



Near-Infrared Spectroscopic Investigation of Inclusion Complex Formation of Cyclodextrins in Room-Temperature Ionic Liquid

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Abstract

Near-infrared spectrometry has been successfully used to determine association binding constants between phenol and α -, β - and γ -cyclodextrin (CD) in [butylmethylimidazolium][chloride] room-temperature ionic liquid (RTIL). It was found that adding CD into the RTIL solution of phenol resulted in an enhancement in the absorption coefficient of the stretching overtone of the aromatic C–H groups. However, the enhancement induced by CDs in RTIL is much lower (order of magnitude) than those corresponding in D₂O. The binding constants in RTIL are also much lower than those in D₂O ($(11 \pm 2) \text{ M}^{-1}$, $(16 \pm 2) \text{ M}^{-1}$ and $(40 \pm 6) \text{ M}^{-1}$ for phenol and α -, β - and γ -CD, respectively, compared to 87 M^{-1} and 214 M^{-1} for α - and β -CD in D₂O). The results obtained seem to suggest that in ionic liquid, the main interaction between phenol and CDs may not be inclusion complex formation but rather external adsorption. A variety of reasons may be responsible for relatively weaker interactions and lower binding constants in ionic liquid including differences in the polarity and viscosity of RTIL and D₂O. However, the main reason may be due to the fact that the cation of the ionic liquid (i.e., butylmethylimidazolium ion) may form inclusion complexes with the cyclodextrin, thereby preventing phenol from being included in cavity of CDs.

Introduction

Room-temperature ionic liquids (RTIL) are a group of organic salts that are liquid at room temperature [1, 2]. They have unique chemical and physical properties including air and moisture stability, high solubility power and virtually no vapor pressure. Because of these properties, they can serve as a “green” recyclable alternative to the volatile organic compounds which are traditionally used as industrial solvents [1–2]. In fact, RTIL have successfully been used in many applications including replacing traditional organic solvents in (1) organic and inorganic syntheses [3–5]; (2) in solvent extractions with crown ethers [5]; (3) in liquid–liquid extractions with supercritical fluid CO₂ [6, 7]; (4) in electrochemical reactions [8, 9]; (5) as medium for enzymatic reactions [10]. Of particular interest are applications of RTIL in analytical chemistry. Specifically, RLIL has been successfully used as matrixes for MALDI-MS [11], as buffer for capillary electrophoresis [12, 13] and as stationary phases (SP) in gas chromatography (GC) [14, 15]. The last application is significant as it is based on the synergistic exploitation of many advantages of the RTIL, namely, its low vapor pressure and extremely high boiling point and its high viscosity and high solubility power. Interestingly, because of its high solubility power, a variety of additive compounds including cyclodextrins and their derivatives can be dissolved into the RTIL-SP to provide additional selectivity and resolution for separations which otherwise are not possible [14,

15]. Successful separations induced by added CDs suggests that there may be interactions between CD and analytes in the RTIL-SP. Unfortunately, due to lack of method which has the required sensitivity and is suitable for this type of study, to date the exact nature of the interactions (e.g., inclusion complex formation or electrostatic interactions) is still unknown. Near-infrared (NIR) spectrometry can offer a solution for this problem.

NIR spectrometry has been used extensively in recent years for chemical analysis and characterization [16]. The popularity stems from the advantages of the technique, namely its wide applicability, noninvasive, nondestructive and real-time and on-line capabilities. NIR region covers the overtone and combination transitions of the C–H, O–H and N–H groups, and since all organic and most inorganic compounds possess at least one or more of these groups, the technique can, in principle, be used for analysis of all organic and most inorganic compounds. It is, therefore, reasonable to expect that CDs and RTIL will have strong absorption bands in the NIR region, and as a consequence, their interactions can be spectroscopically investigated using the NIR technique. Additionally, because it has real-time and on-line capabilities which satisfy one of twelve principles of Green Chemistry [17], the NIR technique is suited as “a Green Method” for the study of “the Green Solvent” RTIL. Unfortunately, in spite of its potentials, NIR technique has not been widely used to study interactions of CDs in RTIL and/or in other solvents. The limitation is probably due to the extensive overlap among NIR spectra of different

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compounds (as almost all of them absorb NIR light). High quality NIR spectra are, therefore, required for subsequent analysis including background subtraction, deconvolution and treatment by chemometric methods such as multivariate methods and partial least square methods [20]. A NIR spectrometer which has high sensitivity, high light throughput, high stability and no drift is therefore, required. Such a spectrometer was successfully constructed in our laboratory using the acousto-optic tunable filter (AOTF) [18–20].

