Tetrahedron: *Asymmetry* 27 (2016) 492–497

Contents lists available at ScienceDirect

Tetrahedron: *Asymmetry*

journal homepage: www.elsevier.com/locate/tetasy

A chiral (*S*)-BINOL based fluorescent sensor for the recognition of Fe(III) and cascade discrimination of α-amino acids

Sathishkumar Munusamy, Sathiyanarayanan Kulathu Iyer *

Chemistry Division, School of Advanced Sciences, Vellore Institute of Technology, Vellore 632014, Tamil Nadu, India

ARTICLE INFO

Article history:
Received 6 April 2016
Accepted 3 May 2016
Available online 14 May 2016

ABSTRACT

Minor groove thiosemicarbazone functionalized (*S*)-BINOL **1** has been synthesized starting from (*S*)-BINOL; these new thiosemicarbazone functionalized (*S*)-BINOL molecules introduce new opportunities in the field of chiral recognition and Fe(III) sensing. The developed sensor can serve as a turn off sensor for Fe(III) with high selectivity among metal ions tested. The in situ generated Fe(III) complex of **1** exhibit remarkable fluorescent chiral discrimination toward unmodified α-amino acids via a ligand displacement mechanism.

1. Introduction

Enantioselective recognition is one of the most important fundamental processes in the biological field. It plays an important role in many areas, such as asymmetric synthesis, chiral drug separation and in understanding the chiral origin of life. Thus, a simple, high-throughput method for enantiomeric excess measurements would be useful in a number of applications, such as the synthesis of most natural products and drug development.[1] While there are successful traditional methods, such as chiral HPLC, gas chromatography and NMR chiral shift reagents, optical methods, such as fluorescence chiral discrimination methods for chiral discrimination,[2] have gained much importance due to their operational simplicity and utility in high-throughput screening. Amino acids are fundamental molecules of life and are associated in many bimolecular processes. Hence, studies on the enantioselective recognition of amino acids and their derivatives are highly desirable.[3]

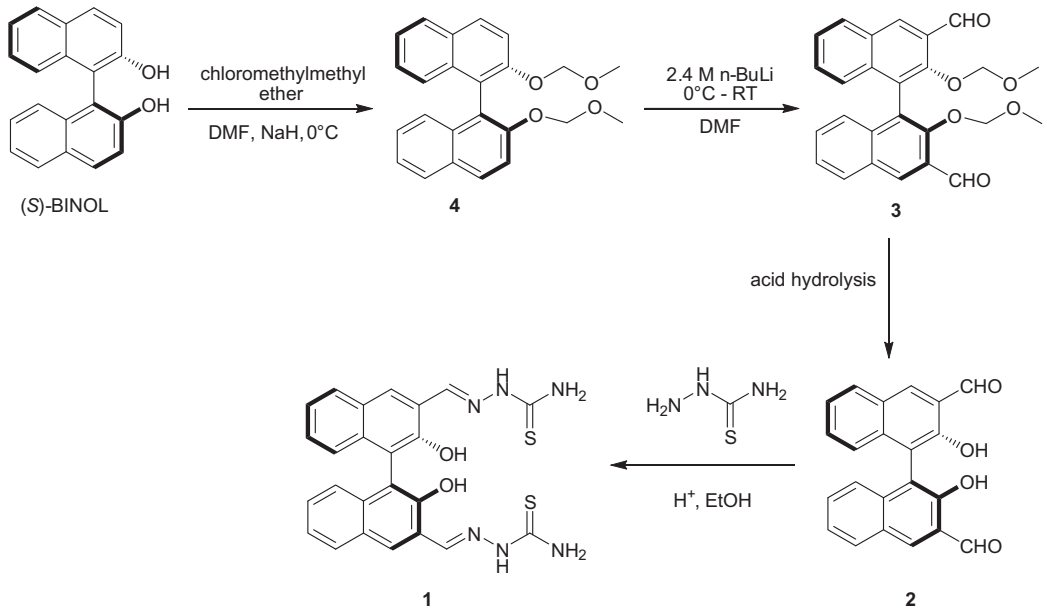
The crucial role of iron in biological functions is well known. The facile, redox chemistry and its high affinity for oxygen make it an important partner in oxygen metabolism and in electron transfer processes in DNA and RNA. Although it plays a significant role in many biological functions, when present in excess, it can have a detrimental effect to the biological system.[4] Although iron is strongly bonded to the enzymes and proteins present in the biological system, a minor fraction of iron, known as labile iron, is loosely bonded to the organic anions, such as phosphates and carboxylates, polyfunctional ligands such as chelates, surface components of membranes (phospholipid head groups). This labile iron, when exposed to molecular oxygen, enters the redox cycle between Fe^{2+} and Fe^{3+} which would in turn assist the formation of an hydroxyl radical via a Fenton reaction. Since radical species are highly reactive, they are prone to react with sugars, lipids, proteins and nucleic acids, which would lead to tissue damage. Severe complications such as β-thalassemia are treated by iron chelation therapy, since the human biological system does not have natural means to control iron overload. Considering the crucial role of iron in biological functions, great importance is attached to rapid and simple analytical method development.[5] The intrinsic paramagnetic properties of Fe^{3+} make it an effective quencher of fluorescence of fluorescent metal chelators. Subsequent effective snatching of Fe^{3+} by Fe^{3+} binding analytes (amino acids, etc.) can turn on the fluorescence lost by chelators. Herein we have designed and synthesized a BINOL-thiosemicarbazide (minor groove) based fluorescent sensor, which could serve as a fluorescent turn off sensor for Fe(III). The in situ generated Fe(III) **1** containing complex was successfully studied for the fluorescent enantioselective recognition of unmodified amino acids.

