.00, 128.16, 129.37, 130.48, 130.99, 131.08, 134.31, 136.78. FT-IR (KBr pellet) cm^{-1} 3036, 2925, 1714; 1400, 1362, 1268, 1115, 1015, 949, 834, 707.

Synthesis of 4-Methoxycarbonylphenylboronic Acid (2). 4-Carboxyphenylboronic acid (1.00 g, 6.03 mmol) was dissolved in methanol (25 mL) and 5 drops of concentrated H_2SO_4 was added. The mixture was stirred at reflux temperature for 1 day. After removal of the solvents in vacuo, the residue was dissolved in EtOAc (20 mL), and the solution was extracted with 5% aqueous Na_2CO_3 and water. The EtOAc layer was dried over $MgSO_4$, and the solvent was removed in vacuo. The resulting residue was purified by recrystallization from toluene to give 0.166 g (15%) of the desired product as a white solid. ^{1}H NMR (DMSO-d_6 plus a drop of D_2O, 270 MHz) δ 7.83−7.94 (m, 4 H, ArH), 3.83 (s, 3 H, CH_3). Anal. Calcd for $C_8H_9BO_4$ (−0.4 H_2O):[16] C, 55.61; H, 4.78. Found: C, 55.74; H, 4.99.

RESULTS AND DISCUSSION

Spectral Properties of 1 in Aqueous DMSO Solution. Probe **1** was prepared in straightforward fashion by condensing 2-(4-carboxyphenyl)-1,3-dioxaborinane with 4-(1-pyrenyl)butanol followed by deprotection of the boronic acid. The absorption and fluorescence spectra of **1** were recorded in aqueous solutions with different DMSO contents. Figure 1a shows the UV−vis spectra of **1** in 2% DMSO solution (spectrum 1). The absorption peaks are quite broad when compared to those in 25% DMSO solution (spectrum 2), indicating that **1** aggregates in water. The addition of β-CyD to a 2% DMSO solution of probe **1** dramatically changes the absorption and fluorescence spectra. The absorption spectrum of **1** in 2% DMSO solution containing 5.0 mM β-CyD (spectrum 3 in Figure 1a) becomes similar to that in 25% DMSO solution.

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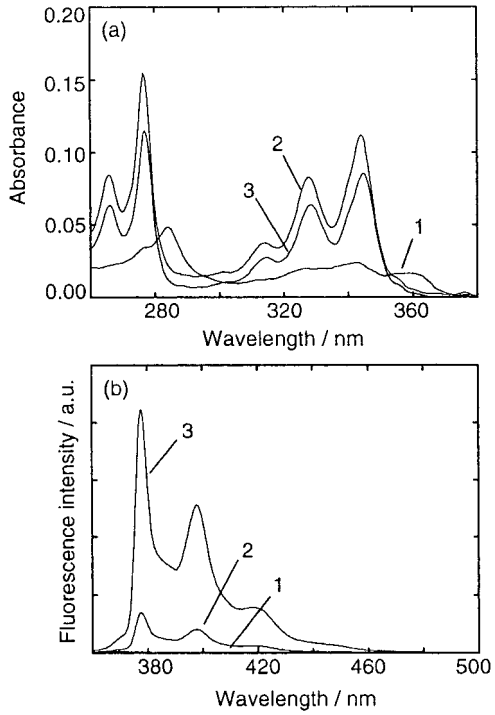


Figure 1. Spectral properties of **1** in aqueous DMSO solution. (a) UV−vis spectra: optical path length, 5 cm. (b) Fluorescence spectra: excitation wavelength, 328.0 nm; excitation bandwidth, 5 nm; emission bandwidth, 3 nm. [**1**] = 1.05 μM in (1) 2% DMSO/98% water (v/v), (2) 25% DMSO/75% water (v/v), and (3) 2% DMSO/98% water (v/v) containing 5.0 mM β-CyD. pH = 7.5, adjusted by 0.015 M phosphate buffer (I = 0.08 M with NaCl).

