







## Geminal-dithiol-based precursors for reactive sulfur species†

Shi Xu,  Geat Ramush, Iris J. Yang, Eshani Das,  Meg Shieh  and Ming Xian \*

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**Caged gem-dithiols have been developed as the donors of reactive sulfur species (RSS), but the chemistry of free gem-dithiols as RSS donors has not been well understood. Herein, we report the study of a free gem-dithiol, 1,3-diphenylpropane-2,2-dithiol, as the precursor for several RSS. It releases H<sub>2</sub>S under physiological conditions and can be converted to a mono-S-nitrosothiol, which serves as a NO donor. Furthermore, it can be converted to 3,3-dibenzylthiirane, which is an active sulfur transfer reagent and can induce S-persulfidation.**

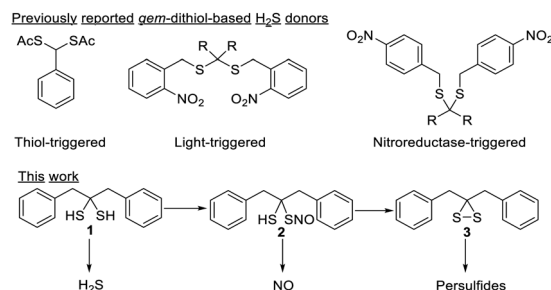
Reactive sulfur species (RSS) are important regulating molecules in biological systems. These include thiols (RSH), hydrogen sulfide (H<sub>2</sub>S), persulfides (RSSH), polysulfides (RSS<sub>n</sub>SR), and post-translational modification products on protein thiols such as S-nitrosothiol (RSNO) and sulfenic acid (RSOH).<sup>1–3</sup> Many RSS are fleeting species that exist in low concentrations, while exhibiting a variety of biological functions such as anti-oxidation and vasodilation. It is therefore important to develop chemicals (*e.g.* donors) that can controllably deliver RSS under physiological conditions. These compounds are useful for understanding the properties and functions of RSS, and have therapeutic potentials. In the past several years, many such donors have been developed, including molecules releasing H<sub>2</sub>S, H<sub>2</sub>S<sub>n</sub>, and RSSH.<sup>4–6</sup> These compounds have greatly advanced the understanding of RSS.

Among the reported H<sub>2</sub>S donors, gem-dithiol-based compounds are particularly interesting. Free gem-dithiols are normally unstable under physiological conditions and quickly decompose to release H<sub>2</sub>S. Therefore, bio-compatible protecting groups have been introduced to cage the –SH groups of gem-dithiols to create the desired H<sub>2</sub>S donors (Scheme 1).<sup>7–9</sup> Interestingly, some free gem-dithiol compounds were synthesized and characterized back in the 1950's.<sup>10</sup> We wondered if these relatively stable gem-dithiols could be directly used as RSS

donors. Herein, we report the study of a representative free gem-dithiol, 1,3-diphenylpropane-2,2-dithiol (**1**), and its derivatives. Their preparation, stability, reactivity, and ability to serve as RSS donors were studied.

While several gem-dithiols (such as methanedithiol, 2,2-propanedithiol, cyclohexanedithiol, phenylmethanedithiol) have been reported before, they are unstable and volatile liquids with pungent smells, making them unsuitable for our studies. 1,3-Diphenylpropane-2,2-dithiol (**1**), first reported by Carmack in 1959,<sup>11</sup> was prepared *via* treating ketone **4** with H<sub>2</sub>S (g) and HCl, with thioketone **5** as an intermediate (Scheme 2). This method allowed us to obtain **1** in the gram scale with 65% yield. Compound **1** is a colorless solid with a faint smell of mercaptan. It was found to be stable at room temperature in its neat form or in organic solvents, with no NMR-observable decomposition after storage for days. In water-containing solutions (for example 20% D<sub>2</sub>O/CD<sub>3</sub>CN), **1** also exhibited good stability, with no decomposition over 12 hours (Fig. S1, ESI†). However, the decomposition of **1** was noted in buffer-containing solutions (such as acetonitrile with 20% pH 7.4 PBS buffer). NMR studies demonstrated that thioketone **5** (in its enethiol form **6**) was the main decomposition product (Fig. S1, ESI†).

The decomposition of compound **1** in buffer solutions prompted us to examine its ability to release H<sub>2</sub>S. A Unisense H<sub>2</sub>S microsensor was used to measure H<sub>2</sub>S production from the solutions of **1** (50 μM) in different buffers (pH 5, 6, 7, 8). Fig. 1a shows that **1** released H<sub>2</sub>S in a pH-dependent manner. At pHs

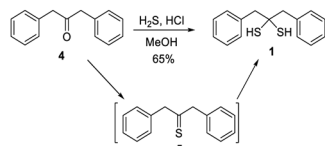


Scheme 1 gem-dithiol-based RSS donors.