2. Results and discussion

The synthesis of chiral ligand **1** is outlined in Scheme 1. Compound **2** was synthesized according to the literature procedure.[6] As shown in Scheme 1, BINOL-thiosemicarbazone ligand **1** was synthesized in 4 steps with 55% overall yield from (*S*)-BINOL. The UV–Vis spectra of **1** (2×10^{-5} M) were recorded in THF solution. There were two absorption peaks at 344 nm and 290 nm. In order to check the absorption change of **1** over the addition of metal ions including alkali earth, p-block and transition metal, UV–vis was

* Corresponding author.
E-mail address: sathiya_kuna@hotmail.com (S. Kulathu Iyer).

http://dx.doi.org/10.1016/j.tetasy.2016.05.002
0957-4166/



Scheme 1. Synthesis procedure of the sensor **1**.

recorded with various metal ions. There was no change in the UV–vis spectra of **1** over the addition of metal ions such as Ba^{2+}, Bi^{2+}, Cd^{2+}, Co^{2+}, Fe^{2+}, Hg^{+}, Ni^{2+}, Pd^{2+}, Sr^{2+}, Cu^{2+}, Mn^{2+} and Zn^{2+}. However, there was a significant change in the absorption spectra of **1** over the addition of Fe^{3+}, i.e., the peak at 344 nm completely disappeared and the intensity of the peak at 290 nm increased (Supporting information). An isobestic point appeared at 324 nm. In order to check the linear change in the absorption of **1** with Fe(III), the absorption was monitored over a constant increment of Fe(III). As expected, a linear change in the absorption of **1** occurred with a constant increment Fe^{3+} concentration (Supporting information). The UV–Vis spectra were recorded with concentrations ranging from 0 to 3×10^{-5} mol/L in order to check the formation of ground state intermolecular aggregates. Suitable concentrations for fluorescence studies should not be greater than 2×10^{-5} mol/L in order to avoid the violation of Lambert–Beer's Law.

Inspired by the UV–Vis results of **1** with various metal ions and its selectivity towards Fe(III), we next investigated the fluorescence change of ligand **1** (1×10^{-5} mol/L in THF) towards Fe^{3+}. The fluorescence spectrum of ligand **1** showed an emission at 394 nm, which can be attributed to ESIPT.[7] A gradual decrease in fluorescent intensities was observed with the addition of Fe^{3+} from 0.1 to 1 equivalent (Fig. 1a). The fluorescence intensity of sensor **1** with Fe^{3+} revealed that there was a good linear response to Fe^{3+} (Fig. 1b).

The emission intensity decrease of **1** can be attributed to the suppression of the excited state intramolecular proton transfer (ESIPT) of ligand **1** over the addition of Fe^{3+}. The selectivity of fluorescence response change of **1** was investigated towards Ba^{2+}, Bi^{2+}, Cd^{2+}, $Co2^{+}$, Fe^{2+}, Hg^{+}, Ni^{2+}, Pd^{2+}, Sr^{2+}, Cu^{2+}, Mn^{2+} and Zn^{2+} under the same experimental conditions. Fortunately, as shown in the Figure 2, almost no or only a moderate fluorescence change was observed with the addition of Ba^{2+}, Bi^{2+}, Cd^{2+}, Co^{2+}, Fe^{2+}, Hg^{+},