This indicates the presence of monomeric **1** due to the formation of an inclusion complex with β-CyD. Figure 1b shows the fluorescence spectra of **1** in the same solvent mixtures. In 2% DMSO solution, the aggregated **1** exhibits no emission, due to a self-quenching. In contrast, probe **1** in 25% DMSO solution shows fluorescence at 370−430 nm with a vibronic structure, which can be ascribed to the monomer emission of a pyrene moiety. It is interesting to note that the fluorescence intensity of **1** is dramatically enhanced in the presence of β-CyD (spectrum 3 in Figure 1b). This is attributed to an enhancement in fluorescence quantum yield for **1,** because it forms an inclusion complex with β-CyD, which restricts the molecular motion of **1** and reduces the radiationless transition process.

Fructose Recognition of the 1/β-CyD Complex in Water. The effect of added fructose on the emission intensity of **1** was monitored at pH 7.5 in 2% DMSO solution, 25% DMSO solution, and 2% DMSO solution containing 5.0 mM of β-CyD. Figure 2a shows a typical fluorescence response for the **1**/β-CyD complex in the presence of fructose. The fluorescence emission of the **1**/β-CyD complex in 2% DMSO solution intensifies as the fructose concentration is raised from 0 to 30 mM (curve 3 in Figure 2b). In contrast, no fluorescence response is noted for **1** in 2% DMSO solution (curve 1 in Figure 2b), and in 25% DMSO solution, probe **1** exhibits a reasonable increase in monomer fluorescence intensity (curve 2). Thus, highly sensitive fructose recognition in water is achieved by the **1**/β-CyD complex sensor.

To clarify the response function, the fluorescence behavior of the **1**/β-CyD complex was examined at different pH conditions.

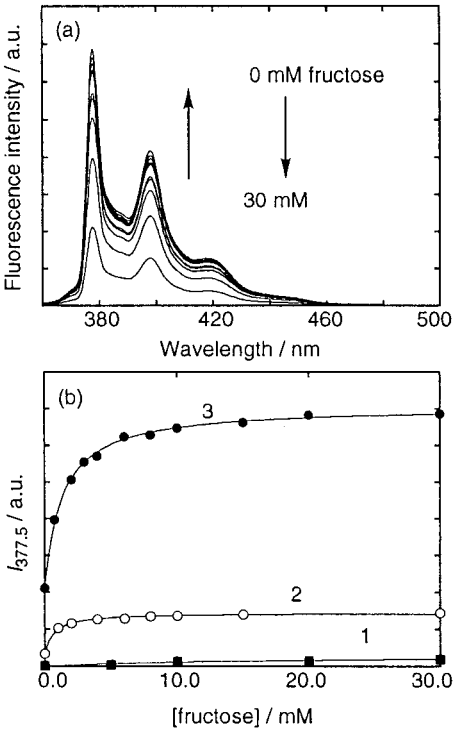


Figure 2. (a) Fluorescence spectra of the **1**/β-CyD complex upon the addition of fructose: [**1**] = 1.05 μM and [fructose] = 0−30.0 mM in 2% DMSO/98% water (v/v) containing 5.0 mM β-CyD; excitation wavelength, 328.0 nm; excitation bandwidth, 5 nm; emission bandwidth, 3 nm; pH = 7.5, adjusted by 0.015 M phosphate buffer (I = 0.08 M with NaCl). (b) Dependence of $I_{377.5}$ on the concentration of fructose: [**1**] = 1.05 μM in (1) 2% DMSO/98% water (v/v), (2) 25% DMSO/75% water (v/v), and (3) 2% DMSO/98% water (v/v) containing 5.0 mM β-CyD; pH = 7.5, adjusted by 0.015 M phosphate buffer (I = 0.08 M with NaCl).