The information presented is indeed provocative and clearly demonstrates that it is possible to use the AOTF based NIR spectrometer to study the interactions between CDs and different analytes in RTIL. Such consideration prompted us to initiate this study which aims to use the NIR technique to determine association constants between different CDs (i.e., α -, β - and γ -CD) and aromatic substrates in RTIL as well as in D₂O. Results obtained will help to gain insight into the interactions between CDs and different substrate in RTIL, in general, and in RTIL-SP, in particular.

Experimental

RTIL 1-butyl-3-methylimidazolium chloride ([BuMIm][Cl]) was synthesized according to procedures previously reported [3, 4]. Specifically, it was prepared by mixing equal molar of freshly vacuum-distilled 1-methylimidazole and freshly vacuum-distilled n-butyl chloride in a round-bottomed flask equipped with a reflux condenser and dried tube, and reacting them for 72 hrs at 90 °C. The resulting viscous liquid was allowed to cool to room temperature and then washed three times with dried ethyl acetate (3 × 100 mL). The ethyl acetate layer was decanted. Any ethyl acetate remaining in the ionic liquid was removed by evacuating the ionic liquid under vacuum at 70 °C overnight. The final ionic liquid was kept either under nitrogen or vacuum to protect it from moisture.

α -, β - and γ -cyclodextrins were a gift of Cerestar USA, Inc.. NIR spectra were taken on the home-built NIR spectrometer based on an acousto-optic tunable filter. Information on this NIR spectrometer was described in details in our previous papers [7, 8]. Normally, each spectrum was an average of 30 spectra taken at 1-nm interval from 1450 nm to 2450 nm.

Results and discussion

NIR spectrum of RTIL ([BuMIm][Cl]) is shown in Figure 1A. The ionic liquid exhibits several bands at 1638, 1719, 2150 and a cluster of bands at >2200 nm. The 1719 nm bands and the cluster of bands at >2200 nm (not shown) can be attributed to the overtones and combinations of the aliphatic C–H groups. Overtones and combination transitions of the aromatic C–H groups may be responsible for bands at 1638 nm and 2150 nm (not shown). Bands at wavelengths longer than 2100 nm were not used in this study as they have rather high absorption coefficients.

Table 1. Molar absorptivities of stretching overtone ($\Delta v = 2$) of C–H groups of phenol at 1680 m

Compound/media	ϵ ($M^{-1} \text{ cm}^{-1}$)
Phenol/D ₂ O	0.159 ^a
Phenol/ α -CD/D ₂ O	1.219 (135% increase) ^a
Phenol/ β -CD/D ₂ O	1.940 (244% increase) ^a
Phenol/ionic liquid	0.665
Phenol/ α -CD/ionic liquid	0.854 (28% increase)
Phenol/ β -CD/ionic liquid	0.884 (33% increase)
Phenol/ γ -CD/ionic liquid	0.897 (35% increase)

^a Values taken from Ref. 18.

The RTIL ([BuMIm][Cl]) can dissolve a large amounts of α -, β - and γ -CD, and a variety of aromatic compounds including benzene, phenol, chlorophenol. This conclusion was made based on the NIR spectra of the RTIL alone (1A), with γ -CD (1B) and with phenol (1C). Figure 1B shows absorption spectra of γ -CD at different concentrations (from 0.10 M to 0.20 M) (with background absorption of RTIL subtracted). As illustrated, γ -CD exhibits a pronounced band at about 1970 nm which can be attributed to the overtones and combination transitions of the O–H groups. Transitions of the aliphatic C–H groups can also be seen at bands at around 1638 and 1850 nm but they have rather low absorption coefficients compared to that of the O–H group. Furthermore, overlap between these bands and those of the ionic liquid makes it difficult to use them for this study.