Department of Chemistry, Brown University, Providence, Rhode Island, 02912, USA.  
E-mail: ming\_xian@brown.edu

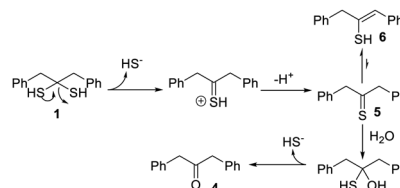
† Electronic supplementary information (ESI) available. See DOI: <https://doi.org/10.1039/d4cc01003e>



Scheme 2 The synthesis of free *gem*-dithiol **1**.

**6** and **7**,  $\sim 50 \mu\text{M}$   $\text{H}_2\text{S}$  was produced after 150 min, while only  $\sim 30 \mu\text{M}$   $\text{H}_2\text{S}$  was produced at pH 5. These results suggest that under these pHs, roughly one equivalent of  $\text{H}_2\text{S}$  could be produced from **1**, while slightly more than one equivalent of  $\text{H}_2\text{S}$  ( $\sim 68 \mu\text{M}$ ) was produced at pH 8.

To further validate  $\text{H}_2\text{S}$  release from **1**, a gas trapping experiment was performed. Briefly, in sealed vials, the solutions of **1** (1.5 mM) in different buffers (pH 5 and 7.4) were placed with a trapping vial containing 10% zinc acetate solution under room temperature for 3 hours.  $\text{H}_2\text{S}$  generated from **1** would diffuse into the trapping vial to form zinc sulfide, which was then treated with the methylene blue cocktail. The concentration of  $\text{H}_2\text{S}$  was analyzed by UV-vis absorbance at 670 nm. As shown in Fig. 1b, a strong absorbance peak at 670 nm was observed, demonstrating the generation of  $\text{H}_2\text{S}$  from **1**. These results suggested the following mechanism: in aqueous solutions, **1** undergoes elimination to produce  $\text{H}_2\text{S}$  (likely in the form of  $\text{HS}^-$ ) and thioketone **5** (the major form is enethiol **6**) (Scheme 3). This occurs both in acidic and basic pHs but basic conditions might be more efficient. Aliphatic thioketones are known to be unstable and can form complex decomposition products including oligomers and ketones.<sup>12</sup> Nonetheless, it is possible for **5** to undergo hydrolysis and release  $\text{H}_2\text{S}$ , forming ketone **4** as a product. Indeed, **4** was obtained when **1** or **6** was incubated in buffers, with 19% and

Scheme 3 The mechanism of  $\text{H}_2\text{S}$  release from **1**.

18% yields, respectively. This finding suggests that thioketones like **5** could release  $\text{H}_2\text{S}$  in buffers, but the efficiency is low.

Some thiocarbonyl compounds like arylthioamides are known  $\text{H}_2\text{S}$  donors, but their  $\text{H}_2\text{S}$  releasing mechanisms are still unclear.<sup>13</sup> The interactions between thiocarbonyls with certain biomolecules (such as cysteine and GSH) may be responsible for their  $\text{H}_2\text{S}$  release. We next wondered if **5/6** could release more  $\text{H}_2\text{S}$  under biomimicking environments. Freshly prepared solutions of **6** (10 mM) were incubated with cysteine (20 mM), HeLa cell lysate, or human plasma for 12 hours. The  $\text{H}_2\text{S}$  released was measured by the  $\text{H}_2\text{S}$  trapping method. As shown in Fig. 2, a notable increase of UV-vis absorbance was detected at 670 nm under these conditions. In contrast, only very weak  $\text{H}_2\text{S}$  production was detected when **6** was incubated in buffer alone. These results indicated biologically-relevant conditions could promote  $\text{H}_2\text{S}$  release from **6**. However, it should be noted that even under these biologically-relevant conditions, the  $\text{H}_2\text{S}$  released from **6** was still significantly less than that of the positive control (5 mM  $\text{Na}_2\text{S}$ ), suggesting that it may not be an effective  $\text{H}_2\text{S}$  donor. This adds to the speculation that the bioactivities of thiocarbonyl-based  $\text{H}_2\text{S}$  donors may not come from  $\text{H}_2\text{S}$ , but rather from the thiocarbonyl group itself.