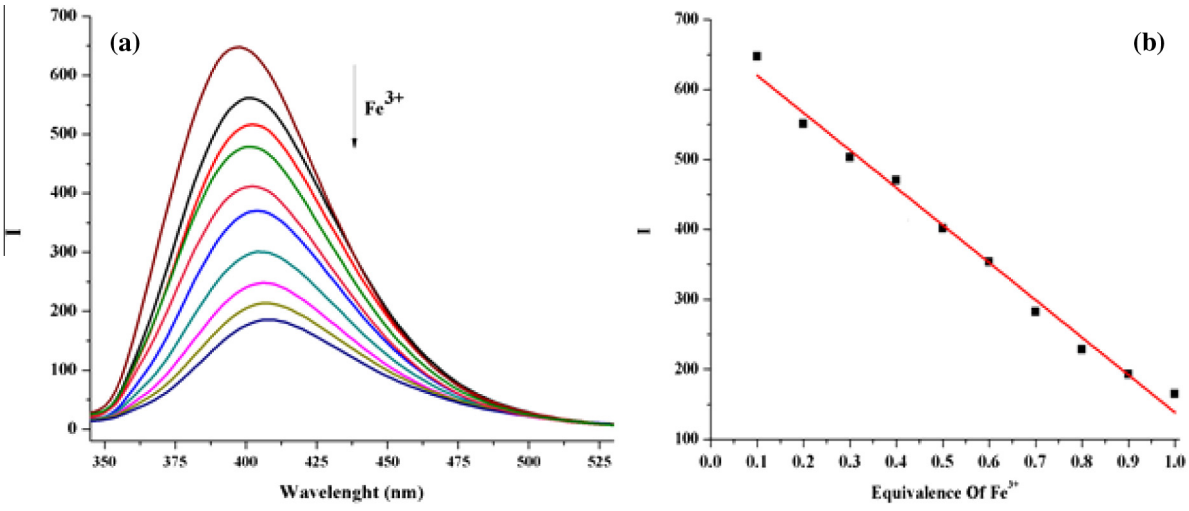


Figure 1. (a) Fluorescence spectra of **1** (1×10^{-5} M) with an increasing concentration of Fe(III) from 0.1 to 1 equivalents (excitation wavelength = 324 nm). (b) Fluorescence decrease of **1** vs concentration of Fe(III).

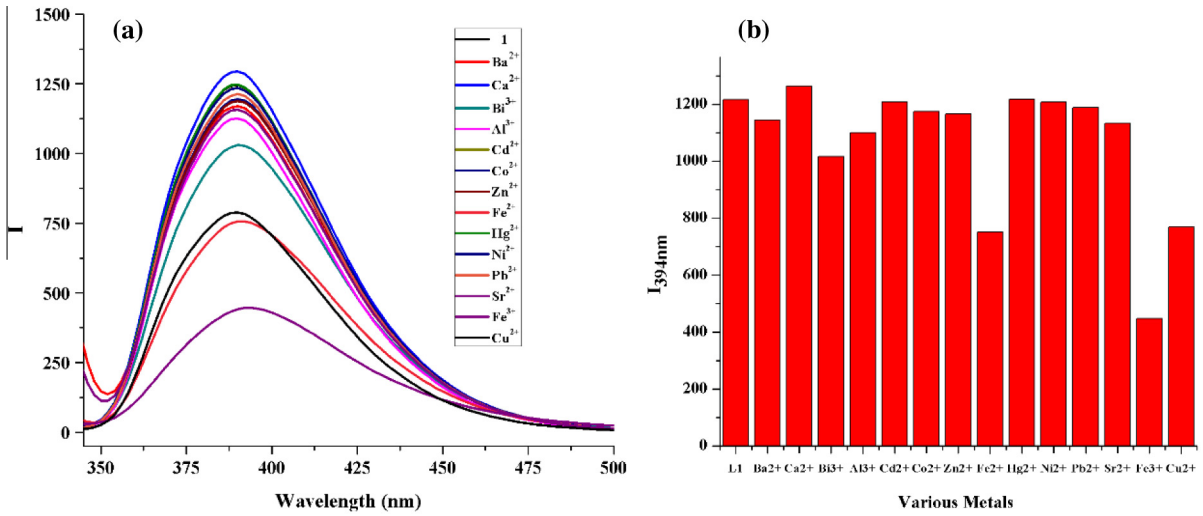


Figure 2. (a) Fluorescence responses of **1** (1.0×10^{-5} mol/L, excitation wavelength = 324 nm) to various metal ions (1.0×10^{-5} mol/L). (b) Bar representation of fluorescence responses of **1** (1.0×10^{-5} mol/L, excitation wavelength = 324 nm) to various metal ions (1.0×10^{-5} mol/L).

Ni^{2+}, Pd^{2+}, Sr^{2+}, Cu^{2+}, Mn^{2+} and Zn^{2+}. Although Cu^{2+} and Fe^{2+} can cause considerable fluorescent emission quenching, significant fluorescence quenching occurred only in the case of Fe^{3+}. Hence, with this high selectivity and sensitivity of ligand **1** towards Fe^{3+}, ligand **1** can be used as fluorescent turn off sensor for Fe^{3+}.

In order to monitor the conformation change of ligand **1** over the addition of Fe^{3+}, CD spectra of sensor **1** in the presence and absence of Fe^{3+} were recorded in THF solvent. As shown in Figure 3, the cotton effect of **1** did not change with the addition of Fe^{3+}. This indicates the conservation of the cisoid conformation of **1**. In addition, the CD spectra of the in situ formed Fe^{3+} complex showed a blue shift of approximately 2 nm relative to **1**, thus indicating that the dihedral angel of the binaphthyl unit was slightly enlarged. This can be attributed to the fact that the Fe^{3+} had possibly been captured by **1** and had entered the minor grooves of ligand **1**. All of these results corroborate and reveal the interaction.

