

Cite this: *Chem. Commun.*, 2018, 54, 13264Received 1st August 2018,  
Accepted 2nd November 2018

DOI: 10.1039/c8cc06262e

rsc.li/chemcomm

## A naphthoimidazolium-cholesterol derivative as a ratiometric fluorescence based chemosensor for the chiral recognition of carboxylates†

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Fluorescent chemosensors for sensing chiral molecules have been actively studied in recent years. In the current study, we report a naphthoimidazolium-cholesterol derivative (**NI-chol 1**) as a fluorescence based chemosensor for chiral recognition, in which the naphthoimidazolium serves not only as a fluorophore but also as a recognition moiety for anions via imidazolium (C–H)<sup>+</sup>–anion binding and the cholesterol unit acts as a chiral barrier. In particular, **NI-chol 1** displayed unique and distinct ratiometric changes with Boc-D-Phe, on the other hand, Boc-L-Phe induced a negligible change. Furthermore, a distinct downfield shift (from 9.64 ppm to 9.96 ppm) of the imidazolium C–H peak was observed for Boc-D-Phe (5 eq.) with severe broadening, which indicates strong ionic hydrogen bonding between the C–H proton and the carboxylate.

Since amino acids, the basic fundamental unit for peptides and proteins, are chiral, important processes in biology involve chiral interactions. Chiral fluorescence based chemosensors can convert enantioselective recognition into fluorescence changes,<sup>1,2</sup> which results in simple and easy detection methods for chiral recognition compared to conventional methods, such as high-performance liquid chromatography (HPLC), capillary electrophoresis (CE), gas chromatography (GC) or NMR. Accordingly, fluorescence-based recognition for chiral anions

has been extensively studied. Host–guest chemistry and molecular recognition have greatly affected the development of chiral fluorescence based chemosensors.<sup>3</sup> The main requirement for the fluorescence based approaches to evaluate enantiomeric compositions is chiral sensors with the ability to differentially interact with opposite enantiomers of a chiral target in a manner that gives rise to different optical signal outputs.

On the other hand, imidazolium based fluorescent chemosensors have been actively studied since they can show strong ionic hydrogen bonding interactions such as imidazolium (C–H)<sup>+</sup>–anions.<sup>4</sup> Over the last decade, fluorescence based imidazolium derivatives have found application in the area of sensing simple anions,<sup>5</sup> nucleotides,<sup>6</sup> IP<sub>3</sub> and IP<sub>6</sub>,<sup>7</sup> RNA or DNA,<sup>8</sup> anionic surfactants,<sup>9</sup> bacteria<sup>10</sup> and CO<sub>2</sub> gas,<sup>11</sup> *etc.*<sup>12</sup> Our group has actively investigated imidazolium based fluorescent chemosensors for various targets.<sup>8</sup> However, there are a paucity of papers for chiral recognition using fluorescence changes using imidazolium groups.<sup>13,14</sup> Yu and coworkers introduced an imidazolium moiety into BINOL (1,1'-bi-2-naphthol), which displayed red shifts with fluoride and acetate in acetonitrile and large fluorescence quenching effects with *t*-Boc Ala anions producing a *K<sub>L</sub>/K<sub>D</sub>* value of 4.5 in acetonitrile.<sup>13a</sup>

Compared to binaphthyl based chemosensors, there are relatively few examples in which the cholesterol moiety has been used as a chiral barrier.<sup>14</sup> In the current study, we report the example of a naphthoimidazolium-cholesterol derivative as a chiral fluorescence based chemosensor. Naphthoimidazoliums are inherently fluorescent, so an extra fluorophore is not required as in the case with imidazolium based fluorescence based chemosensors. **NI-chol 1** displayed a unique ratiometric change with Boc-D-Phe, while Boc-L-Phe induced very little change compared to that of the D-isomer. Similar but less distinct changes were also observed for Boc-D-Val over Boc-L-Val. In addition, a distinct downfield shift (from 9.64 ppm to 9.96 ppm) of the imidazolium C–H peak of **NI-chol 1** was observed for Boc-D-Phe (5 eq.) with severe broadening, which can be attributed to the strong ionic hydrogen bonding interaction between the C–H proton and the carboxylate.

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† Electronic supplementary information (ESI) available: Experimental details,

<sup>1</sup>H NMR spectra of compound **1**. See DOI: 10.1039/c8cc06262e

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Fig. 4 Fluorescence based titrations of **NI-chol 1** (10  $\mu$ M) in  $\text{CH}_3\text{CN}$ -DMSO (95 : 5, v/v) with various equivalents of Boc-L-Phe.