*S*-Nitrosothiols (SNOs) are one of the key molecules involved in nitric oxide (NO) signal transduction and possess unique chemical and biological properties.<sup>14</sup> Since we had *gem*-dithiol **1** in hand, we tested its nitrosation in the hopes of preparing the *gem*-bis-SNO compound. Interestingly, we were only able to access the mono-SNO compound **2** (in 90% purity, *via* nitrosation of **1** with organic nitrites at low temperature,  $-20^\circ\text{C}$ ). SNO **2** showed the characteristic green color of tertiary SNO compounds with an obvious UV-vis absorbance peak at

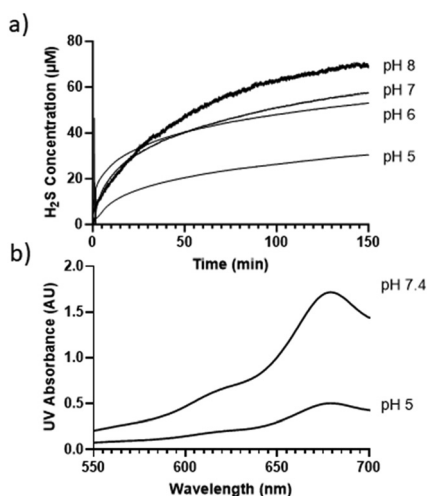


Fig. 1 (a)  $\text{H}_2\text{S}$  release profiles of **1** ( $50 \mu\text{M}$ ) in different buffers. (b) Methylene blue UV-vis absorbance spectra of  $\text{H}_2\text{S}$  released from **1** as measured by the gas trapping method (1.5 mM **1** was incubated in buffers for 3 hours.  $\text{H}_2\text{S}$  gas was trapped by zinc acetate and measured by the methylene blue method).

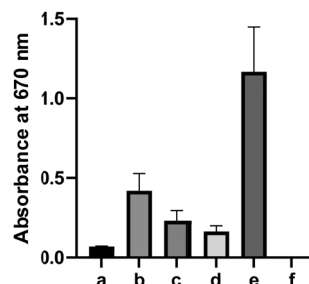


Fig. 2  $\text{H}_2\text{S}$  release from **6** measured by the gas trapping method. **6** (10 mM) or  $\text{Na}_2\text{S}$  (5 mM) was incubated in PBS buffer (pH 7.4) under various conditions.  $\text{H}_2\text{S}$  gas was trapped by zinc acetate and measured by the methylene blue method. (a) **6** only; (b) **6** with 20% HeLa cell lysate; (c) **6** with 10% plasma; (d) **6** with 20 mM cysteine; (e)  $\text{Na}_2\text{S}$  only; (f) blank.



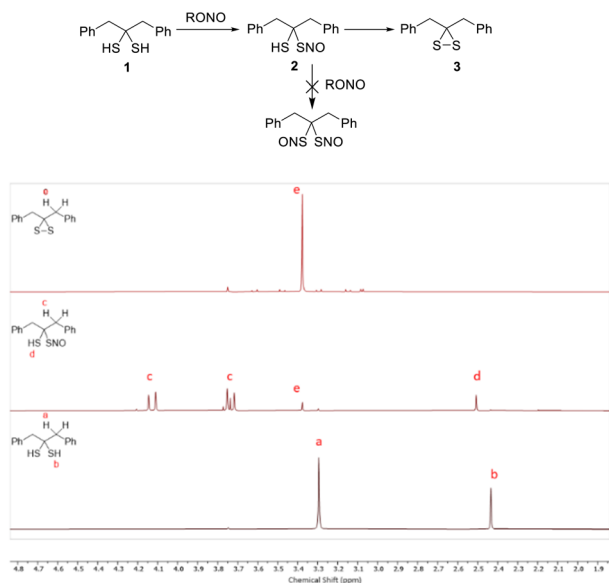


Fig. 3 Nitrosation of **1** and  $^1\text{H}$ -NMR spectra of compounds **1**, **2**, and **3**.

618 nm (Fig. S2 (ESI $^\dagger$ ),  $\epsilon = 26 \text{ M}^{-1}\text{cm}^{-1}$  in  $\text{CHCl}_3$ ). It also exhibited decent stability in solutions as determined by clean NMR spectra (Fig. 3). Attempts to further nitrosate **2** were unsuccessful, and this may be explained by the hydrogen bonding between the  $-\text{SH}$  and  $\text{NO}$  group of **2**.  $\text{SH}$ -based hydrogen bonding is known to stabilize certain structures. $^{15}$  DFT calculations were carried out to estimate the H-bond energy (see ESI $^\dagger$ ). Nevertheless, the solution of **2** could degrade in a few hours to form dithiirane **3**.

