1. Introduction

Fluorescent probe assays have been studied for many years due to their high sensitivity, selectivity, real-time imaging and ease of manipulation. Using both the literature and our own experience, there are a number of interesting phenomenon which can help guide the design of a fluorescent probe. For example, the fluorescence “turn on” probe is normally better than the “turn off” probe given the associated low background interference. Secondly, a larger Stokes shift and higher sensitivity for a fluorescent probe can be achieved by reducing self-quenching and auto-fluorescence, which results from minimal overlap of the excitation and emission spectra. Thirdly, ratiometric fluorescent probes are accurate as they measure the observed changes in the ratio of the intensities of the emission at two wavelengths, which provides a built-in correction for environmental effects. In other words, they are not influenced by the microenvironment, probe concentration, photobleaching, excitation intensity, and so on.

4-(Benzothiazol-2-yl)phenol and its derivatives are good probe candidates as they possess the above advantages. As fluorophores, they have many excellent photophysical and photochemical characteristics such as a relatively high fluorescent quantum yield and good cell membrane permeability. Meanwhile, their ease of synthetic modification and good photostability are also attractive attributes. Further, they can exhibit dual emission via the excited state intramolecular proton transfer (ESIPT) processes upon being excited, which means they can be developed as ratiometric probes.

Considering all of this, 4-(benzothiazol-2-yl)phenol seems to be an ideal fluorophore for constructing an efficient multifunctional fluorescent probe. Indeed, a number of excellent fluorescent probes have been explored which contain one benzothiazole moiety as a fluorophore. However, how about if we introduce more than one benzothiazole fluorophore? Will their properties be better? Herein, we have designed and synthesized a tripodal fluorescent probe \( L \) by introducing three 4-(benzothiazol-2-yl)phenols as the ESIPT fluorophore. Impressively, probe \( L \) exhibited excellent recognition capability towards the ions \( \text{Cr}^{3+}, \text{Al}^{3+}, \text{Zn}^{2+} \) and \( F^{-} \) and \( \text{Cr}^{3+}, \text{Al}^{3+}, \text{Zn}^{2+} \) and \( F^{-} \) were different. The presence of \( \text{Cr}^{3+} \) and \( \text{Al}^{3+} \) recovered the ESIPT, but the presence of \( \text{Zn}^{2+} \) trigger a moderate deprotonation of the phenolic OH and induced an ESIPT red shifted (60nm) emission wavelength. Finally, the presence of \( F^{-} \) completely deprotonated the free phenolic OH and a remarkable red shifted (130 nm) ESIPT emission was observed. In other words, the ESIPT process of probe \( L \) is controllable. Furthermore, the utility of probe \( L \) as a biosensor in living cells (PC3 cells) towards \( \text{Cr}^{3+} \), \( \text{Al}^{3+} \) and \( \text{Zn}^{2+} \) ions has been demonstrated.
2. Results and discussion

2.1. Synthesis

The tripodal fluorescence probe \( L \) was obtained by the convenient condensation of tren and three equivalents of 4-(benzo[d]thiazol-2-yl)-2,5-dihydroxybenzaldehyde (3) in one step (Scheme 1). Its structure was fully characterized by IR, \(^1\)H NMR and \(^{13}\)C NMR spectroscopy and MS. The proton signal of the precursor 3 aldehyde group hydrogen disappeared, whilst a new singlet appeared at about 8.22 ppm, which is attributed to the formation of the CH=N linkage of the Schiff base skeleton in probe \( L \). Besides, the appearance of two new triplets at 3.69 and 2.93 ppm is associated with the methylene group of the tren moiety further confirming the success of the condensation reaction (for details, see the Supporting Information, Fig. S20-S23).

