A ratiometric fluorescent probe for detection of exogenous mitochondrial SO₂ based on a FRET mechanism†

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A novel imidazo[1,5-a]pyridine-hemicyanine based ratiometric fluorescent probe for detection of mitochondrial SO₂ was designed and synthesized. The probe is based on a fluorescence resonance energy transfer (FRET) mechanism. It exhibits high selectivity and sensitivity towards SO₂⁻ with a fast response time (3 min) and detection limit of 0.13 μM. Further, it showed low cytotoxicity and was successfully applied to image exogenous mitochondrial SO₂ in cells.

Introduction

Sulfur dioxide (SO₂), which used to be considered as a toxic environmental pollutant, is now considered to be a new possible signal molecule following nitric oxide, carbon monoxide and hydrogen sulfide.⁴⁻⁷ Cancers, neurological disorders and cardiovascular diseases could be caused by high exogenous SO₂ levels. As exogenous SO₂ is produced via oxidation of some sulphur-containing amino acids and hydrogen sulfide in mitochondria,⁵,⁶ it is extremely important to develop selective, sensitive and rapid methods for SO₂ detection in mitochondria. When hydrated in aqueous media, SO₂ can be transformed into its derivatives bisulfite (HSO₃⁻) and sulfite (SO₃²⁻). Therefore, methods for the detection of HSO₃⁻/SO₃²⁻ such as electrochemistry, chromatography, titration and capillary electrophoresis have been developed.⁷⁻¹⁰ However, those methods can not realize imaging in cells.

Since the first sulfite fluorescent probe was reported by Chang group in 2010,¹¹ numerous probes based on nucleophilic reactions with aldehydes, Michael additions, dequenching of levulinate and coordinative interactions have been developed in recent years.¹²⁻¹⁹ Despite the remarkable progress achieved, limitations such as long detection times and poor water solubility still remain. More importantly, those intensity-based probes are susceptible to factors like external environment, substrate concentration and instrument sensitivity.

Ratiometric fluorescent probes are more advantageous than intensity-based ones. Förster resonance energy transfer (FRET) mechanism is most widely used to construct well-performing ratiometric probes.²⁰⁻³² To date, some well-behaved ratiometric fluorescent probes for SO₂ derivatives have been developed.²¹⁻³⁶ However, there is great room for improvement since these probes are still subject to some drawbacks such as unsatisfactory detection limits, long response time, and poor selectivity over H₂S. Recently, we successfully synthesized the imidazo[1,5-a]pyridine via a tandem reaction.³⁷⁻³⁹ Some fluorescent probes based on this new fluorophore for Cu²⁺, and Hg²⁺ have been constructed subsequently.⁴⁰⁻⁴² Continuing our efforts to search for new fluorophore and extend their applications,⁴³⁻⁴⁵ herein, we report a new FRET platform for the rapid detection of SO₂. Imidazo[1,5-a]pyridine was selected as donor, hemicyanine dyad as receptor, and piperazine as connection unit. The probe IPIN-SO₂ can detect SO₂⁻ rapidly (3 min) and sensitively in a wide pH range of 5–10. More importantly, IPIN-SO₂ can be used for imaging exogenous mitochondrial SO₂ in cells.

Experimental

Materials and apparatus

UV-vis spectra were recorded on a U-2600 UV-vis spectrometer (Hitachi) and fluorescence spectra were recorded on a RF-5301PC luminescence spectrophotometer (Shimadzu) at room temperature. ¹H NMR and ¹³C NMR spectra were measured on a Bruker Avance 400 (400 MHz) spectrometer (CDCl₃ as solvent and tetramethylsilane (TMS) as an internal standard). HRMS spectra were recorded on a Q-TOP6510 spectrograph (Agilent). Nikon fluorescence inverted microscope (TI 2-U) was used to record cell imaging. All reagents and solvents were purchased from commercial sources and used without further purification. Metal ion solution was prepared by dissolving the deionized water with metal chloride as raw material. The anionic solution was prepared by dissolving sodium containing compounds into deionized water. Deionized water was used in the whole absorption and fluorescence detection process.
Cell culture and imaging

Brain glioma cells were cultured in RPMI-1640 containing 10% bovine serum in a 5% CO₂/95% air incubator at 37 °C. For cell imaging experiments, the growth medium was removed and replaced by RPMI-1640 without CS. The cells were incubated in a 1 μM IPIN-SO₂ incubator at 37 °C and 5% CO₂/95% air for 30 minutes. The cells were washed with PBS three times and cell images were obtained via an inverted fluorescence microscope from Ti 2-U (Nikon, ECLIPSE, equipped with FRET system, Mercury lamp light source). For the probe, the excitation light source is 405 nm and the emission collected is 560–580 nm. The colocalization experiments have been carried out through Laser Scanning Confocal Microscope (FV1000, Olympus). For the probe, the excitation light source is 405 nm and the emission collected is 560–620 nm. For the MitoTracker® Deep Red, the excitation light source is 633 nm and the emission collected is 633 nm and the emission collected through filter is 650–700 nm.