With the relatively stable SNO **2** in hand, we wondered if its conversion to **3** could release  $\text{NO}$ . To this end, an indirect  $\text{NO}$  trapping and detection experiment was performed. The *in situ* generated **2** was incubated in buffers under different pHs in a sealed 20 mL vial.  $\text{NO}$  generated in the solution was diffused into an Eppendorf vial containing  $\text{NO}$  red, an  $\text{NO}$ -specific fluorescent probe. $^{16}$  As shown in Fig. 4, the formation of  $\text{NO}$  was noted in a pH-dependent manner in all conditions. In  $\text{CHCl}_3$  and in more acidic buffers (pH 3 and 5),  $\text{NO}$  released from **2** was comparable to the positive control, a pyrrolidine-based  $\text{NONOate}$ . Under pH 7.4, 9, and 10, less  $\text{NO}$  production

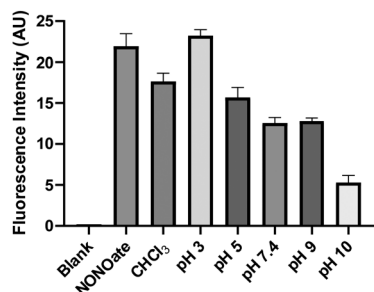
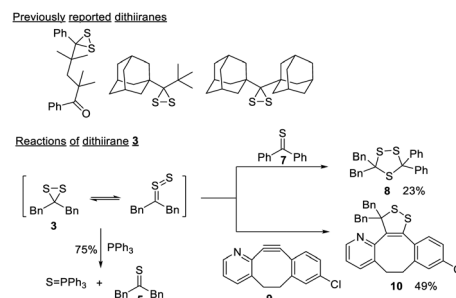


Fig. 4  $\text{NO}$  release from **2** measured by  $\text{NO}$  red. 6.4 mM **2** was incubated with  $\text{CHCl}_3$  or PBS buffers (containing 10% THF) for 1.5 h.  $\text{NO}$  was then trapped by  $\text{NO}$  red (40  $\mu\text{M}$ ), and its fluorescence ( $\lambda_{\text{em}}$  593 nm,  $\lambda_{\text{ex}}$  540 nm) was measured.

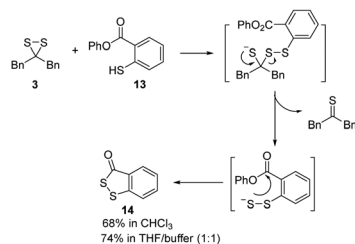
from **2** was observed. The formation of  $\text{NO}$  from **2** suggested a homolytic  $\text{S}-\text{N}$  bond cleavage process with a thiyl radical intermediate. This was confirmed by  $\text{TEMPO-9-Ac}$ , a thiyl radical fluorescent probe. $^{17}$  When **2** was incubated with  $\text{TEMPO-9-AC}$  in 10% THF/PBS, significant fluorescence turn on at 432 nm was observed (Fig. S3, ESI $^\dagger$ ) while other more stable SNOs (trityl SNO and GSNO) gave much weaker fluorescence. It is interesting to note that  $\text{NO}$  formation from **2** at higher pH (10) decreased. The results suggested that the conversion of **2** to **3** could also proceed *via* an anionic pathway to form nitroxyl ( $\text{HNO}$ ). We attempted to trap  $\text{HNO}$  using  $\text{GSH}$ , $^{18}$  but were unable to obtain the corresponding sulfina-mide product. Nevertheless,  $\text{HNO}$  generation was still possible. These results suggest **2** could be considered as an interesting  $\text{NO}$  (or  $\text{HNO}$ ) donor.

Dithiiranes are the smallest cyclic disulfides. $^{19}$  The  $\text{S}-\text{S}$  bond of dithiiranes is forced to adopt a ‘‘cisoid’’ geometry, resulting in maximum lone pair interactions and a weak  $\text{S}-\text{S}$  bond. $^{20}$  Due to this property, most dithiiranes are unstable and can only exist as reaction intermediates. $^{21,22}$  A few isolable dithiiranes $^{23-25}$  have been reported (Scheme 4), and they are derived from highly sterically hindered substrates. To verify the compound obtained in our reactions was indeed a dithiirane, we studied its properties and reactions. **3** could be generated from the direct reaction between **1** and an excess of *t*-butyl nitrite. It was isolated as a yellow liquid ( $\sim 90\%$  purity) once the solvent was removed. **3** showed a UV-vis absorbance at 441 nm (Fig. S4, ESI $^\dagger$ ), which corresponds to the  $n\pi \rightarrow \sigma^*$  transition of the dithiirane ring and is similar to the dithiirane reported before (at 452 nm). $^{24}$  In its neat form, **3** was found to be unstable at room temperature and could degrade completely in 6 hours. When it was dissolved in organic solvents, it appeared to be more stable, but still decomposed in  $\sim 4$  days. The degradation products were complex, with thioketone **5** being one of the identified compounds, and this matched the properties of reported dithiiranes. $^{26}$  The treatment of **3** with  $\text{PPh}_3$  or  $\text{Et}_3\text{N}$  resulted in more rapid formation of **5**. In the case of  $\text{PPh}_3$ , triphenyl phosphine sulfide ( $\text{Ph}_3\text{P}=\text{S}$ ) was isolated in 75% yield (Scheme 4). The reaction between **3** and  $\text{PPh}_3$  indicated that dithiiranes could be effective sulfur transfer reagents while the corresponding thioketones appeared to lack this reactivity.