2.2. Recognition properties of probe \( L \) towards metal ions

The recognition properties of probe \( L \) were investigated by fluorescence spectroscopy. In DMF/H\(_2\)O (v/v = 96/4, Tris-HCl buffer, pH = 7) solution, probe \( L \) (10 \( \mu \)M) exhibited a weak emission at about 480 nm (\( \lambda_{\text{ex}} = 320 \text{ nm} \)), which is attributed to the keto emission generated from the excited-state intramolecular proton transferred (ESIPT) process in probe \( L \).\(^{5c,7a} \) However, fast C=N isomerization was the predominant decay process for the excited state of probe \( L \), and this greatly diminished the emission intensity at 480 nm.\(^8 \) Hence, we only observed a weak fluorescent emission for probe \( L \) at 480 nm (Fig. 1a). In other words, the ESIPT process was greatly affected (adversely) by the presence of the Schiff base group in \( L \). Interestingly, upon addition of \( \text{Cr}^{3+} \) and \( \text{Al}^{3+} \), an acute fluorescence enhancement at 480 nm with a large Stokes shift (160 nm) was observed. This is ascribed to the formation of the \( L\)-\( \text{Cr}^{3+} \) or \( L\)-\( \text{Al}^{3+} \) complexes inhibiting the C=N isomerization of probe \( L \). Besides, the addition of \( \text{Zn}^{2+} \) ion not only induced an enhancement at 480 nm but also a new emission peak appeared at 540 nm, which indicated a different recognition pathway for probe \( L \) towards \( \text{Zn}^{2+} \). In contrast, the presence of any other metal ions did not bring about significant fluorescence changes, which indicated the higher selectivity of probe \( L \) towards \( \text{Cr}^{3+}, \text{Al}^{3+} \) versus \( \text{Zn}^{2+} \). Furthermore, the two different wavelength responses are accompanied by two different colour changes (cyan and a yellow/green colour, Fig. 1a inset) enabling probe \( L \) to possess the capability to further differentiate between \( \text{Cr}^{3+}, \text{Al}^{3+} \) versus \( \text{Zn}^{2+} \) by the naked eye.

In order to investigate the detailed recognition processes, fluorescence titration experiments were carried out. Upon increasing the concentration of \( \text{Cr}^{3+} \), only a fluorescence enhancement at 480 nm (Stokes shift =160 nm) was observed, which reached equilibrium upon addition of about 1.0 equivalent of \( \text{Cr}^{3+} \). This suggested a 1:1 binding ratio (the quantum yield \( \Phi = 0.36 \) versus quinine sulfate as reference material, \( \Phi = 0.55 \), Fig.1b). Similar phenomena were observed upon the addition of \( \text{Al}^{3+} \) (\( \Phi = 0.35 \), Fig. S1). It should be noted that a large Stokes shift (Stokes shift > 100 nm) normally indicates that the ESIPT process has occurred. The enhancement of the fluorescence band at 480 nm indicated the suppression of C=N isomerization and the recovery of the ESIPT process. Interestingly, upon addition of \( \text{Zn}^{2+} \), the fluorescence significantly increased, and not only gave an emission at 480 nm but also observed at 540 nm.
Upon the addition of Al$^{3+}$ and Cr$^{3+}$, both of the absorption proton (a necessary step for the emission shift)\(^9\). The Cr$^{3+}$/Al$^{3+}$ ions only induced an enhanced emission at 480 nm, which is tentatively attributed to a weak interaction of the Cr$^{3+}$/Al$^{3+}$ ions with the -CH=N- and adjacent hydroxyl groups. As a result, the system could not remove the phenolic proton (a necessary step for the emission shift)\(^9\).

To elucidate the metal ion-binding mode present, the UV-vis spectra of probe \(L\) in the presence of Cr$^{3+}$, Al$^{3+}$ or Zn$^{2+}$ were investigated. The absorption of probe \(L\) exhibited a major peak at 320 nm (\(\pi-\pi^*\)) and a minor peak at 400 nm (\(n-\pi^*\)) (Fig. 2). Upon the addition of Al$^{3+}$ and Cr$^{3+}$, both of the UV results are consistent with the fluorescence spectra analysis. The 