However, the addition of Boc-L-Phe induced only a small change as illustrated in Fig. 4. The association constant ( $K_{\text{f}}$ ) for Boc-L-Phe was  $1.5 \times 10^2 \text{ M}^{-1}$ . Thus, the enantioselectivity could be obtained via  $K_{\text{D}}/K_{\text{L}}$  as ca. 14, which is higher than those for most of the reported imidazolium-based chiral sensors. In addition, the fluorescence titrations with  $\text{D-Val}$  are illustrated in the ESI $^\dagger$  (Fig. S11 and S12). Even though the changes were smaller than those with Boc-D-Phe, similar ratiometric changes were observed at 370 nm and 452 nm.

To understand the interaction of **NI-chol 1** with Boc-D-Phe,  $^1\text{H}$  NMR titrations were performed in  $\text{CD}_3\text{CN}$ -DMSO- $d_6$  (95 : 5, v/v) (Fig. 5 and Fig. S13, ESI $^\dagger$ ). When 1.0 eq. of Boc-D-Phe was added to the solution of **NI-chol 1**, the imidazolium C-H peak at 9.64 ppm downfield shifted to 9.96 ppm, which indicates a hydrogen bonding interaction between the C-H proton and the carboxylate.

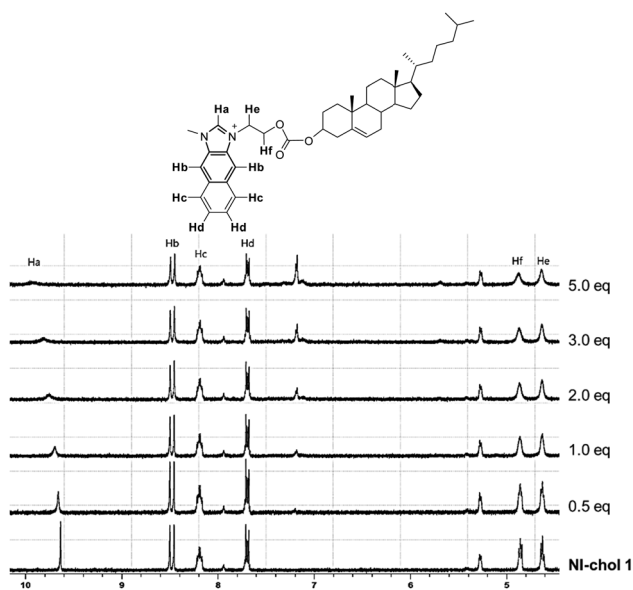


Fig. 5 Partial  $^1\text{H}$  NMR spectra (300 MHz) of **NI-chol 1** (5 mM) upon the addition of Boc-D-Phe (tetrabutylammonium salt) in  $\text{CD}_3\text{CN}$ -DMSO- $d_6$  (95 : 5, v/v).

Furthermore, severe broadening of this peak was observed, which also supports the presence of strong ionic hydrogen bonding. With  $>5.0$  eq. of Boc-D-Phe, the peak of imidazole C-H of **NI-chol 1** disappeared due to partial deprotonation. However, a smaller shift to 9.87 ppm was observed upon the addition of Boc-L-Phe (5 eq.) and the sharp singlet of Ha was preserved (Fig. S13, ESI $^\dagger$ ). In addition, there were slight downfield shifts for ethylene linkers between the naphthoimidazolium and the cholesteryl moiety. Since there are no significant changes in the  $^1\text{H}$  NMR spectra for other peaks, it is not easy to predict the exact binding mode. Hydrogen bonding interactions between carboxylates and imidazolium C-H protons could be clearly deduced based on NMR data and the cholesteryl unit successfully served as a chiral barrier based on the selectivity for  $\text{D-}$ isomers of Phe and Val.

Furthermore, DFT calculations were used to understand the enantioselectivity of **NI-chol 1** for Boc-D-Phe and the ratiometric fluorescence change. First, the optimized structures of **NI-chol 1** with Boc-D-Phe or Boc-L-Phe were obtained as shown in Fig. 6. In the optimized structures, the oxygen atom in the carboxyl group of Phe is found to form a hydrogen-bond to  $\text{H}_a$ . This result agrees well with the NMR spectra in which the  $\text{H}_a$  proton is significantly influenced when **NI-chol 1** binds to Boc-D-Phe in Fig. 5. As shown in Fig. 6 and movie clips (ESI $^\dagger$ ), both phenyl and Boc groups of Boc-D-Phe interact with the cholesterol moiety of **NI-chol 1**. However, only the phenyl group of Boc-L-Phe interacts with the cholesterol moiety of **NI-chol 1**. The energy of **NI-chol 1** with Boc-D-Phe (Fig. 6(b)) is found to be  $98.2 \text{ kcal mol}^{-1}$  lower than that of **NI-chol 1** with Boc-L-Phe (Fig. 6(d)). This DFT calculation result indicates that the