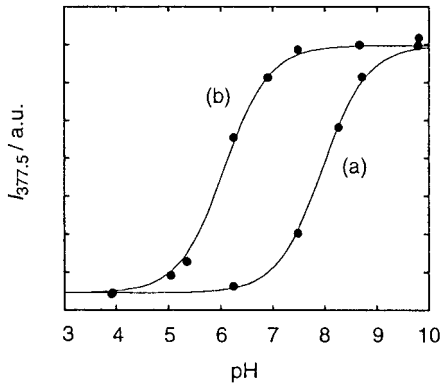
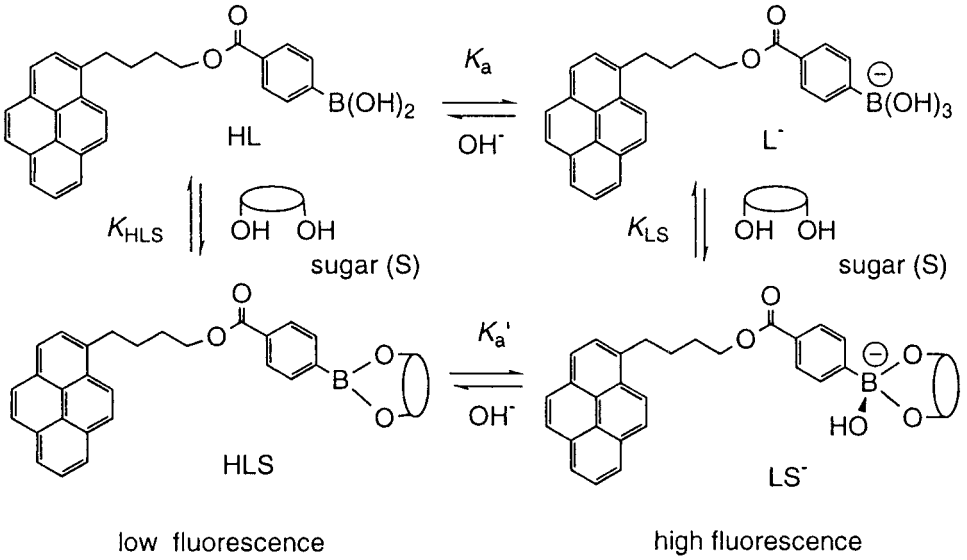


Figure 3. Dependence of $I_{377.5}$ as a function of pH: [**1**] = 1.05 μM in 2% DMSO/98% water (v/v) containing 5.0 mM β-CyD: (a) [fructose] = 0.0 mM; (b) [fructose] = 30.0 mM.

The pH-dependent changes in the fluorescence intensity of the **1**/β-CyD complex in the absence (a) and presence (b) of 30 mM fructose are presented in Figure 3. The solid lines show the theoretical curves calculated from eq 1,

$$I = \frac{\beta[\mathrm{L}]_t\left(\phi_{\mathrm{HL}} + \phi_{\mathrm{L}}\dfrac{K_a}{[\mathrm{H}^+]}\right)}{1 + \dfrac{K_a}{[\mathrm{H}^+]}} \quad (1)$$

Scheme 1. Proton Dissociation and Sugar Binding Equilibria of 1 in Aqueous Solution



where ϕ_{HL} and ϕ_L are the fluorescence quantum yields for HL and L^- species of **1**, respectively, and β is a constant that is proportional to the intensity of the excitation light and the molar extinction coefficient of **1**. K_a represents the boronic acid dissociation constant of **1**. As can be seen from Figure 3, the addition of 30 mM fructose decreases the apparent pK_a value of **1** from 7.95 ± 0.03 to 6.06 ± 0.03. This pK_a shift enables **1** to recognize fructose at neutral pH. The sugar recognition process is illustrated in Scheme 1. The fluorescence quantum yield for **1** apparently increases when **1** is converted to its tetrahedral boronate form. Thus, the increased amount of tetrahedral boronate induced by sugar binding causes an enhancement in the emission intensity. It is notable that the ratio of quantum yield between the acidic and basic forms of **1** (ϕ_L/ϕ_{HL}) reaches 15.2. This pH-dependent fluorescence profile is opposite to that observed with the previously reported fluorescence quenching probes.[2−4] In addition, Shinkai and co-workers have developed probes exhibiting increased emission response to sugars, but their fluorescence intensities become reduced with increasing pH, which is different from the profile shown in Figure 3. This demonstrates a clear difference in the response mechanism of the **1**/β-CyD complex.