The Job’s plot analysis revealed a 1:1 binding stoichiometry for probe \(L\) towards Cr$^{3+}$ or Al$^{3+}$. The UV-vis spectra were observed in the presence of Al$^{3+}$ and Cr$^{3+}$ which suggested weak binding of the Al$^{3+}$ and Cr$^{3+}$ ions with the -CH=N- moiety and its adjacent phenol. In other words, the presence of Al$^{3+}$ and Cr$^{3+}$ cannot remove the phenolic proton of probe \(L\). Contrastingly, when Zn$^{2+}$ ions were added, the absorption band at 328 nm increased, but the absorption band at 400 nm decreased and shifted to 415 nm which indicated that the Zn$^{2+}$ ion was bonded to the Schiff base. A new (\(\pi-\pi^*\)) absorption band was simultaneously generated at about 475 nm which was attributed to the removal of a phenolic proton required for the formation of the \(L^{2-}\)-Zn$^{2+}$ complex. The UV results are consistent with the fluorescence spectra analysis.

The \(^1\)H NMR titration experiments gave further insight into the possible recognition mechanism. Upon increasing the concentration of Cr$^{3+}$, a remarkable up-field chemical shift of the OH proton (\(H_{11}\)) was observed. Meanwhile, the singlet protons of the imine (\(H_I\)) were converted to triplets and slightly shifted downfield which indicated this OH proton was removed. The adjacent protons (\(H_3\) and \(H_4\)) were also affected and were shifted downfield. Due to the complexation of Cr$^{3+}$, the nature of the structure of probe \(L\) was fixed, and the C=N isomerization of probe \(L\) was inhibited. Hence, the fluorescence of probe \(L\) was switched on which is consistent with the fluorescent result. However, no significant chemical shift

changes for the benzothiazol protons (\(H_6, H_7, H_8 & H_9\)) were observed which means the binding site is far removed from the benzothiazol moiety. Similar phenomena were observed in the case of Al$^{3+}$, which suggested the same recognition mechanism for Cr$^{3+}$ and Al$^{3+}$. The Job’s plot analysis revealed a 1:1 binding stoichiometry for probe \(L\) towards Cr$^{3+}$ or Al$^{3+}$ (Fig. S2), and the 1:1 nature of the \(L\)-Cr$^{3+}$ and \(L\)-Al$^{3+}$ complexes was further confirmed by MALDI-TOF mass spectrometry. The difference of the mass charge ratio between mass peaks at \(m/z\) 930.804 (calculated value 930.178), 931.843 and 932.718 were about 1, which means [\(L+Al-2H\)]$^+$ was a single charged isotope peak. Similarly, the difference of mass charge ratio between mass peaks at \(m/z\) 958.552 (calculated value 958.161), 959.606, and 960.772 were about 1, which means [\(L+Cr+H\)]$^+$ was also a singly charged isotope peak. All the results indicated the formation of 1:1 complexes of the type \(L\)-Al$^{3+}$ and \(L\)-Cr$^{3+}$ (Fig. S3 & S4). Combining all of the above observations, a plausible recognition mechanism for the probe \(L\) towards Cr$^{3+}$/Al$^{3+}$ is shown in Fig. 3b.

On the other hand, the \(^1\)H NMR titration experiments involving Zn$^{2+}$ (Fig. 4a), revealed obvious differences compared with the addition of Cr$^{3+}$/Al$^{3+}$. Upon addition of Zn$^{2+}$, the proton signal of OH (\(H_I\)) was split into two peaks, and at the same time, the imine \(H_{11}\) (at \(\delta\) 8.51 ppm) was also split into two peaks and shifted downfield to about \(\delta\) 8.57 & 8.71 ppm. This suggested that both the imine and hydroxyl groups participated in the complexation process with Zn$^{2+}$. Noteworthy, in the presence of Zn$^{2+}$, the Schiff base proton (\(H_1\)) and the hydroxyl protons were clearly split into two, and the ratio was about ~ 2:1. The two kinds of proton signal for the Schiff base and

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**Figure 2.** Absorption spectra of probe \(L\) (10 \(\mu\)M, DMF/H$_2$O, v/v = 96/4) without or with 20 equiv. Cr$^{3+}$, Al$^{3+}$ or Zn$^{2+}$.