Next, in order to explore the cascade chiral recognition of ligand **1** with Fe^{3+}, subsequent chiral recognition evaluations of the in situ generated ligand **1** containing Fe^{3+} complex toward amino acids

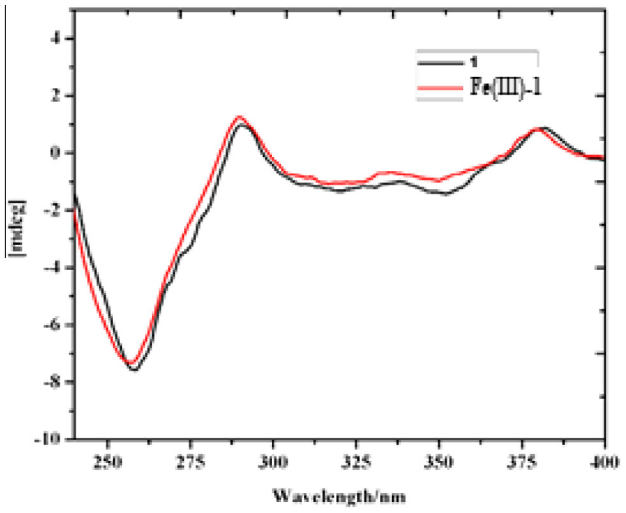


Figure 3. CD spectra of **1** and **1** with an equivalent amount of Fe^{3+} in acetonitrile ($c1 = 1 \times 10^{-5}$ mol/L, cFe(III) = 1×10^{-5} mol/L).

were carried out. Since amino acids can associate with Fe^{3+} and displace ligand **1**, they may bring back the fluorescence of **1**. In addition to this, since **1** is chiral, there would be difference in the ligand displacing efficiency between the two enantiomers of amino acids. We investigated enantioselective recognition of the in situ generated 1:1 Fe(III)-containing complex sensor towards various unprotected amino acids. The effect of the enantiomers of alanine (1×10^{-5} mol/L in THF, 50% v/v water) on fluorescence enhancement of the solution of ligand **1** and Fe^{3+} (1×10^{-5} mol/L in THF) is illustrated in Figure 4. As shown in Figure 4, both enantiomers could enhance the fluorescence response, whereas L-alanine causes a large increase in the fluorescence intensity; conversely, the D-isomer had little effect on the fluorescence intensity of the solution of ligand **1** and Fe^{3+} under the same experimental conditions. Furthermore, there was no difference in the absorption wavelength between the guest-free sensor and the sensor with a guest. The enantioselective recognition effect of the sensor on the chiral enantiomer of the amino acids can be measured by calculating the enantiomeric fluorescent difference ratio, ef [ef = $(I_L - I_o)/(I_D - I_o)$]. Herein, I_o represents fluorescence intensity of the complex sensor in the absence of a chiral guest, while I_D and I_L represent the fluorescence intensities of sensor in the presence of L-/D-isomers. The enantiomeric fluorescent difference ratio in the case of alanine is 2.52 at 1:100 molar ratio, which indicates that the in situ prepared chiral Fe^{3+} complex of ligand **1** exhibits an enantioselective fluorescent response towards L-alanine. We further investigated the fluorescence enhancement of yjr in situ generated complex sensor with alanine by gradually increasing the concentration. Upon the addition of L-alanine and D-alanine in the range from 1:10 to 1:100 molar ratios, the fluorescence showed a gradual increase (Fig. 4d).

Inspired by the preliminary results of alanine, we then investigated the fluorescence chiral discrimination ability of the complex sensor with various other unprotected amino acids such as proline, valine, serine and methionine. The selected amino acids were engaged in titration experiments with the in situ prepared Fe^{3+} complex of ligand **1**. As expected, we obtained a fluorescence response similar to that of alanine. The respective enantiomeric fluorescent difference ratio is given in Table 1.

The influence of the enantiomeric composition of alanine on the fluorescence intensity of Fe^{3+} complex of ligand **1** (1×10^{-6} M in THF) was studied for the quantitative analysis of amino acids. In