Response Mechanism of the 1/β-CyD Complex in Water. The low fluorescence intensity for **1** when its boronic acid group is trigonal suggests that the arylboronic acid can act as an electron acceptor from the excited-state pyrene donor.[17] To test this idea, we examined the UV−vis and fluorescence spectra of **1** in 95% methanol/5% water (v/v). The fluorescence quantum yield of **1** is greatly enhanced by the addition of 1.0 mM benzyltrimethylammonium hydroxide (Figure 4). No changes are observed in the UV−vis spectra (dotted lines in Figure 4), which indicates that no ground state interaction is taking place. This result strongly supports a PET pathway from the pyrene donor to the acid form of the arylboronic acid acceptor.[17] The 95% methanol is relatively hydrophobic and no UV−vis spectral change is noted, which is evidence against a sensing mechanism based on changes in solubility or aggregation.[5]

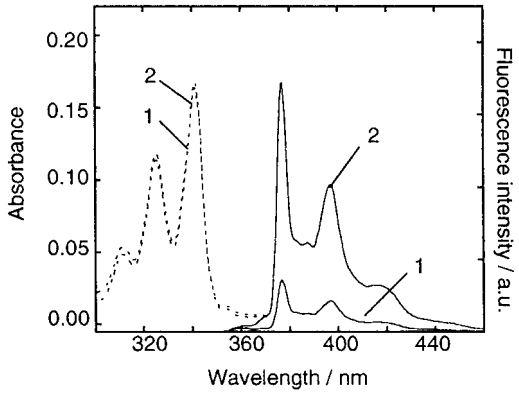


Figure 4. UV−vis and fluorescence spectra of **1** in 95% methanol/5% water (v/v): [**1**] = 1.05 μM when (1) [BTA] = 0.0 mM and (2) [BTA] = 1.0 mM; BTA, benzyltrimethylammonium hydroxide.

To obtain further evidence, we studied 1-methylpyrene and 4-methoxycarbonylphenylboronic acid (**2**) as donor and acceptor models of the intramolecular pyrene/arylboronic acid system in **1**. A fluorescence quenching study was carried out in 95% methanol/5% water (v/v). The UV−vis and fluorescence spectra of 1-methylpyrene (5×10^{-5} M) and increasing amounts of the acidic form of **2** (0−20 mM) are depicted in Figure 5a. Similar to the result in Figure 4, the fluorescence of 1-methylpyrene is significantly quenched by addition of the acid form of **2** without changing its UV−vis spectra; however, when 40 mM benzyltrimethylammonium hydroxide is added, which converts **2** to its tetrahedral boronate form, no quenching behavior is observed. The Stern−Volmer plot for this system in the absence (condition 1) and presence (condition 2) of base is shown in Figure 5b. A clear straight line is obtained for condition 1, and the Stern−Volmer constant (K_{SV}) is determined to be 110 M^{-1} from its slope analysis. On the assumption that the fluorescence lifetime of 1-methylpyrene is ∼100 ns,[18] the quenching rate constant is estimated to be $\sim 10^9$ M^{-1} s^{-1}, which is in the expected range for a diffusion-controlled quenching by **2**. Thus, the main mechanism