**Figure 3.** (a) Partial \(^1\)H NMR spectra of probe \(L\) (5.0 mM) and increasing concentrations of Cr$^{3+}$ in DMSO-d$_6$ at 298K; (b) Plausible recognition mechanism of the probe \(L\) towards Cr$^{3+}$/Al$^{3+}$. 
OH were ascribed

(a) Partial $^1$H NMR spectra of probe L (5.0 mM) and increasing concentrations of Zn$^{2+}$ in DMSO-d6 at 298K; (b) Plausible recognition mechanism of the probe L towards Zn$^{2+}$.

Figure 4.

For the recognition properties of probe L towards anions, we found that probe L exhibited a high selectivity towards F$^-$ in 1,4-dioxane solution by using the fluorescence method. Upon the addition of 10 equiv. of various anions (F$^-$, Cl$^-$, Br$^-$, I$^-$, PF$_6^-$, NO$_3^-$, H$_2$PO$_4^-$, HSO$_4^-$, AcO$, $ClO$$_4^-$), only the presence of F$^-$ induced a dramatically ratio metric change and resulted in a remarkable colour change which enable us to distinguish F$^-$ by the naked eye ($\Phi = 0.19$, Fig. 5a). Although there were some slight spectral changes in the presence of AcO$^-$ and H$_2$PO$_4^-$, it proved too difficult to utilize this system for practical application in the detection of these two anions due to the near lack of fluorescence.

The fluorescent titration experiments provided information relating to the recognition process. Upon increasing the concentration of F$^-$, the emission at 480 nm gradually decreased, whilst the emission at 610 nm increased with an isobestic point at 525 nm (the Stokes shift is higher than 260 nm, Fig. 5b) which indicated probe L can serve as a ratiometric fluorescent probe for F$^-$. The remarkable red shifted emission can be attributed to the F$^-$ induced deprotonation of a phenolic OH (H$_{11}$) which is adjacent to the Schiff base bond in probe L. The mol ratio method and Job’s plot suggested a 1:1 binding stoichiometry for probe L towards F$^-$ (Fig. S8). We further employed $^1$H NMR spectroscopic titrations to try and elucidate the binding mechanism of F$^-$ (Fig. 6a). Due to the poor solubility of probe L in 1,4-dioxane, we conducted the $^1$H
NMR spectroscopic titration experiments in DMSO solution. Upon the addition of F-, the proton signals of OH (H5 & H11) disappeared and remarkable chemical shifts for the protons (H6 & H10) in the phenolic ring and the adjacent Schiff base proton (H3) were observed. However, no significant chemical shift changes for the other protons (the benzothiazol moiety, H6 H7; H8 & H9) were observed. All of the observations further supported the suggestion that the F- anion was interacting with the phenolic moiety of probe L, via deprotonation of the phenolic OH. Binding with fluoride is probably driven by processes associated with hydrogen bond formation and deprotonation, and are attributed to the basicity of the fluoride anion and its strong ability to form hydrogen bonds. The occurrence of this process further enhanced the electron donating ability of the phenolic O to the thiazole core acceptor, resulting in an intramolecular charge transfer process.\(^{11}\) With this in mind, a possible recognition mechanism for probe L towards F\(^{-}\) is shown in Figure 6b.

Competitive experiments were carried out to investigate the practical applicability of probe L as a Cr\(^{3+}\) or Al\(^{3+}\) or F\(^{-}\) ion selective fluorescent probe. There was no obvious interference to the selective response of probe L towards Cr\(^{3+}\) or Al\(^{3+}\) or F\(^{-}\) ions in the presence of most of the other ions screened (Fig. S9) which suggested a high selectivity for probe L. Under the optimal conditions, a linear range for the calibration curve was detected; binding constants and limits of detection (LOD = 3σ/slope) for probe L with Cr\(^{3+}\), Al\(^{3+}\), Zn\(^{2+}\) and F\(^{-}\) are summarized in Table 1. The larger binding constant indicates the stable nature of the complex of probe L with Cr\(^{3+}\), Al\(^{3+}\), Zn\(^{2+}\) and F\(^{-}\). All of the LODs for probe L towards Cr\(^{3+}\), Al\(^{3+}\), Zn\(^{2+}\) and F\(^{-}\) were of the order of 10\(^{-8}\) M by fluorescence, which indicated that probe L is sensitive to these four ions.

