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Fluorogenic hydrogen sulfide (H₂S) donors based on sulfenyl thiocarbonates enable H₂S tracking and quantification†

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Hydrogen sulfide (H₂S) is an important cellular signaling molecule that exhibits promising protective effects. Although a number of triggerable H₂S donors have been developed, spatiotemporal feedback from H₂S release in biological systems remains a key challenge in H₂S donor development. Herein we report the synthesis, evaluation, and application of caged sulfenyl thiocarbonates as new fluorescent H₂S donors. These molecules rely on thiol cleavage of sulfenyl thiocarbonates to release carbonyl sulfide (COS), which is quickly converted to H₂S by carbonic anhydrase (CA). This approach is a new strategy in H₂S release and does not release electrophilic byproducts common from COS-based H₂S releasing motifs. Importantly, the release of COS/H₂S is accompanied by the release of a fluorescent reporter, which enables the real-time tracking of H₂S by fluorescence spectroscopy or microscopy. Dependent on the choice of fluorophore, either one or two equivalents of H₂S can be released, thus allowing for the dynamic range of the fluorescent donors to be tuned. We demonstrate that the fluorescence response correlates directly with quantified H₂S release and also demonstrate the live-cell compatibility of these donors. Furthermore, these fluorescent donors exhibit anti-inflammatory effects in RAW 264.7 cells, indicating their potential application as new H₂S-releasing therapeutics. Taken together, sulfenyl thiocarbonates provide a new platform for H₂S donation and readily enable fluorescent tracking of H₂S delivery in complex environments.

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Introduction

Hydrogen sulfide (H₂S) is an important gaseous molecule that plays critical roles in living systems.^{1–3} Endogenous H₂S is primarily produced from cysteine (Cys) and homocysteine (Hcy) by four main enzymes, including cystathionine β-synthase (CBS), cystathionine γ-lyase (CSE), 3-mercaptopyruvate sulfur transferase (3-MST), and cysteine aminotransferase (CAT).^{4–8} Due to its bioregulatory and protective roles, H₂S is considered as an important cellular signaling molecule, much like nitric oxide (NO) and carbon monoxide (CO).^{8–11}

Although many H₂S-related biological functions have been discovered in the past two decades, many investigations have been limited due to the lack of controllable and refined H₂S delivery systems (H₂S donors). Inorganic sulfide salts, such as sodium sulfide (Na₂S) and sodium hydrosulfide (NaHS), are widely used in H₂S investigations, but they release H₂S quickly in aqueous media, thus failing to mimic the slow and well-regulated *in vivo* H₂S generation.¹² By contrast, the H₂S release

from GYY4137, a phosphorodithioate-based H₂S donor, is slow in aqueous buffer, and the low H₂S releasing efficiency remains as a major concern when applying it to the living systems.¹³ Building from these donor scaffolds, a series of synthetic H₂S donors have been developed in the last decade.^{14–19} These donors are activated by different triggers, such as enzymes,^{20,21} cellular thiols,^{22–27} pH modulation,^{28,29} and photo activation,^{30–33} and the released H₂S exhibits promising activities in different physiological and pathological processes.^{17,18}

To expand the library of H₂S donors, we recently developed the carbonyl sulfide (COS)-based platform for H₂S donation. In this approach, caged-thiocarbamates are activated and the resultant intermediates undergo a cascade reaction to release COS, which is quickly converted to H₂S by the ubiquitous enzyme carbonic anhydrase (CA) (Fig. 1a).³⁴ Expanding on this initial report, we, as well as others, have applied the similar caged-COS systems to include a series of triggerable COS-based H₂S donors which can be activated by different mechanisms, such as reactive oxygen species (ROS),^{35–37} esterase,^{38,39} cellular nucleophiles,⁴⁰ click chemistry,⁴¹ light,^{42–44} and Cys,⁴⁵ to release H₂S under various conditions.^{45,46}