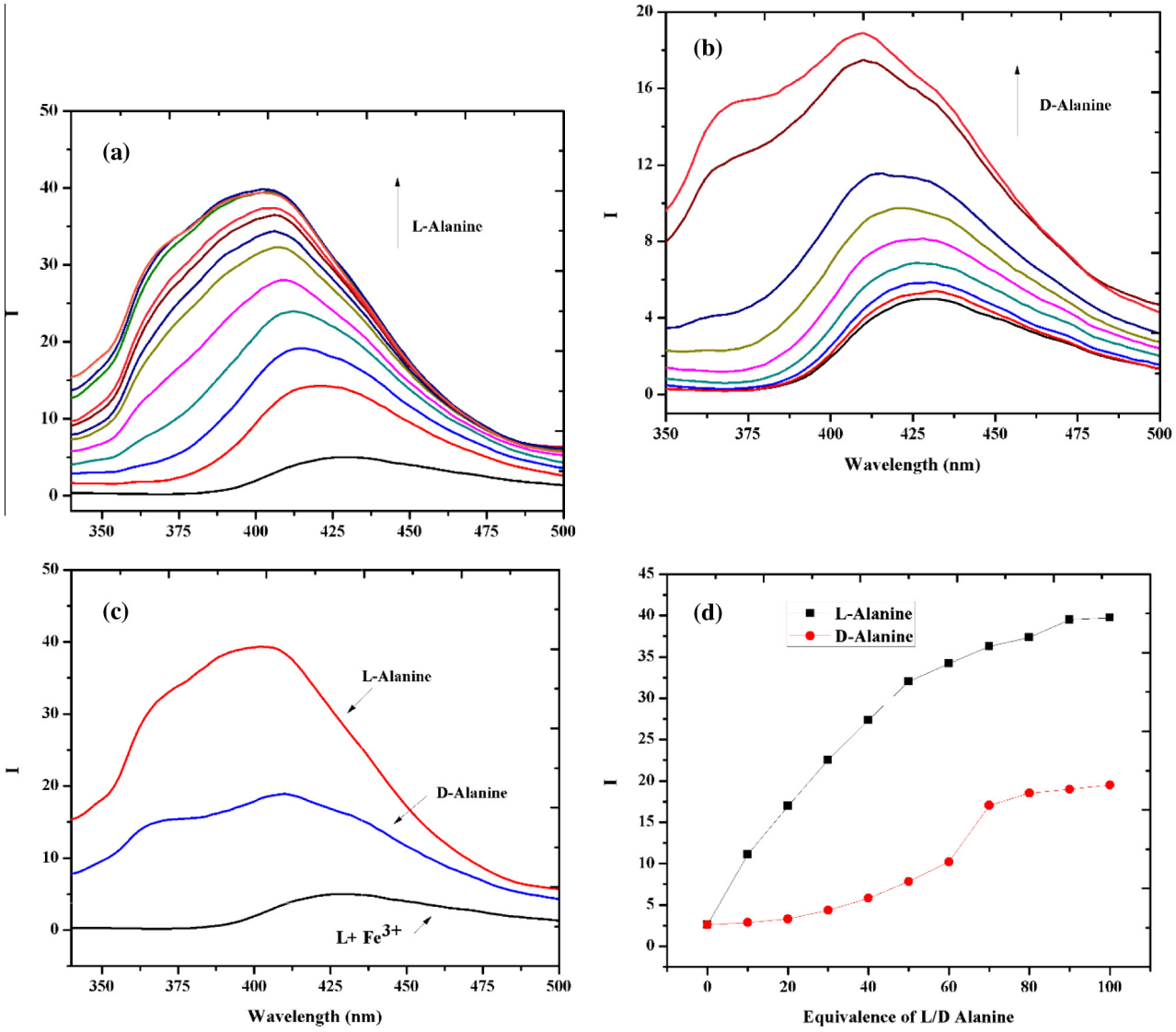


Figure 4. (a) Fluorescent spectra of complex sensor with increasing concentration fluorescent spectra of complex sensor with L-alanine. (b) Fluorescent spectra of complex sensor with increasing concentration fluorescent spectra of complex sensor with D-alanine. (c) Combined fluorescence spectra of complex sensor with and without the addition L and D-alanine. (d) Fluorescent enhancement of complex sensor versus the increasing concentration L and D-alanine (complex sensor: 1×10^{-6} mol/L in acetonitrile: excitation wavelength = 324 nm).

Table 1
Amino acids employed in enantioselective sensing studies and their respective enantiomeric fluorescent difference ratio

Amino acid	$(\Delta I/I_o)_{max}$	ef
L- and D-alanine	4.4	2.52
L- and D-valine	4.4	1.61
L- and D-serine	2.0	2.1
L- and D-methionine	6.5	1.9
L- and D-phenylalanine	0.43	0.12

Figure 5, curve (a) shows the fluorescence enhancement of complex sensor over the addition of alanine at various enantiomeric composition of D- and L-amino acids. Curve b shows the fluorescence enhancement of complex sensor with the same amount of L-alanine alone. As can be seen from Figure 5, the L-isomer exhibited a greater enhancement in the fluorescence intensity than in the case of both L- and D-enantiomers. The fluorescence enhancement of the sensor at 394 nm showed an almost linear relationship with the enantiomeric composition of L- and D-alanine. Thus, by using this in situ preparation and by monitoring the fluorescence response towards the enantiomers of amino acids under the same conditions will provide an easy means of determining the enantiomeric excess.

The chiral discrimination studies of phenylalanine with the in situ prepared complex were carried out. There was no significant emission difference of the complex sensor over the introduction of L- and D-phenylalanine. Due to the presence of a bulky aromatic group at the α-position of phenylalanine, this amino acid was unable to enter the minor grooves of the sensor. Hence the replacement of Fe(III) with amino acid was hindered, which led to a similar emission enhancement of the complex sensor by both L- and D-phenylalanine. While ligand **1** was treated with enantiomers of alanine without the addition of Fe(III), there was no change in the fluorescence intensity of **1**. Even after the excessive addition of the enantiomers of alanine, the fluorescence response behaviors of the two enantiomers remained the same, thus indicating the necessity of Fe(III) for chiral recognition.