Synthesis

Synthesis of compound 3. Compound 1 and 2 were synthesized according to the literature.³

Compound 1 (315 mg, 1 mmol) was dissolved in ethanol (15 mL), then compound 2 (190 mg, 1 mmol) was added, and 3 drops of piperidine were added. After heating and refluxing for 12 hours, the solvent was removed under reduced pressure. A deep red solid was obtained which was used for the next step without further purification.

Synthesis of the probe IPIN-SO₂. Compound 4 were synthesized according to the literature.³

Compound 4 (253 mg, 1 mmol) was added to 30 mL dichloromethane and then DMAP (183 mg, 1.5 mmol) and EDC (288 mg, 1.5 mmol) were added. After heating and refluxing for 12 hours, the solvent was removed under reduced pressure. A deep red solid was obtained which was used for the next step for further purification.

Results and discussion

Synthesis of the probe IPIN-SO₂

The synthetic route of probe IPIN-SO₂ is shown in Scheme 1. Synthetic of compound 3 was carried out according to the literature.³ Compound 1 and 2 were added to the 30 mL dichloromethane and then DMAP (183 mg, 1.5 mmol) and EDC (288 mg, 1.5 mmol) were added. After heating and refluxing for 12 hours, the solvent was removed under reduced pressure. A deep red solid was obtained which was used for the next step without further purification.

The interaction between IPIN-SO₂ and SO₃²⁻ was further studied by UV-vis spectroscopic titration in 0.1 M PBS (pH = 7.4) buffer solution. IPIN-SO₂ showed characteristic absorption at 500 nm. However, when the sulfate was added to the IPIN-SO₂ solution, the absorption peak at 500 nm decreased rapidly with the increase of sulfate concentration as shown in Fig. S1. When 10 equiv. amount of SO₃²⁻ was added to IPIN-SO₂ solution, the fluorescence intensity immediately increased at 475 nm and the fluorescence intensity at 580 nm decreased significantly. By contrast, the other competitive cations did not cause any significant fluorescence changes, indicating that IPIN-SO₂ has a better selectivity for SO₃²⁻ in the fluorescence spectrum as shown in Fig. 2.

As shown in Fig. 3, the fluorescence titration process of IPIN-SO₂ was recorded. In IPIN-SO₂ aqueous solution, with the addition of 10 equiv. of SO₃²⁻, SO₄²⁻, Cl⁻, Br⁻, H₂PO₄⁻, HCO₃⁻, F⁻, HPO₄²⁻, I⁻, NO₂⁻, NO₃⁻, S₂O₃²⁻, SO₄²⁻, HS⁻, Fe³⁺, Ca²⁺, Cu²⁺, K⁺, Na⁺, Zn²⁺, GSH (glutathione), Hcy (homocysteine), Cys (cysteine), RSC Advances Paper

Fig. 1 Ultraviolet absorption spectra of IPIN-SO₂ (10 μM) in 0.1 M PBS (pH = 7.4) buffer solution with addition of 100 μM of various species (SO₃²⁻, AcO⁻, Br⁻, H₂PO₄⁻, Cl⁻, CO₃²⁻, HCO₃⁻, F⁻, HPO₄²⁻, I⁻, NO₂⁻, NO₃⁻, S₂O₃²⁻, SO₄²⁻, HS⁻, Fe³⁺, Ca²⁺, Cu²⁺, K⁺, Na⁺, Zn²⁺, GSH (glutathione), Hcy (homocysteine), Cys (cysteine), RSC Advances Paper

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increase of \( \text{SO}_3^{2-} \) concentration, the fluorescence intensity increases at 475 nm and decreases at 580 nm, and the two emission peaks can be well separated (105 nm). The results show that the developed FRET system can effectively avoid the overlap of emission spectra and ensure the high resolution and accuracy of the determination. Moreover, when \( \text{SO}_3^{2-} \) concentration increased from 0 to 30 equiv., the fluorescence intensity ratio increased from 0.29 to 12.78, about 44 times. When \( \text{SO}_3^{2-} \) concentration was in the range of 1.5–4.0 \( \mu \text{M} \), there was a good linear relationship as shown in Fig. S2.†

According to LOD = \( 3\sigma/k \) (\( \sigma \) is the standard deviation of ten blank solutions and \( k \) is the slope of the linear calibration plot between the fluorescence intensity and the concentration of \( \text{SO}_3^{2-} \)), the detection limit was as low as 0.13 \( \mu \text{M} \).

In addition, the interference experiments were carried out under the coexistence of various species (Fig. 4). Background ions did not interfere with fluorescence intensity. Sulfite-induced fluorescence enhancement \( (I_{475}/I_{580}) \) remained unaffected by the coexistence of other species.