Although H₂S release from these donors has been measured using different methods, the real-time tracking of donor activation and H₂S delivery in living systems remains a key challenge due to the inherent limitations of current H₂S detection

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signals (Fig. 2b). In addition, to confirm the H₂S delivery from **FLD-1**, we treated **FLD-1** (10 μM) with Cys (100 μM) in PBS containing CA (25 μg mL⁻¹) and quantified H₂S release using the MB assay. In this experiment, 15 μM of H₂S was detected (75% releasing efficiency), which is consistent with our hypothesis that 2 equivalents of COS/H₂S would be released upon **FLD-1** activation (Fig. S2†). Taken together, these experiments demonstrate that **FLD-1** is highly responsive to Cys activation.

To determine whether H₂S release correlated directly with the observed fluorescence response, we measured the fluorescent response from **FLD-3** in the presence of Cys and CA and quantified H₂S release using the MB assay. We chose to use **FLD-3** as the model compound for these investigations because it only contains one sulfenyl thiocarbonate moiety, and therefore should simplify the reaction kinetics. In comparison, **FLD-1** contains two sulfenyl thiocarbonate groups, and the cleavage of one sulfenyl thiocarbonate would generate **FLD-4** as a reaction intermediate, which exhibits moderate fluorescence (see Fig. 4). Incubation of **FLD-3** (10 μM) with Cys (100 μM) resulted in a rapid fluorescence response with 96% of the H₂S release measured by MB. At extended time points, we observed a slight decrease in measured H₂S, possibly due to volatilization of H₂S in the headspace of the closed system or adventitious oxidation of released H₂S. Negligible H₂S was detected in the absence of CA, indicating that Cys-triggered H₂S delivery from **FLD-3** proceeds through intermediate COS formation (Fig. 3a). Importantly, the strong linear correlation between the measured fluorescence and H₂S measured from the MB method detection (first 25 min, R² = 0.988) demonstrates that fluorescent readouts can serve as reliable optical tools to track COS/H₂S release from **FLD** donors with temporal resolution (Fig. 3b). Moreover, this linear correlation suggests that choice of other fluorophores with different brightnesses and photophysical properties could be used to access different dynamic ranges of H₂S release, thus enabling this approach to be translated to different types of experimental designs.



Fig. 2 (a) Time-dependent fluorescence spectra of **FLD-1** (10 μM) in PBS (pH 7.4, 10 mM) containing Cys (100 μM) and CA (25 μg mL⁻¹). (b) Cys-dependent (0–200 μM) fluorescence turn on of **FLD-1** (10 μM) in PBS. λ_{ex} = 490 nm, λ_{em} = 500–650 nm, and slit width = 0.3 nm. The experiments were performed in triplicate and results are expressed as mean ± SD (n = 3).



Fig. 3 (a) Time-dependent fluorescence turn on (red) and H₂S release (blue) upon **FLD-3** (10 μM) activation in PBS (pH 7.4, 10 mM) containing Cys (100 μM) and CA (25 μg mL⁻¹). No H₂S was detected in the absence of CA (black). λ_{ex} = 454 nm, λ_{em} = 500–650 nm, and slit width = 0.3 nm. (b) Correlation between fluorescence measurement and MB detection. The experiments were performed in triplicate. The results are expressed as mean ± SD (n = 3).

Having confirmed the efficiency of Cys-triggered fluorescence turn on and COS/H₂S release, we next evaluated the reactivity of other **FLD** donors towards Cys activation. Treating **FLD-1–3** (10 μM) with Cys (100 μM) in PBS buffer (pH 7.4, 10 mM) resulted in a 120–500-fold fluorescence turn on over 2 h. We attribute the faster response of **FLD-2** to the more electrophilic phenyl sulfenyl thiocarbonate in comparison to the less electrophilic benzyl sulfenyl thiocarbonate in **FLD-1**. **FLD-4**, however, provided minimal fluorescence enhancement due to its strong background fluorescence. No fluorescence response from **TCN-1** (10 μM) was observed under the identical conditions, which demonstrates the stability of the thiocarbonate group in the presence of Cys (Fig. 4).