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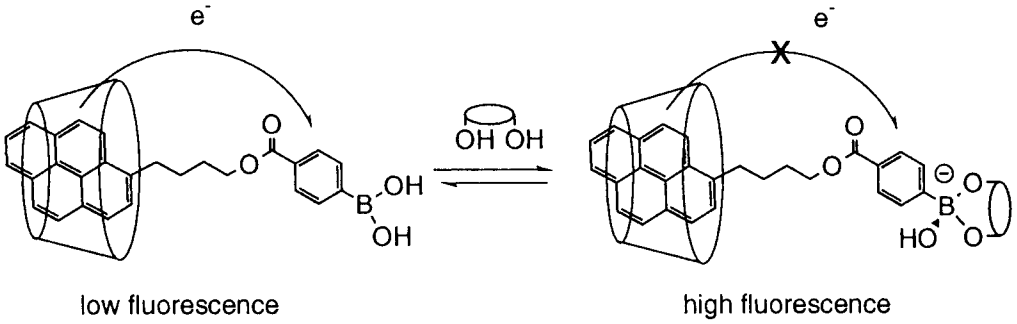
Scheme 2. Response Mechanism of the 1/*β*-CyD Complex for Sugar Binding



for fluorescence quenching appears to be electron transfer from the excited 1-methylpyrene to the acid form of **2**, which acts as electron acceptor.

These results strongly support intramolecular PET from the pyrene donor in **1** to the trigonal form of its arylboronic acid acceptor. Sugar binding converts the boronic acid to tetrahedral boronate, which decreases the amount of PET quenching and increases the monomer fluorescence intensity (Scheme 2). Overall, the **1**/*β*-CyD complex provides a new mechanism for sugar sensing in water.[19]

Binding Equilibrium and Recognition Selectivity of 1/*β*-CyD Complex for Sugars. According to the equilibria shown in Scheme 1, the different equilibrium constants can be expressed by the following equations:[20]

$$K_a = \frac{[H^+][L^-]}{[HL]} \tag{2}$$

$$K_a' = \frac{[H^+][LS^-]}{[HLS]} \tag{3}$$

$$K_{LS} = \frac{[LS^-]}{[L^-][S]} \tag{4}$$

$$K_{HLS} = \frac{[HLS]}{[HL][S]} \tag{5}$$

Because K_a' is equal to K_aK_{LS}/K_{HLS}, at least three main equilibrium constants must be taken into consideration. From eqs 2−5, the fluorescence intensity of **1**/*β*-CyD is expressed as

$$I = \frac{\beta[L]_t\left(\phi'_{HL} + \phi'_L\dfrac{K_a(1+K_{LS}[S])}{[H^+](1+K_{HLS}[S])}\right)}{1+\dfrac{K_a(1+K_{LS}[S])}{[H^+](1+K_{HLS}[S])}} \tag{6}$$

$$\phi'_{HL} = \frac{\phi_{HL} + \phi_{HLS}K_{HLS}[S]}{1+K_{HLS}[S]} \tag{7}$$

$$\phi'_L = \frac{\phi_L + \phi_{LS}K_{LS}[S]}{1+K_{LS}[S]} \tag{8}$$

where ϕ_{HLS} and ϕ_{LS} are the fluorescence quantum yields for HLS and LS^- species of the **1**/*β*-CyD complex, respectively. As can