The high selectivity of probe L towards Cr\(^{3+}\), Al\(^{3+}\) and Zn\(^{2+}\) may depend on the unique molecular structure of probe L. The three flexible chains of probe L not only participate in the coordination action of ions, but also provide some special shielding effects due to the bulky 3D nature of the structure, which can further improve the selectivity. The \(^1\)H NMR titration analysis and the density function theory calculations revealed that only two flexible chains of probe L participate in the coordination with Zn\(^{2+}\), and that the configuration of probe L-Zn\(^{2+}\) complex is a partial cone structure. By contrast, the configurations of probes L-Al\(^{3+}\) and L-Cr\(^{3+}\) are a cone structure due to the three flexible chains of probe L participating in the coordination. The cooperation of coordination and spatial effects of probe L are the key factors dictating the recognition ability towards different ions.

The sensitivity of probe L towards Cr\(^{3+}\), Al\(^{3+}\) and Zn\(^{2+}\) may also be due to the presence of the benzothiazole moiety which possesses the ESIPT ability and high quantum yields. Herein, we introduced three benzothiazole moieties as fluorophores which greatly enhanced the fluorescent intensity and also can improve the sensitivity.

### 2.5. Cell imaging study

The capability of probe L to monitor Cr\(^{3+}\), Al\(^{3+}\) and Zn\(^{2+}\) ions within living cells was investigated by fluorescence imaging on an inverted fluorescence microscope. Given their emission wavelength, for Cr\(^{3+}\) and Al\(^{3+}\), the optical window at the blue channel was chosen as a signal output; for the Zn\(^{2+}\), the optical windows at the green and red channel were chosen as a signal output. After incubation of the PC3 cells with 20 μM of probe L for a pre-longed period, the cells were still alive (bright-field image, Fig. 7a) which indicated that probe L exhibited low toxicity. Cytotoxicity was further confirmed by using MTT (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide) assays. It was performed by...

### Table 1 Analysis parameters for probe L and detection of Cr\(^{3+}\), Al\(^{3+}\), Zn\(^{2+}\) and F\(^{-}\).

| Ion     | Solvent   | λ\(_{ex}\)/λ\(_{em}\) (nm) | The linear range of the calibration curve (μM) | Correlation coefficient | Limits of detection (×10\(^{-8}\) M) | Binding constant (M\(^{-1}\)) |
|---------|-----------|-----------------------------|-----------------------------------------------|------------------------|--------------------------------------|-------------------------------|
| Cr\(^{3+}\) | DMF/H\(_2\)O | 320/480                      | 0.5–10                                       | 0.98773 (n = 12)       | 2.5                                  | 1.9905×10\(^7\)               |
A tripodal multifunctional fluorescence probe L was synthesized in one-step and high yield by the convenient condensation of tren and three equivalents of 4-(benzo[d]thiazol-2-yl)-2,5-dihydroxybenzaldehyde. The presence of the benzothiazol moiety allows probe L to possess ESPIT capability. The fluorescent analysis revealed that probe L not only exhibited excellent recognition capability towards Cr$^{3+}$, Al$^{3+}$, Zn$^{2+}$ and F$^{-}$ ions with a large Stokes shift, but also possessed a low detection limit which is of the order of 10$^{-8}$ M towards these four ions. The UV analysis, fluorescent and $^1$H NMR spectroscopic titration experiments revealed information about the recognition mechanism of probe L towards Cr$^{3+}$, Al$^{3+}$, Zn$^{2+}$ and F$^{-}$: namely probe L exhibited a weak emission at about 480 nm due to fast C=N isomerization which inhibited the ESPIT process. Furthermore, the introduction of either Cr$^{3+}$ or Al$^{3+}$ can suppress the C=N isomerization and lead to recovery of the ESPIT process, which in-turn results in the fluorescence enhancement at 480 nm. Whilst the presence of Zn$^{2+}$ can trigger some deprotonation of the phenolic OH leading to an ESPIT emission red shift (60 nm) to 540 nm, the addition of F$^{-}$ can completely deprotonate the free phenolic OH and result in a remarkable ESPIT emission red shift (130 nm) to 610 nm. In other words, the ESPIT process of probe L is controllable by addition of Cr$^{3+}$, Al$^{3+}$, Zn$^{2+}$ and F$^{-}$. Probe L have also demonstrated that it has low toxicity and can serve as a biosensor in living cells (PC3 cells) towards Cr$^{3+}$, Al$^{3+}$ and Zn$^{2+}$ ions.