To further support our proposed activation mechanism in Fig. 1b, as well as the activation of the sulfenyl thiocarbonate group by other thiols, we incubated **FLD-1** (10 μM) in PBS



Fig. 4 Fluorescence turn on of **FLD-1** (gray), **FLD-2** (red), **FLD-3** (blue), **FLD-4** (black), and **TCN-1** (dark yellow) (10 μM) in PBS (pH 7.4, 10 mM) containing Cys (100 μM). λ_{ex} = 490 nm for **FLD-1**, 2, 4, and **TCN-1**, λ_{ex} = 454 nm for **FLD-3**, λ_{em} = 500–650 nm, and slit width = 0.3 nm. The experiments were performed in triplicate. The results are expressed as mean ± SD (n = 3).



(pH 7.4, 10 mM) with 10 equivalents of benzyl mercaptan (100 μM) for 1 h and analyzed the reaction products by HPLC (Fig. S3†). Consistent with our proposed activation mechanism, we observed **FLD-1** consumption and the formation of both benzyl disulfide and fluorescein, which supports the proposed mechanism.

In addition to Cys and BnSH, other cellular thiols and biological nucleophiles were tested to determine whether they resulted in donor activation. In these experiments, **FLD-1** (10 μM) was incubated with GSH, homocysteine (Hcy), *N*-acetyl cysteine (NAC), penicillamine (PEN), or bovine serum albumin (BSA) (100 μM), in PBS buffer (pH 7.4, 10 mM) containing CA (25 $\mu\text{g mL}^{-1}$) and the fluorescence intensity was measured after 2 h. As expected, **FLD-1** is stable in PBS at physiological pH in the absence of thiols (Fig. 5 bar 1). Incubation of **FLD-1** with Cys, NAC, GSH, and Hcy, however, led to a significant fluorescence enhancement, indicating successful donor activation and COS/H₂S release (Fig. 5 bars 2–5 and S4†). In addition, these results demonstrate that the sulfenyl thiocarbonate group is responsive to different types of thiols. In comparison, PEN resulted in only minimal fluorescence response and BSA failed to activate the donor presumably due to the bulkiness of these two thiol species, which hindered their reactions with **FLD-1** (Fig. 5 bars 6 and 7). Additionally, *N*-ethylmaleimide (NEM) pretreatment of Cys samples significantly reduced the fluorescence enhancement from **FLD-1**, confirming the necessity of the thiol-induced reduction for the donor activation (Fig. 5 bar 8).

We also tested the response of the **FLD** donors in the presence of other cellular reactive sulfur, oxygen, and nitrogen species (RSONs). **FLD-1** (10 μM) was incubated with RSONs (100 μM), such as hydrogen peroxide (H₂O₂), hyperchlorite (ClO⁻), superoxide (O₂⁻), *tert*-butyl hydroperoxide (TBHP), serine (Ser), lysine (Lys), glycine (Gly), oxidized glutathione (GSSG), and *S*-nitrosoglutathione (GSNO), and COS/H₂S release was monitored by tracking the fluorescein formation. As expected, minimal fluorescence was observed in these

experiments, confirming the stability of **FLD-1** to common RSONs (Fig. 5 bars 9–17). Because the carbonate functional group may be sensitive to esterase-catalyzed hydrolysis, we also tested the esterase stability of the sulfenyl thiocarbonate group by incubating **FLD-1** (10 μM) with porcine liver esterase (PLE, 1 U mL⁻¹). Although a slight fluorescence turn on was observed after a 2 h incubation, the observed response was much lower than that from thiol activation (Fig. 5 bar 18). Taken together, these studies demonstrate that **FLD-1** is highly responsive and selective to thiol activation and common cellular RSONs do not trigger **FLD-1** to release COS/H₂S.