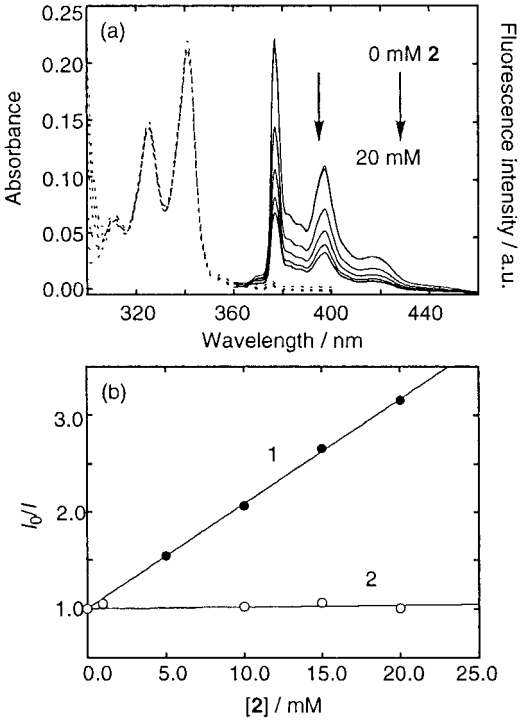


Figure 5. (a) UV−vis and fluorescence spectra of 1-methylpyrene upon the addition of **2** in 95% methanol/5% water (v/v): [1-methylpyrene] = 50.0 *μ*M and [**2**] = 0−20 mM; (b) Stern−Volmer plots, (1) [BTA] = 0.0 mM and (2) [BTA] = 40.0 mM.

be seen from eqs 1 and 6, the apparent acid dissociation constant (K_a^{app}) is defined as

$$K_a^{app} = K_a\frac{1+K_{LS}[S]}{1+K_{HLS}[S]} \tag{9}$$

$$\Delta pK_a = -\log\frac{K_a}{K_a^{app}} = \log\frac{1+K_{LS}[S]}{1+K_{HLS}[S]} \tag{10}$$

When the K_{HLS} value is comparable to the K_{LS} value, eqs 9 and 10 imply that no pK_a shift can be observed upon the addition

(19) The glucose-selective fluorescent probe reported by Eggert et al. seems to respond using the same mechanism as described here, although they do not discuss the details. See: Eggert, H.; Frederiksen, J.; Morin, C.; Norrild, J. C. *J. Org. Chem.* **1999**, *64*, 3846−3852.

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Table 1. Binding Constants of Various Fluorescent Probes for Monosaccharides

probes	Binding constants (K_{LS}/M^{-1}) D-fructose	D-galactose	L-arabinose	D-glucose	ref.
phenylboronic acid	4370	276	391	110	14
4	6300			71	3
5 (in 33% MeOH)	1000		158	63	6
1/β-CyD complex	2515 ± 134	197 ± 28	269 ± 28	79 ± 33	this work

of sugars; however, it is known, at least in dilute aqueous solution, that the trigonal boronate esters (HLS) are very unstable, and only anionic boronate complexes (LS^-) are formed to a detectable extent.[14,21] Thus, in Scheme 1, the formation of HLS complex is negligible in water ($1 \gg K_{HLS}[S]$). In addition, because the fluorescence intensity of the **1**/β-CyD complex in the presence of fructose reaches the same level of fluorescence intensity as the sugar-free **1**/β-CyD complex at pH 10, we can assume that ϕ_L is mostly equal to ϕ_{LS}. Thus, eq 6 is more simply expressed as

$$I = \frac{\beta[L]_t\left(\phi_{HL} + \phi_L\frac{K_a}{[H^+]}(1 + K_{LS}[S])\right)}{1 + \frac{K_a}{[H^+]}(1 + K_{LS}[S])} \qquad (11)$$

Equation 11 clearly indicates that the binding constant (K_{LS}) can be determined by nonlinear curve fitting analysis of fluorescence intensity (I) as a function of sugar concentration ([S]) at the fixed pH condition. The determination of pK_a shift (ΔpK_a) is the alternative method to obtain the K_{LS} value upon the basis of eq 12.

$$\Delta pK_a = \log(1 + K_{LS}[S]) \qquad (12)$$

It should be noted that a Benesi-Hildebrand plot[22] is only applicable at a constant pH, with the reservation of $1 \ll K_{LS}[S]$. In this condition, the apparent experimental binding constant (K_{LS}^{app}) can be expressed as eq 13.