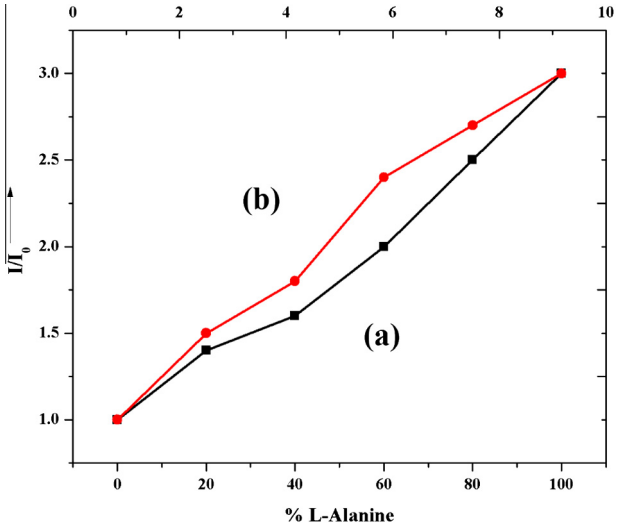


Figure 5. (a) Fluorescence enhancement of complex sensor (1×10^{-6} mol/L) in the presence of various enantiomeric compositions of alanine. (b) Fluorescence enhancement of complex sensor (1×10^{-6} mol/L) in the presence of enantiomerically pure L-alanine.

3. Conclusion

In conclusion, a new (*S*)-BINOL based chiral ligand **1** has been designed and synthesized, with excellent fluorescence turn-off sensitivity towards Fe(III). This ligand exhibited good selectivity among a series of various group metals tested. Furthermore, the in situ generated Fe(III) complex of **1** showed considerable fluorescence enhancement responses with remarkable enantioselectivities towards unmodified α-amino acids. The ligand displacement mechanism[8] can be attributed to the recognition of Fe(III) and unmodified α-amino acids.

4. Experimental

4.1. General

Commercially available solvents and regents were purchased from Sigma Aldrich and Avra synthesis. Nuclear magnetic resonance spectra were recorded on a Bruker Ascent 400 MHz spectrometer. Chemical shift values are reported in δ in parts per million using trimethyl silane (TMS) as the standard. Absorbtion spectra were recorded on a Shimadzu 3600 spectrophotometer. Emission spectra were recorded on a Perkin Elmer LS-55 luminescence spectrometer.

4.2. Synthesis of 2-(methoxymethoxy)-1-(2-(methoxymethoxy)-naphthalen-1-yl)naphthalene 4

Stirred suspension of sodium hydride (60% suspension in mineral oil, 1.18 g, 29.5 mmol) in dimethylformamide (DMF) (20 ml) was added to a solution of (*S*)-BINOL (1.2 g, 4.2 mmol) in DMF at 0 °C. After stirring the reaction mixture for 10 min at 0 °C, methoxy methyl chloride (1.25 ml, 16.65 mmol) was added and the reaction mixture was allowed to stir at 0 °C for 1 h. The reaction was continued at room temperature for 3 h. The reaction mixture was quenched with water and extracted with diethyl ether (60 ml). The extracted organic layer was washed with saturated $NaHCO_3$ solution, brine, and dried over magnesium sulfate. The title compound, with diethyl ether as the solvent, was allowed to recrystallize at room temperature. Colorless crystals of the title compound appeared with 95% isolated yield. R_f = 0.39 (hexane/ethyl acetate 3:1); $[\alpha]_D^{25}$ = +98 (*c* 1, THF). ^{1}H NMR (400 MHz, $CDCl_3$). δ 8.03–8.00 (d, *J* = 12 Hz, 2H), 7.95–7.93 (d, *J* = 8 Hz, 2H), 7.67–7.94 (d, *J* = 12H, 2H), 7.43–7.39 (m, 2H), 7.31–7.24 (m, 4H), 5.16–5.14 (d, *J* = 8 Hz, 2H), 5.05–5.03 (d, *J* = 8 Hz, 2H), 3.2 (s, 6H); ^{13}C NMR (400 MHz, $CDCl_3$) δ 152.7, 134.1, 129.9, 129.4, 127.9, 126.3, 125.6, 124.1, 121.3, 117.3, 95.2, 55.8.

4.3. (*S*)-3,3′-Diformyl-2,2′-bis(methoxymethoxy)-1,1′-binaphthalene 3

Compound **4** (1.23 g, 3.3 mmol) was taken in two neck RB flask and dissolved in 50 ml of THF. To this N_2 was purged and the temperature was reduced to 0 °C. Next, *n*-butyllithium (2.5 M in hexane, 4.5 mL, 11 mmol) was added to the reaction mixture via syringe. After the addition of *n*-butyllithium, the reaction mixture was stirred for 3 h at room temperature. The reaction mixture was turned into grey suspension. After this, the reaction mixture was cooled to 0 °C and DMF (0.92 ml, 12 mmol) was added. The reaction mixture was allowed to stir at room temperature overnight. Next, saturated NH_4Cl (25 ml) was added to the reaction mixture to quench the reaction. The reaction mixture was extracted with ethyl acetate (100 ml). The organic layer was washed with brine and dried over $MgSO_4$. The solvent was removed under reduced pressure and the residue was purified by column chromatography on silica gel using hexane/ethyl acetate (4:1) to give the title compound. Isolated yield, 55%. R_f = 0.17 (hexane/ethyl acetate 4:1). ^{1}H NMR (400 MHz, $CDCl_3$). δ 10.67 (s, 1H), 8.57 (s, 1H), 8.04–7.98 (m, 2H), 7.90–7.87 (d, *J* = 12 Hz, 1H), 7.61–7.59 (d, *J* = 8 Hz, 1H), 7.47–7.43 (t, *J* = 8 Hz, 1H), 7.39–7.33 (q, *J* = 8 Hz, 2H), 7.30–7.20 (m, 2H), 7.18–7.16 (d, *J* = 8 Hz, 1H), 5.15–5.14 (d, H = 4 Hz, 1H), 5.04–5.03 (d, *J* = 4 Hz, 1H), 4.75–4.74 (d, *J* = 4 Hz, 1H), 4.64–4.63 (d, *J* = 4 Hz, 1H), 3.15 (s, 3H), 2.99 (s, 3H); ^{13}C NMR (400 MHz, $CDCl_3$) δ 191.2, 152.9, 131.0, 133.7, 131.0, 130.3, 130.2, 129.6, 129.0, 128.0, 126.9, 126.8, 126.0, 125.9, 125.2, 124.3, 119.4, 116.3, 100.2, 94.9, 57.1, 56.0.