After confirming the thiol-triggered COS/H₂S release from **FLD-1** in aqueous buffer, we next investigated the H₂S delivering capacity of **FLD-1** in cellular environment. In these experiments, HeLa cells were treated with **FLD-1** (50 μM) or **TCN-1** (50 μM) and H₂S release was monitored using C7-Az, a H₂S-responsive fluorescent probe.^{50,51} Incubation of HeLa cells with C7-Az (50 μM) alone resulted in a negligible fluorescence response, indicating minimal endogenous H₂S (Fig. 6 top row). Treatment with **TCN-1** also failed to provide a fluorescence signal, suggesting that the thiocarbonate group was stable and did not decompose to generate false signals in cellular environments (Fig. 6 middle row). By contrast, a strong C7-Az fluorescent signal was observed when incubating HeLa cells with **FLD-1**, suggesting that H₂S release was successfully triggered by endogenous thiols. In addition, a strong fluorescence signal was also observed from activated **FLD-1** in the fluorescein channel, confirming the fluorescence response upon donor activation (Fig. 6 bottom row). Taken together, these results demonstrate that the **FLD** donors not only function as efficacious H₂S donors in live cells, but also provide a fluorescence signal that enables observing H₂S release.

To further demonstrate the H₂S-releasing fidelity of the **FLD** donors we also investigated the anti-inflammatory activities of **FLD-1**. We pretreated macrophage RAW 264.7 cells with **FLD-1** (0–25 μM) for 2 h, followed by a 24 h incubation with lipopolysaccharide (LPS, 0.5 $\mu\text{g mL}^{-1}$) to trigger the inflammatory

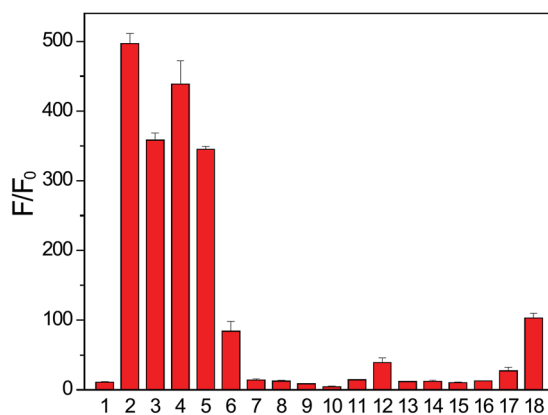


Fig. 5 Fluorescence turn on of **FLD-1** (10 μM) in the presence of cellular RSONs (100 μM): (1) **FLD-1** only, (2) Cys, (3) NAC, (4) GSH, (5) Hcy, (6) PEN, (7) BSA, (8) Cys + NEM, (9) H₂O₂, (10) ClO⁻, (11) O₂⁻, (12) TBHP, (13) Ser, (14) Lys, (15) Gly, (16) GSSG, (17) GSNO, and (18) PLE (1 U mL⁻¹). Fluorescence intensity was measured after 2 h incubation. The experiments were performed in triplicate. The results were expressed as mean \pm SD ($n = 3$).

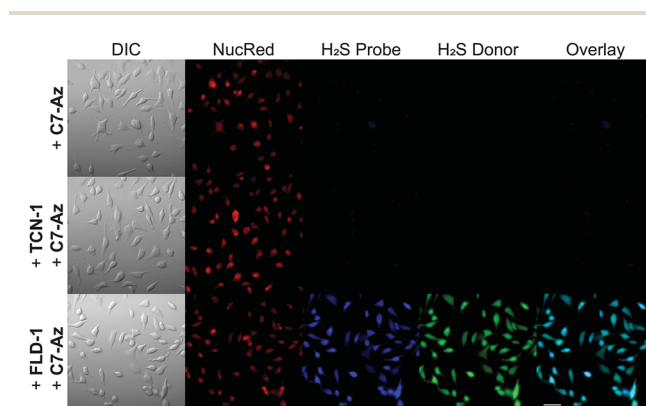


Fig. 6 H₂S delivery from **FLD-1** in HeLa cells. HeLa cells were treated with NucRed nuclear dye and C7-Az (50 μM) in DMEM or DMEM containing **TCN-1** (50 μM) (middle row) or **FLD-1** (50 μM) (bottom row) for 30 min. Cells were then washed with PBS and cell images were taken in PBS using a fluorescent microscope. Bar scale: 50 μm .