Absorption spectra of phenol in RTIL at different concentrations, with contribution of the RTIL subtracted, are shown in Figure 1C. Similar to the O–H group of the γ -CD, the O–H group of phenol also exhibits a large band at about 1950 nm. Additionally, there are several other bands with maxima at about 1680 and 1730 nm which can be attributed to transitions of the aromatic C–H groups. The C–H bands may be particularly useful for the determination of inclusion complexes of CDs. This is because we have shown, in our earlier study using NIR spectrometry to investigate the inclusion complex formation between phenol, its derivatives and CD in D₂O [18] that upon forming complexes, the oscillator strengths of the C–H stretching overtones ($\Delta v = 2$ at ~ 1650 nm) of the aromatic guest compounds were increased by several hundred percents. For instance, as summarized in Table 1, adding α -CD into phenol solution increases the molar absorptivity of the latter by 135% (from $0.519 \text{ M}^{-1} \text{ cm}^{-1}$ to $1.219 \text{ M}^{-1} \text{ cm}^{-1}$) whereas adding β -CD increase it by 244%. The observed increases are rationalized in terms of the enhancement in the anharmonicity and the libration motions of the guest molecule in the CD cavity [18]. The changes in the absorption of this aromatic C–H band upon inclusion complex formation were exploited for the determination of association constants between phenol and α -CD or β -CD. They were found to be 87 M^{-1} and 214 M^{-1} for, respectively [18]. The results obtained seem to suggest that the stronger are the inclusion complexes, the larger is the enhancement in the oscillator strength of the C–H groups of the aromatic guest compound.