$$K_{LS}^{app} = K_{LS}\frac{K_a}{[H^+]} \qquad (13)$$

Binding of the monosaccharides L-arabinose, D-galactose, D-glucose, and D-fructose with the **1**/β-CyD complex was examined in water containing 2% DMSO. Figure 6 shows the fluorescence intensity changes of the **1**/β-CyD complex as a function of sugar concentration at pH 7.5. The observed results are fitted well with eq 11 (solid lines), and the 1:1 binding constants that are calculated from the nonlinear program are summarized in Table 1, together with the reported data of phenylboronic acid,[14] indolylboronic acid **4**,[3] and the tertiary-amine-supported fluorescent probe **5**.[6] As is seen from Table 1, the monosaccharides binding selectivity of the **1**/β-CyD complex is essentially the same as phenylboronic acid; thus, the binding constants decrease in

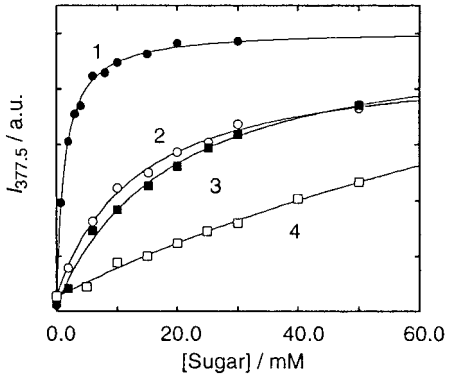

Figure 6. Effect of sugar concentration on the fluorescent response of the **1**/β-CyD complex: [**1**] = 1.05 μM in 2% DMSO/98% water (v/v) containing 5.0 mM β-CyD; excitation wavelength, 328.0 nm; excitation bandwidth, 5 nm; emission bandwidth, 3 nm; pH = 7.5, adjusted by 0.015 M phosphate buffer (I = 0.08 M with NaCl); (1) D-fructose; (2) L-arabinose; (3) D-galactose; and (4) D-glucose.

the order D-fructose ≫ L-arabinose > D-galactose > D-glucose. The binding constant of **1**/β-CyD complex for D-fructose calculated from the ΔpK_a value in eq 12 is 2554 M^{-1}, which coincides well with the K_{LS} value of 2515 M^{-1} in Table 1.

It should be noted that the Shinkai group produced efficient glucose sensors, as well as probes for chiral sugar recognition, by incorporating two boronic acid units as a sugar recognition site with a tertiary amine PET system.[5,23,24] In comparison, the advantages of the self-assembled **1**/β-CyD complex sensor shown here are (1) the high probe solubility in water, and (2) the high fluorescent quantum yield due to an inclusion complex formation. In addition, the combination of boronic acid probes with the CyD derivatives bearing various functional groups[25] may provide multipoint sugar recognition. The evolutional development of additional probe/CyD complex sensors is actively underway in our laboratory.

CONCLUSION

This study demonstrates that a boronic acid fluorophore **1**/β-CyD complex binds sugars and produces increased fluorescence emission in water. The fluorescence quantum yield is greatly enhanced by forming an inclusion complex of sugar−**1**/β-CyD. A pH-fluorescence profile for the **1**/β-CyD complex reveals that the fluorescence intensity increases upon formation of the bor-

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onate conjugate base (pK_a = 7.95). Upon the addition of 30 mM fructose, the apparent pK_a decreases to 6.06, which results in increased fluorescence at neutral pH. The fluorescence emission response of the **1**/β-CyD complex upon sugar binding appears to be due to suppression of the photoinduced electron transfer (PET) from a pyrene donor to a trigonal arylboronic acid acceptor. The 1:1 binding constants of the **1**/β-CyD complex decrease in the order: D-fructose (2515 ± 134 M^{-1}) ≫ L-arabinose (269 ± 28 M^{-1}) > D-galactose (197 ± 28 M^{-1}) > D-glucose (79 ± 33 M^{-1}), which is consistent with the known binding selectivity of phenylboronic acid.

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