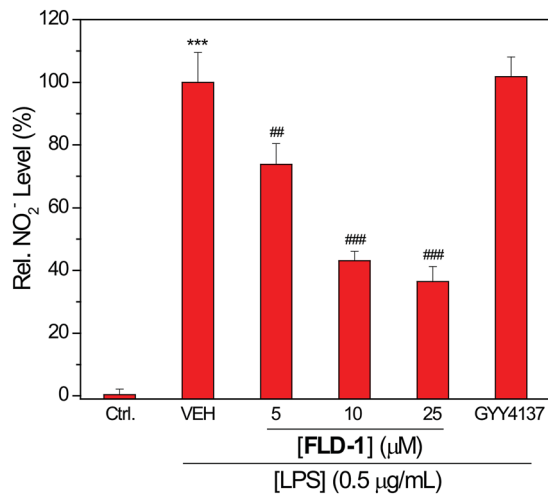


Fig. 7 Effects of FLD-1 on LPS-induced NO₂⁻ accumulation. RAW 264.7 cells were pretreated with FLD-1 (5–25 μM) or GYY4137 (25 μM) for 2 h, followed by a 24 h treatment of LPS (0.5 μg mL⁻¹). Results are expressed as mean ± SD (n = 4). ***P < 0.001 vs. the control group; ##P < 0.01 vs. vehicle-treated group; ###P < 0.001 vs. vehicle-treated group.

response. The inflammation event usually results in the NO generation, which can be monitored by measuring nitrite (NO₂⁻) accumulation. We chose to use concentrations of FLD-1 up to 25 μM because these concentrations did not induce cytotoxicity (Fig. S6†).

As expected, the pretreatment of RAW 264.7 cells with FLD-1 showed a dose-dependent inhibition of NO₂⁻ accumulation, indicating anti-inflammatory activity from FLD-1. Although GYY4137 has shown anti-inflammatory effects at higher concentration and longer incubation time (*i.e.* 100–1000 μM and 24 h incubation),⁵² such cytoprotection was not observed at the 25 μM concentration used for comparison, highlighting the efficacious H₂S release from FLD-1 in the cellular environment (Fig. 7). To further confirm that the observed effects were due to H₂S rather than other components of donor activation, we treated cells with 25 μM of TCN-1, fluorescein or benzyl mercaptan and measured NO₂⁻ production. None of these compounds attenuated NO₂⁻ generation, confirming that the anti-inflammatory activities of FLD-1 is due to H₂S release (Fig. S7†). Overall, these studies demonstrate that FLD-1 releases COS/H₂S in complex cellular environment and exhibits promising anti-inflammatory protections, indicating potential applications of FLD-1 as H₂S-releasing therapeutics.

Conclusions

In conclusion, we prepared and evaluated a class of caged sulfenyl thiocarbonates as new controllable and fluorescent COS/H₂S donors. Thiol-triggered COS/H₂S release from these molecules has been detected and visualized in both aqueous buffer and in live cells. Importantly, the concomitant release of a fluorescein reporter after H₂S release enables the real-time monitoring of H₂S release dynamics. In addition, we

demonstrate that FLD-1 exhibits a dose-dependent inhibition of the LPS-induced NO formation, which is consistent with anti-inflammatory activities of H₂S. Taken together, caged-sulfenyl thiocarbonates are promising new class of COS/H₂S donors with high potential for accessing H₂S-related protective activities, and the developed fluorescent donors provide new methods for monitoring H₂S release in real-time in complex environments.

Conflicts of interest

There are no conflicts to declare.

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