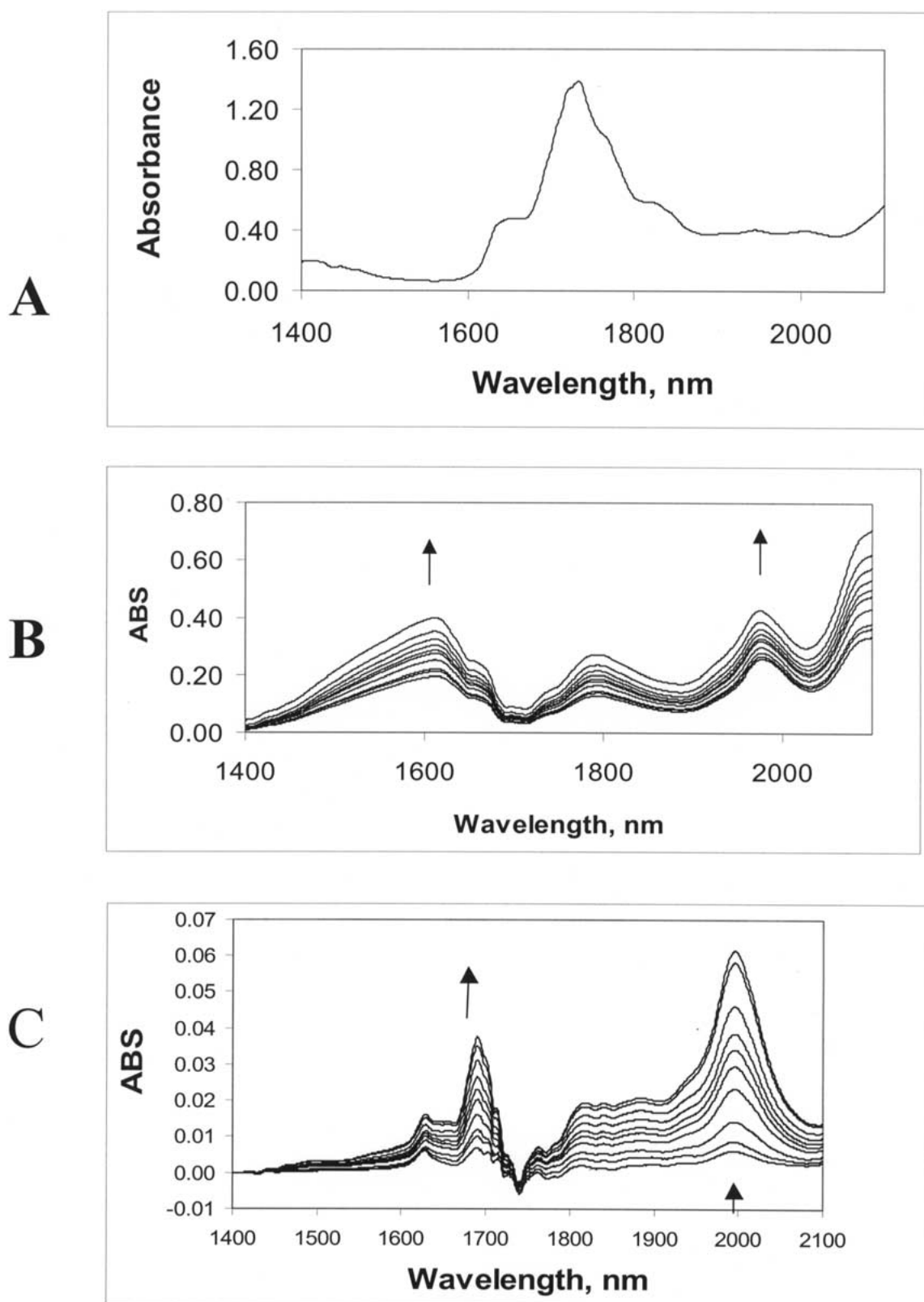


Figure 1. (A) NIR spectrum of Butylmethylimidazolium Chloride RTIL in 0.5-cm pathlength cell; (B) NIR spectra of different concentrations of γ -CD in [BuMIm][Cl] in 0.5-cm pathlength cell (background absorption of [BuMIm][Cl] was removed). Concentrations of γ -CD (from bottom to top): 0.1037, 0.1120, 0.1217, 0.1333, 0.1474, 0.1556, 0.1647, 0.1750, 0.1867 and 0.2000 M and (C) NIR spectra of different concentrations of phenol in [BuMIm][Cl] in 0.5-cm pathlength cell (background absorption of [BuMIm][Cl] was removed). Concentrations of phenol (from bottom to top): 0.0121, 0.0239, 0.0356, 0.0470, 0.0581, 0.0691, 0.0799, 0.0904, 0.1008 and 0.1110 M.