4.4. Synthesis of (*S*)-3,3′-diformyl-2,2′-dihydroxy-1,1′-binaphthalene 2

Compound **3** (1 g, 2.5 mmol) was dissolved in THF (10 ml). The temperature of the reaction mixture was reduced to 0 °C, and then 12 M HCl (10 ml) was added over 5 min with stirring. After the addition of the acid, the reaction mixture was allowed to stir at room temperature for approximately 3 h. After completion of the reaction, the reaction mixture was extracted with ethylacetate. The organic layer was washed with satd. $NaHCO_3$, brine and dried over $MgSO_4$. The organic layer was allowed to evaporate at room temperature, after which a yellow color solid that settled was dried and recrystallized (0.95 g, 99%). R_f = 0.35 (hexane/ethyl acetate 4:1); mp 285 °C; $[\alpha]_D^{25}$ = +249.5 (*c* 0.8, CH_2Cl_2). ^{1}H NMR (400 MHz, DMSO-D_6). δ 10.58 (s, 2H), 10.18 (s, 2H), 8.34 (s, 2H), 8.00–7.98 (m, 2H), 7.43–7.37 (m, 4H), 7.25 (s, 1H), 7.21–7.19 (m, 2H); ^{13}C NMR (400 MHz, DMSO-D_6) δ 196.7, 153.6, 138.5, 137.4, 130.7, 130.0, 127.6, 124.8, 124.5, 122.1, 166.3.

4.5. Synthesis of 1

A mixture of **2** (2 mmol), ammonium acetate (4 mmol), benzil (4 mmol) and iodine (10 mol %) in 10 ml of ethanol was added to an oven dried RB flask. The reaction mixture was refluxed for approximately 4 h. Completion of the reaction was monitored by TLC. After completion of the reaction, iodine was removed by the addition of saturated solution of $Na_2S_2O_3$. The crude product obtained was purified by column chromatography using 20% ethylacetate in hexane as eluent to yield **1**. The structure of the product was confirmed by their spectral analysis (^{1}H, ^{13}C and mass spectroscopic analysis) (0.28 g,

20%). R_f = 0.21 (hexane/ethyl acetate 4:1); mp 285 °C; $[\alpha]_D^{25}$ = +230.0 (*c* 0.8, CH_2Cl_2); ^{1}H NMR (400 MHz, DMSO-D_6) δ 13.42 (s, 2H), 13.13 (s, 2H), 8.76 (s, 2H), 7.87–7.85 (d, *J* = 8 Hz, 2H), 7.55 (s, 4H), 7.46–7.43 (m, 10H), 7.30–7.27 (t, *J* = 4 Hz, 2H), 7.22–7.15 (m, 8H), 7.03–7.01 (d, *J* = 8 Hz, 2H); ^{13}C NMR (400 MHz, DMSO-D_6) δ 151.1, 145.7, 134.3, 133.7, 133.3, 130.1, 128.8, 128.4, 128.2, 127.1, 127.0, 126.8, 126.6, 124.3, 123.3, 116.9, 114.9. HRMS (EI) calcd for $C_{50}H_{34}N_4O_2$ (M+) 722.2682, found 722. 2685.

Acknowledgments

Sathishkumar Munusamy thanks CSIR for providing Senior Research Fellowship. The DST-FIST NMR facility at VIT University and VIT management are duly acknowledged. Authors would like to thank Dr. R. Srinivasan, SSL, and VIT University for his support for English corrections.

Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.tetasy.2016.05.002.