4. Experimental

4.1. Materials and methods

Unless otherwise stated, all reagents used were purchased from commercial sources and were used without further purification. The solutions of the metal ions were prepared from their perchlorate salts (Aldrich and Alfa Aesar Chemical Co., Ltd.). All the anions used were tetra-n-butylammonium salts (Sigma-Aldrich Chemical Co., Ltd.), and were stored in a desiccator under vacuum containing self-indicating silica. Double distilled water was used throughout. Fluorescence spectral measurements were performed on a Cary Eclipse fluorescence spectrophotometer (Agilent Technologies) equipped with a xenon discharge lamp using a 1 cm quartz cell. UV-Vis absorption spectra were conducted on a UV-1800 spectrophotometer (Shimadzu) in a 1 cm quartz cell. IR spectra were obtained using a Vertex 70 FT-IR spectrometer (Bruker). $^1$H and $^{13}$C NMR spectra were measured on a JEOL JNM-ECD200S 400 MHz NMR spectrometer (JEOL) and a WMNR-I 500 MHz NMR spectrometer respectively at room temperature.

3. Conclusions

Figure 7 Fluorescence images of PC3 cells: (a) bright-field image of cells after incubation with probe L (20 μM); (b) fluorescence image of (a); (c) and (d) fluorescence image of probe L on further treatment with cells after incubation with Cr$^{3+}$ and Al$^{3+}$ (100 μM) solution in the blue channel; (e) and (f) fluorescence image of probe L on further treatment of cells after incubation with Zn$^{2+}$ (100 μM) solution in the green channel or red channel.
temperature using TMS as an internal standard. MALDI-TOF mass spectra were measured on an AB SCIEX TripleTOF5600 system. Microelectrode layers used the sputtering and lift-off process with the standard photo-lithography (EVG 610, Austria). Cell fluorescence imaging was performed using a Ti (Nikon) fluorescent inverted phase contrast microscope.

4.2. Synthetic of intermediate 1

A mixture of p-dimethoxybenzene (5.52 g, 40 mmol), tetramethylethylenediamine (TMEDA, 30 mL, 200 mmol) and dry ether (140 mL) was cooled to 0°C in an ice bath under an N₂ atmosphere. n-Butyllithium (100 mL, 200 mmol) was then added to quench the reaction. The product was extracted with chloroform (100 mL × 3) three times, washed with water (60 mL × 2) and dried with anhydrous MgSO₄. The crude product was obtained by vacuum rotary evaporation to remove organic solvents. The desired intermediate 1 was purified by column chromatography (n-hexane/toluene, 6/4, v/v, silica gel) to give a yellow solid in 76% yield. m.p. 151.9 ~ 152.7°C. ¹H NMR (500 MHz, CDCl₃) δ: 12.09 (s, 1 H, -OH), 10.37 (s, 1 H, -CHO), 9.93 (s, 1 H, -OH), 8.07 (d, J = 8.5Hz, 1 H, ArH), 7.97 (d, J = 8.0Hz, 1 H, ArH), 7.57 (t, J = 7.5Hz, 1 H, ArH), 7.50 (t, J = 8.0Hz, 1 H, ArH), 7.36 (s, 1H, ArH) and 7.32 (s, 1H, ArH) ppm; ¹³C NMR (500 MHz, CDCl₃) δ: 151.74, 150.58, 133.27, 127.15, 126.53, 125.37, 123.57, 122.87, 122.60, 121.72, 121.30 and 115.97 ppm. MS (ESI) m/z: Caled for [C₆H₇NO₃S]+ 271.0, Found 270.3 [M-H]⁺.