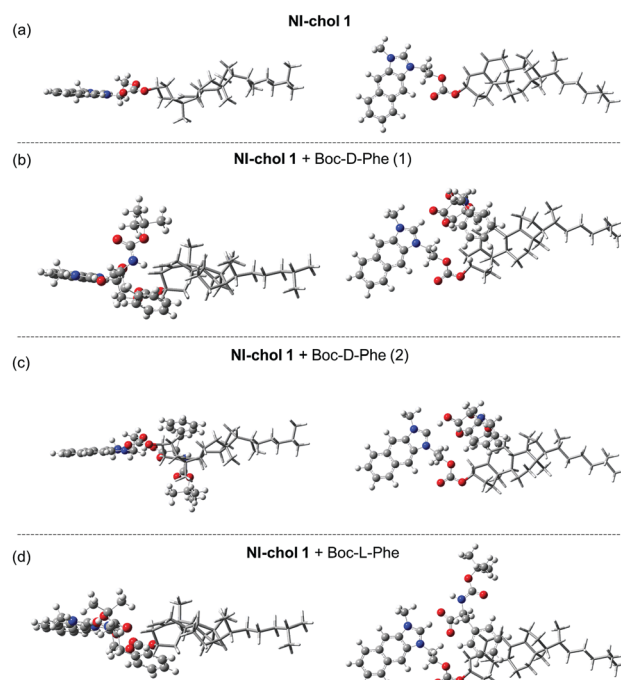


Fig. 6 The optimized structures of **NI-chol 1** (a) and **NI-chol 1** with Boc-D-Phe (b and c) or Boc-L-Phe (d). In (c), the  $\text{H}_a$  proton of the NI unit is significantly transferred to the carbonyl group of Boc-D-Phe. The cholesterol moiety of **NI-chol 1** is displayed in tube form for clarity.



interaction between Boc-D-Phe and **NI-cho1** is much stronger than the interaction between Boc-L-Phe and **NI-cho1**. Such a significant difference in the binding energy between **NI-cho1** and Boc-D-Phe or Boc-L-Phe is responsible for the enantioselectivity of **NI-cho1** for Boc-D-Phe.

Fig. 6(b and c) display the two optimized structures of **NI-cho1** with Boc-D-Phe and their calculated absorption spectra are shown in Fig. S14 (ESI<sup>†</sup>). Note that the H<sub>a</sub> proton of the NI unit is transferred to the carboxyl group of Boc-D-Phe, shown in Fig. 6(c). This result indicates that the absorption spectrum of NI is blue-shifted when the H<sub>a</sub> proton moves significantly away from the NI unit. Similar results are expected from the emission spectra of NI units. To confirm this, the emission spectra of protonated and deprotonated NI units were calculated in Fig. S15(a) (ESI<sup>†</sup>). The calculated emission spectra of NI units agree well with the fluorescence spectra of **NI-cho1** with and without Boc-D-Phe as shown in Fig. S15 (ESI<sup>†</sup>). This result indicates that after Boc-D-Phe binds to **NI-cho1**, the NI unit is deprotonated by the carbonyl group of Boc-D-Phe and as a result, its fluorescence spectrum is blue-shifted.

In summary, we have developed a new naphthoimidazolium-cholesteryl derivative **NI-cho1** for chiral anion recognition. The naphthoimidazolium moiety serves not only as a hydrogen bonding donor but also as a fluorescence unit. On the other hand, the cholesteryl moiety acts as a chiral barrier to induce enantiomer selectivity. Chiral fluorescence based receptor **1** displayed a unique ratiometric change in its emission with Boc-D-Phe. When Boc-D-Phe is added, the blue shifted emission at 370 nm increases with a concurrent decrease of the original emission at 452 nm, which results in a clear ratiometric fluorescence change. On the other hand, Boc-L-Phe did not induce any significant change. D-Val also induces similar but smaller ratiometric changes. The ionic hydrogen bonding interactions between the imidazolium C-H proton and carboxylate anions were confirmed by NMR analysis. Finally, the DFT calculations explain (1) the enantioselectivity of **NI-cho1** for Boc-D-Phe, (2) emission spectra of **NI-cho1** with and without Boc-D-Phe, and (3) the mechanism for ratiometric fluorescence detection of Boc-D-Phe by **NI-cho1**.

This work was supported by the National Research Foundation of Korea (NRF), which is funded by the Korea government (MSIP) (No. 2012R1A3A2048814 for J. Y.; No. 2017R1A6A3A04004954 for S. L.; No. 2016R1A2B4011522 for S. P.). X. Z. thanks the National Natural Science Foundation of China (21502040) and the Youth Top-notch Talent Foundation of the Education Department of Hebei Province (No. BJ2014039) for support. TDJ thanks the Royal Society for a Wolfson Research Merit Award. The mass spectral data were obtained at Korea Basic Science Institute (Seoul) using MS Q-TOF/G6550A (Agilent).

## Conflicts of interest

There are no conflicts to declare.

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