References

1. (a) Joyce, L. A.; Maynor, M. S.; Canary, J. W.; Dragna, J. M.; Anslyn, E. V.; Cruz, M. D.; Lynch, M. *J. Am. Chem. Soc.* **2011**, *133*, 13746; (b) You, L.; Pescitelli, G.; Anslyn, E. V.; Bari, L. D. *J. Am. Chem. Soc.* **2012**, *134*, 7117; (c) Jo, H. H.; Lin, C. Y.; Anslyn, E. V. *Acc. Chem. Res.* **2014**, *47*, 2212.
2. (a) Akdeniz; Mosca, L.; Minami, T.; Anzenbacher, P., Jr. *Chem. Commun.* **2015**, 5770; (b) Huang, Z.; Yu, S.; Wen, K.; Yu, X.; Pu, L. *Chem. Sci.* **2014**, *5*, 3457; (c) Jiao, J.; Wei, G.; Li, F.; Mao, X.; Cheng, Y.; Zhu, C. *RSC Adv.* **2014**, *4*, 5887; (d) Zhang, L.; Jin, Q.; Lv, K.; Qin, L.; Liu, M. *Chem. Commun.* **2015**, 423; (e) Li, Q.; Xu, K.; Song, P.; Dai, Y.; Yang, L.; Pang, X. *Dyes Pigments* **2014**, *109*, 169; (f) Wu, X.; Xie, M.; Zhao, X.; Liu, X.; Lin, L.; Feng, X. *Tetrahedron Lett.* **2014**, *55*, 3446; (g) Wang, F.; Nandhakumar, R.; Hu, Y.; Kim, D.; Kim, K. M.; Yoon, J. *J. Org. Chem.* **2013**, *78*, 11571; (h) Li, F.; Li, L.; Yang, W.; Zheng, L. S.; Zheng, Z. J.; Jiang, K.; Lu, Y.; Xu, L. W. *Tetrahedron Lett.* **2013**, *54*, 1584; (i) Xu, K.; Jiao, S. Y.; Yao, W. Y.; Kong, H. J.; Zhang, J. L.; Wang, C. J. *Sens. Actuators, B* **2013**, *177*, 384.
3. (a) Childers, W. E., Jr.; Baudy, R. B. *J. Med. Chem.* **2007**, *50*, 2557; (b) Barshop, B. A. *Mitochondrian* **2004**, *4*, 521; (c) Bandell, M.; Lolkema, J. S. *Biochemistry* **2000**, *39*, 13059.
4. (a) D'Autréaux, B.; Tucker, N. P.; Dixon, R.; Spiro, S. *Nature* **2005**, *437*, 769; (b) Lee, J. W.; Helmann, J. D. *Nature* **2006**, *440*, 363.
5. (a) Weerasinghe, A. J.; Schmiesing, C.; Varaganti, S.; Ramakrishna, G.; Sinn, E. *J. Phys. Chem. B* **2010**, *114*, 9413; (a) Kagit, R.; Yildirim, M.; Ozay, O.; Yesilot, S.; Ozay, H. *Inorg. Chem.* **2014**, *53*, 2144; (c) Dong, X. Y.; Wang, R.; Mak, T. C. W.; Wang, J. Z.; Zang, S. Q. J. *Mater. Chem. A* **2015**, *3*, 641; (d) Yi, C.; Tian, W.; Song, B.; Zheng, Y.; Qi, Z.; Qi, Q.; Sun, Y. *J. Luminesc.* **2013**, *141*, 15; (e) Chereddya, N. R.; Sumana, K.; Korrapatib, P. S.; Thennarasua, S.; Mandalc, A. B. *Dyes Pigments* **2013**, *95*, 606; (f) Yang, Z.; She, M.; Yin, B.; Cui, J.; Zhang, Y.; Sun, W.; Li, J.; Shi, Z. *J. Org. Chem.* **2012**, *77*, 1143; (g) Chai, M.; Zhang, D.; Wang, M.; Hong, H.; Ye, Y.; Zhao, Y. *Sens. Actuators, B* **2012**, *174*, 231.
6. Belokon, Y. N.; Chusov, D.; Borkin, D. A.; Yashkina, L. V.; Bolotov, P.; Skrupskaya, T.; North, M. *Tetrahedron: Asymmetry* **2008**, *19*, 459.
7. (a) Luxami, V.; Kumar, S. *RSC Adv.* **2012**, *2*, 8734; (b) Udhayakumari, D.; Saravanamoorthy, S.; Ashok, M.; Velmathi, S. *Tetrahedron Lett.* **2011**, *52*, 4631; (c) Sahoo, S. K.; Bera, R. K.; Baral, M.; Kanungo, B. K. *J. Photochem. Photobiol., A: Chem.* **2007**, *188*, 298.
8. (a) Nguyen, B. T.; Anslyn, E. V. *Coord. Chem. Rev.* **2006**, *250*, 31189; (b) Folmer-Andersen, J. F.; Lynch, V. M.; Annslyn, E. V. *J. Am. Chem. Soc.* **2005**, *127*, 7986; (c) Leung, D.; Anslyn, E. V. *J. Am. Chem. Soc.* **2008**, *130*, 12328; (d) Mei, X. F.; Wolf, C. *J. Am. Chem. Soc.* **2006**, *128*, 13326; (e) Liu, S. L.; Pestano, J. P. C.; Wolf, C. *J. Org. Chem.* **2008**, *73*, 4267; (f) Li, M.; Fu, Y.; Cui, X.; Chen, M.; Liu, X.; Lin, L.; Feng, X. *Tetrahedron Lett.* **2010**, *51*, 3511.