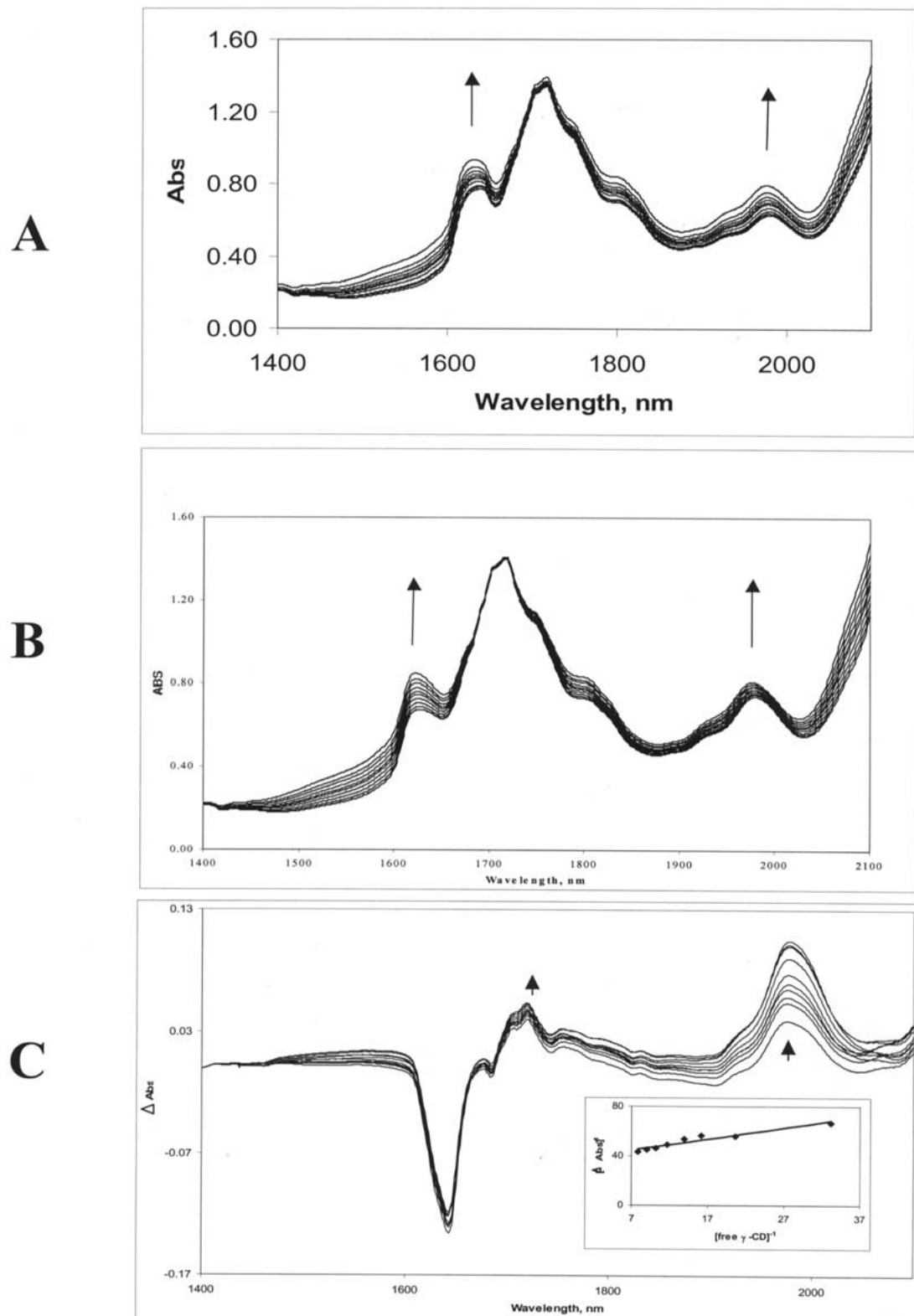


Figure 2. (A) NIR spectra of RTIL solutions containing 0.075 M of phenol and different concentrations of γ -CD in a 0.5-cm pathlength cell. Concentrations of γ -CD (from bottom to top): 0.1037, 0.1120, 0.1217, 0.1333, 0.1474, 0.1556, 0.1647, 0.1750, 0.1867 and 0.2000 M; (B) NIR spectra of different concentrations of γ -CD in RTIL in 0.5-cm pathlength cell. Concentrations of γ -CD (from bottom to top): 0.1037, 0.1120, 0.1217, 0.1333, 0.1474, 0.1556, 0.1647, 0.1750, 0.1867 and 0.2000 M and (C) Corrected spectra obtained by subtracting Spectra 2B from Spectra 2A to remove contributions of RTIL and γ -CD. Insert: Double reciprocal plot. See text for detailed information.

Similar to the case in D₂O, it was found that in RTIL, the oscillator strength of the C–H groups of phenol was also increased in the present of α -, β - or γ -CD. However, the magnitudes of the enhancement are much smaller than those in D₂O: adding α -, β - or γ -CD to the RTIL solution of phenol increase \tilde{N} values of the aromatic C–H group by only 28%, 33% and 35%, respectively. Because these enhancements are order of magnitude lower than those in D₂O, it is possible that the interactions between phenol and CDs in RTIL are much weaker and maybe of different type than those in D₂O.