Scheme 4 The structures of reported dithiiranes and dithiirane **3**'s reactions.





Scheme 5 Assessing the sulfur transferring capability of **3** using **13**.

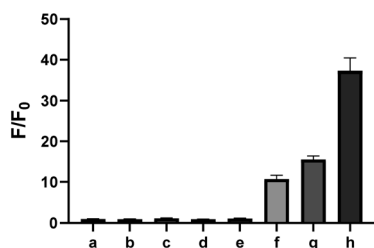


Fig. 5 Fluorescence enhancements of SSP4 (5 μM) with persulfidated papain samples and controls. (a) blank; (b) **3** only; (c) **6** only; (d) papain only; (e) papain + **6**; (f) papain + **3**; (g) papain + DTNB + **1**; (h) papain + DTNB + Na<sub>2</sub>S; results are represented as the mean ± SEM (*n* = 3).

Dithiiranes can be considered as the isomers of thiocarbonyl *S*-sulfides,<sup>19</sup> which are usually *in situ* generated by the prolonged heating of trithiolanes. These thiocarbonyl *S*-sulfides are known to react with alkynes or thioketones to form cycloaddition products.<sup>27</sup> We thus treated **3** with thiobenzophenone **7** and a strained cyclooctyne **9** (Scheme 4). The corresponding products (trithiolane **8** and the cyclic disulfide **10**) were obtained in modest yields. These results demonstrated that isolated dithiiranes could perform thiocarbonyl *S*-sulfide-mediated 1,3-dipolar cycloadditions under mild conditions.

Given the possibility of **3** being a unique sulfur transfer reagent, we wondered if it could transfer its sulfur to thiols (RSH), which would form persulfides (RSSH). This type of sulfur species plays important roles in redox biology,<sup>1</sup> but currently reliable methods to induce persulfidation in biological systems are still needed. We treated **3** with a model RSH compound **13** in both organic and water-containing solvents (Scheme 5). The desired sulfur transfer product **14** was obtained in good yields. Although **3** was found to be unstable and would degrade to complex products (including **6**) in aqueous solutions, we tested its ability in inducing protein persulfidation. Briefly, papain (a cysteine protease) was treated with **3** in tris buffer for 30 min. The protein was then purified by a PD-10 column to remove excess small molecules and their byproducts. The level of papain persulfidation was analyzed by an established protocol using the fluorescent probe SSP4.<sup>28</sup> As shown in Fig. 5, papain treated with **3** gave significant fluorescence, albeit not as strong as the signal from papain treated with DTNB and Na<sub>2</sub>S, an authentic method for protein persulfide formation. The combination of compound **1** with DTNB also resulted in considerable

fluorescence. Other controls, including papain treated with **6**, did not give detectable fluorescence. The control experiment with only compound **3** was to demonstrate that the PD-10 column could effectively remove small molecules. As such, the signal from papain treated with **3** was not due to the incomplete removal of **3** from the sample. These results suggest that dithiirane compounds have the potential to be developed as useful persulfidation reagents. However, structural modifications to enhance their stability in aqueous solutions will be needed.

In conclusion, we studied the reactions and properties of a stable *gem*-dithiol **1** and its derivatives. **1** can serve as a H<sub>2</sub>S donor. Its SNO derivative **2** shows good stability. To the best of our knowledge, compound **2** is the first compound with both free thiol and nitrosothiol moieties in the structure, making it a unique precursor for both NO (or HNO) and reactive sulfur species. Dithiirane **3**, which is generated from **2** after NO release, is a sulfur transfer reagent and can be used to induce protein persulfidation. Further structural optimization on these molecules may provide reagents with better stability and specificity (as H<sub>2</sub>S donors, NO donors, or protein persulfidation reagents), and that is ongoing research in our lab.

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## Conflicts of interest

There are no conflicts to declare.

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