**Kinetic study**

In Fig. 5, the time course of fluorescence response of IPIN-SO\(_2\) aqueous solution with \( \text{SO}_3^{2-} \) is shown. The fluorescence intensity ratio \( (I_{475}/I_{580}) \) reached the maximum value in 3 min when 10 equiv. \( \text{SO}_3^{2-} \) was added and the fluorescence ratio of IPIN-SO\(_2\) almost remained unchanged with time, which indicates that IPIN-SO\(_2\) can be used as a fast response \( \text{SO}_3^{2-} \) probe.

**Effect of pH**

As shown in Fig. 6, in order to detect \( \text{SO}_3^{2-} \) efficiently and selectively, the effect of different acid concentrations on IPIN-SO\(_2\) was studied to find the suitable pH range. In PBS buffer solution, the fluorescence titration curves of IPIN-SO\(_2\) and IPIN-SO\(_2\) have no obvious change between pH 5.0 and 10.0 of fluorescence intensity ratio \( (I_{475}/I_{580}) \), indicating that the sensor...
IPIN-SO$_2$ and the sensor IPIN-SO$_2$ existing in SO$_3^{2-}$/C$_{0}$ are stable within this pH range.

**Mechanism**

As shown in Scheme 2, once the IPIN-SO$_2$ energy donor is excited, FRET will enter the hemicyanine group from the imidazole[1,5-$\alpha$]pyridine fluorescent group, which may weaken or even quench the fluorescence of the imidazole[1,5-$\alpha$]pyridine fluorescent group. Interruption of the p-$\pi$ conjugation in the hemicyanine fluorophore results in increasing the energy of its first singlet level above that of the donor group. In addition, both the probe IPIN-SO$_2$ and the donor can be activated at 380 nm, but the receptor cannot, which further confirms the FRET process in probe IPIN-SO$_2$.

To further clarify the proposed mechanism, HRMS of the reaction product was conducted. A clear mass ($m$/z 676.2735) of adduct appeared after the probe reacted with SO$_3^{2-}$ (Fig. S8†).

**Cell imaging**

As probe IPIN-SO$_2$ shows excellent optical response to SO$_3^{2-}$ in vitro, cell imaging of IPIN-SO$_2$ has been further studied in glioma cells. IPIN-SO$_2$ fluorescence is stable in living cell (Fig. S3†) and cytotoxicity is negligible at 1–16 $\mu$M concentration (Fig. S4†). Because cationic cyanine dyes may accumulate in mitochondria,$^{24,55}$ colocalization assays were performed with MitoTracker@ Deep Red FM and IPIN-SO$_2$ (Fig. 7). The fluorescence of IPIN-SO$_2$ and MitoTracker@ Deep Red FM has a significant overlap, and the overlap coefficient is 0.948 (Fig. 7d), indicating that IPIN-SO$_2$ was well distributed in mitochondria.

Then the probe IPIN-SO$_2$ was applied to SO$_3^{2-}$ imaging in living glioma cells. When the glioma cells were incubated with probe IPIN-SO$_2$ for 1 hour, the red channel showed strong fluorescence and blue channel weak fluorescence (Fig. S5†). When incubated for 0.5 hour with different concentrations of Na$_2$SO$_3$, the cells showed enhanced fluorescence of red channel and decreased fluorescence of blue channel.

Furthermore, we studied whether the probes could be used to detect exogenous bisulfite in cells. Glioma cells were

![Scheme 2 Proposed sensing mechanism of IPIN-SO$_2$ with SO$_3^{2-}$](image-url)
incubated with probe IPIN-SO$_2$ for 1 hour, washed with PBS solution three times, incubated with 0.5 mM GSH (glutathione) and 0.25 mM Na$_2$S$_2$O$_3$ for 0.5 hour, and then photographed with fluorescence inverted microscope to observe obvious fluorescence changes in glioma cells (Fig. 8). On the contrary, no significant fluorescence changes were observed when the glioma cells incubated with IPIN-SO$_2$ were incubated only with GSH or Na$_2$S$_2$O$_3$. These results indicate that the probe can detect exogenous bisulfite in glioma cells.

Conclusions

In summary, a novel FRET-based ratio fluorescence probe of imidazole[1,5-a]pyridine substituted hemicyanines has been developed. IPIN-SO$_2$ has unique selectivity and high sensitivity (detection limit 0.13 µM) for SO$_3^{2-}$, which can detect SO$_3^{2-}$ rapidly (3 min) over a wide pH range of 5 to 10. It is noteworthy that the new ratio fluorescence probe avoids automatic fluorescence, severe self-quenching and fluorescence detection errors. More importantly, the probe has been successfully applied to the identification of exogenous SO$_2$ in mitochondria in cells.

Conflicts of interest

There are no conflicts to declare.

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Notes and references

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