Subsequently, association constants between phenol and CDs were determined by use of changes in absorption coefficients of the aromatic C–H groups. The measurements were performed by initially recording spectra of a set of RTIL solutions containing 0.075 M of phenol and different concentrations of γ -CD (or α -CD or β -CD with concentrations ranging from 0.104 M to 0.20 M) (Set 1) (Figure 2A). Spectra of a second set of solutions containing the same γ -CD (or α -CD or β -CD) concentrations but without phenol were also taken (Figure 2B). It is important to point out that spectra in this figure is different from those in Figure 1B. The difference is due to the fact that in Figure 1B the background contribution of the RTIL was subtracted whereas all spectra in Figure 2B include background absorption of the RTIL. Subtraction of spectra from the second set from those of the first set facilitates removal of contribution of RTIL and γ -CD from phenol spectra. The resulted spectra (Figure 2C) reflect absorbance change (Δ Abs) as a function of added host concentration and of the dilution effect by the host. Association constants (K_S) were then calculated by linearization of changes in ΔA versus CD concentration using the Benesi-Hilderbrand double reciprocal plot. A typical plot of $1/\Delta A$ versus $1/[\text{CD}]_{\text{free}}$ is shown in the insert of Figure 2C. Initially, $[\text{CD}]_{\text{free}}$ was approximated by assuming that there were no free phenol in any solutions. Subsequently, $[\text{CD}]_{\text{free}}$ was recalculated using changes in molar absorptivity ($\Delta\epsilon$) value obtained from the intercept of the double reciprocal plot. After several reruns and convergence of $\Delta\epsilon$ and K_S values, the most probable K_S values were selected and listed in Table 2 for α -, β -, and γ -CD. For reference, association constants between phenol and α - and β -CD in D₂O, reported in our previous work [18] were also listed. Association binding constants for phenol with α -, β - and γ -CD were found to be $(11 \pm 2) \text{ M}^{-1}$, $(16 \pm 2) \text{ M}^{-1}$ and $(40 \pm 6) \text{ M}^{-1}$, respectively. These values are much lower than corresponding values of 87 and 214 for α - and β -CD in D₂O. The interactions between phenol and CDs are, therefore, much weaker in ionic liquid than in D₂O. The combination of lower enhancement in the absorption coefficients of the aromatic C–H groups of phenol and the weaker binding seems to suggest that the interaction between phenol and CDs in ionic liquid may be of different nature than that in D₂O. The main interaction between phenol and CD may not be inclusion complex formation but rather external adsorption. It is possible that the cation of the ionic liquid (i.e., butylmethylimidazolium ion) forms inclusion complexes with the cyclodextrin, thereby preventing phenol from being included

Table 2. Binding constants (in M^{-1}) of phenol with α - and β - and γ -CD in D₂O and in ionic liquid

Media	α -CD	β -CD	γ -CD
D ₂ O	87	214	
Ionic liquid	11 ± 2	16 ± 2	40 ± 6

in cavity of CDs. In fact, it has been reported that imidazole can form inclusion complexes with cyclodextrins [15, 21].

In summary, it has been demonstrated that NIR spectrometry can be successfully used to determine association binding constants between phenol and α -, β - and γ -CD in [BuMIm][Cl] ionic liquid. It was found that adding CD into the ionic liquid solution of phenol resulted in an enhancement in the absorption coefficient of the stretching overtone of the aromatic C–H groups. However, the enhancement induced by CDs in ionic liquid is much lower (order of magnitude) than those corresponding in D₂O. The binding constants in ionic liquid are also much lower than those in D₂O (11 ± 2 , 16 ± 2 and 40 ± 6 for phenol and α -, β - and γ -CD, respectively, compared to 87 and 214 for α - and β -CD in D₂O). Taken together, the results seem to suggest that in ionic liquid, the main interaction between phenol and CDs may not be inclusion complex formation but rather external adsorption. A variety of reasons may be responsible for relatively weaker interactions and lower binding constants in ionic liquid including differences in the polarity and viscosity of RTIL and D₂O. However, the main reason may be due to the fact that the cation of the ionic liquid (i.e., butylmethylimidazolium ion) may form inclusion complexes with the cyclodextrin, thereby preventing phenol from being included in cavity of CDs. We are currently investigating these possibility by changing the anion of the ionic liquids from chloride to BF_4^- , PF_6^- and Tf_2N^- as it is known that polarity and viscosity of the RTIL are readily changed by their anion [1, 2]. Interactions between [BuMIm] cation with CDs are also a subject of our intense investigation.

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