4.3. Synthetic of intermediate 2

A mixture of intermediate 1 (4.2 g, 21.65 mmol), 2-aminothiophenol (2.36 g, 21.65 mmol) and potassium metabisulphite (5.3 g, 23.84 mmol) in DMF (150 mL) was refluxed for 3h under an N₂ atmosphere. After the mixture was cooled to room temperature, it was poured into ice-water (250 mL) to afford a yellow precipitate, which was isolated (filtration) and dried with anhydrous MgSO₄. The crude product was obtained by vacuum rotary evaporation to remove organic solvents. The desired intermediate 2 was purified by column chromatography (n-hexane/toluene, 6/4, v/v, silica gel) to give a yellow solid in 65.8% yield. m.p. 214.3 ~ 215.5°C. ¹H NMR (500 MHz, CDCl₃) δ: 12.09 (s, 1 H, -OH), 10.37 (s, 1 H, -CHO), 9.93 (s, 1 H, -OH), 8.07 (d, J = 8.5Hz, 1 H, ArH), 7.97 (d, J = 8.0Hz, 1 H, ArH), 7.57 (t, J = 7.5Hz, 1 H, ArH), 7.50 (t, J = 8.0Hz, 1 H, ArH), 7.36 (s, 1H, ArH) and 7.32 (s, 1H, ArH) ppm; ¹³C NMR (500 MHz, CDCl₃) δ: 151.35, 149.14, 136.75, 128.58, 126.33, 123.06, 125.37, 123.23, 121.47, 112.43, 110.47, 56.37 and 56.35 ppm. MS (ESI) m/z: Caled for [C₆H₇NO₃S]⁺ 299.1, Found 300.1 [M + H]⁺.

4.4. Synthetic of intermediate 3

A solution of intermediate 2 (1.05 g, 5.31 mmol) in dry CH₂Cl₂ (50 mL) was cooled to -30°C under an N₂ atmosphere. Then 14 mL BBr₃ (14.04 mmol) was slowly added to the cold solution. The mixture was stirred at -30°C for 1h, and then at room temperature for another 24h. 70 mL water was added to the reaction and stirring continued for 2h. The reaction solution was extracted with ethyl acetate (100 mL × 3) three times, washed with water, and dried with anhydrous MgSO₄. The organic solvent was removed by evaporation and the crude residue was further purified by silica gel chromatography using n-hexane/CH₂Cl₂ (6/4, v/v) as eluent affording 0.42 g of yellow powder 3 (44.1% yield), m.p. 214.3 ~ 215.5°C. ¹H NMR (500 MHz, CDCl₃) δ: 12.09 (s, 1 H, -OH), 10.37 (s, 1 H, -CHO), 9.93 (s, 1 H, -OH), 8.07 (d, J = 8.5Hz, 1 H, ArH), 7.97 (d, J = 8.0Hz, 1 H, ArH), 7.57 (t, J = 7.5Hz, 1 H, ArH), 7.50 (t, J = 8.0Hz, 1 H, ArH), 7.36 (s, 1H, ArH) and 7.32 (s, 1H, ArH) ppm; ¹³C NMR (500 MHz, CDCl₃) δ: 189.35, 155.80, 129.17, 110.96 and 56.29 ppm. MS (ESI) m/z: Caled for [C₁₀H₁₀O₄S]+ 271.0, Found 270.3 [M-H]⁻.
for 60 min, respectively. The cells were rinsed with fresh culture medium containing phosphate-buffered saline (PBS) three times to remove the remaining probe, then fluorescent images of intracellular Al³⁺, Cr³⁺ and Zn²⁺ were collected with an eclipse Ti-U (Nikon, Japan) inverted fluorescence microscope.

4.8. Determination of cytotoxicity by MTT assay

Cell viability was determined by using MTT (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide) assays (Sigma-Aldrich). Breast cancer cell lines MCF-7 were plated in a 96-well plate at a concentration of 1×10⁴ cells per well. The cells were treated with different concentrations of the probe sulfoxide. The absorbance was measured at a wavelength of 570 nm for 4 h in each well of the plate, followed by incubation at 37 °C for 4 h. The supernatants were then aspirated carefully, and the formazan product was dissolved with 150 μL dimethyl sulfoxide. The absorbance was measured at a wavelength of 630 nm with a microplate reader (Multiskan GO, Thermo, USA).

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