Chemiluminescent probes for imaging H$_2$S in living animals†

J. Cao,$^{a,b}$ R. Lopez,$^c$ J. M. Thacker,$^a$ J. Y. Moon,$^a$ C. Jiang,$^d$ S. N. S. Morris,$^e$
J. H. Bauer,$^b$ P. Tao,$^{a,b}$ R. P. Mason$^c$ and A. R. Lippert$^{a,b}$

Hydrogen sulphide (H$_2$S) is an endogenous mediator of human health and disease, but precise measurement in living cells and animals remains a considerable challenge. We report the total chemical synthesis and characterization of three 1,2-dioxetane chemiluminescent reaction-based H$_2$S probes, CHS-1, CHS-2, and CHS-3. Upon treatment with H$_2$S at physiological pH, these probes display instantaneous light emission that is sustained for over an hour with high selectivity against other reactive sulphur, oxygen, and nitrogen species. Analysis of the phenol/phenolate equilibrium and atomic charges has provided a generally applicable predictive model to design improved chemiluminescent probes. The utility of these chemiluminescent reagents was demonstrated by applying CHS-3 to detect cellularly generated H$_2$S using a multi-well plate reader and to image H$_2$S in living mice using CCD camera technology.

Introduction

Hydrogen sulphide (H$_2$S) is increasingly recognized as an important mediator of mammalian physiology and pathology, playing roles in vasorelaxation,$^4$ angiogenesis,$^7$ redox regulation,$^4$ neuromodulation,$^4$ lifespan,$^3$ Huntington’s disease,$^6$ Down syndrome,$^7$ diabetes,$^6$ and cancer.$^9$ In mammals, endogenous H$_2$S is generated from cystathionine β-synthase (CBS),$^{10}$ cystathionine γ-lyase (CSE),$^{11}$ and 3-mercaptopyruvate sulphur transferase (3MST).$^{12}$ Similar to its reactive cousins, nitric oxide (NO) and hydrogen peroxide (H$_2$O$_2$),$^{13}$ H$_2$S mediates cellular function via direct chemical interaction with biological molecules and can have widely disparate effects that depend on concentration, tissue localization, and the molecular environment.$^{14-16}$ For example, H$_2$S in colon cancer promotes tumour growth by stimulating angiogenesis and supporting cellular energetics,$^{17}$ whilst H$_2$S in prostate cancer slows cell growth, disrupts androgen receptor transactivation, and reduces angiogenesis by inhibiting the function of hypoxia-inducible factor 1.$^{19}$ Given the delicate site- and concentration-dependent actions of H$_2$S, easy methods for accurate spatiotemporal detection in living cells and animals are in urgent demand and promise to significantly contribute to an increased understanding of this reactive signalling molecule.

Common methods of H$_2$S detection, including the methylene blue assay, ion-selective electrodes, amperometric sensors, and gas chromatography, have varying strengths and weaknesses, but all generally fall short of being able to detect H$_2$S inside of intact living organisms.$^{19}$ Fluorescent probes offer the ability to target specific analytes$^{20,21}$ and there has been an explosion of recent activity in the development of dyes responsive to H$_2$S and its derivatives.$^{22-24}$ Unfortunately, imaging endogenous H$_2$S remains rare, and often requires advanced confocal microscopy setups to allow precise same-cell tracking or two-photon excitation coupled with ratiometric imaging.$^{25,26}$

This instrumentation is unavailable to many researchers, reducing the potential impact of these newly developed tools.$^{27}$ Furthermore, there are few examples of in vivo imaging of H$_2$S$^{28}$ and imaging deep mammalian tissue remains a frontier field for H$_2$S detection. At the heart of the matter is a lack of sensitivity and depth penetration due to background autofluorescence, light scattering, photoactivation/photobleaching, and probe kinetics that require long incubation times to accumulate signal. In order to address these technological challenges and develop tools to better elucidate the precise mechanisms of H$_2$S production and function, we have herein developed a series of selective and sensitive chemiluminescent probes for rapid imaging of H$_2$S in living animals.

Triggered chemiluminescence emission can provide a highly sensitive readout of biological analytes.$^{29}$ Chemiluminescence
and chlorinated 3-methoxybenzaldehyde derivatives 1a–c were reacted with trimethyl orthoformate in the presence of p-toluenesulfonic acid to give acetals 2a–c. These acetals were subjected to triethyl phosphite and boron trifluoride diethyl etherate at 0 °C, which afforded the diethyl methoxy (3-methoxyphenyl) methyl phosphonates 3a–c. Next, enol ethers 4a–c were obtained through Horner–Wadsworth–Emmons reaction by treating phosphonates 3a–c with nBuLi and 2-adamantanone.44 Nucleophilic demethylation using sodium ethanethiolate provided the phenols 5a–c. The activated ester 6, prepared according to analogous literature procedures, was coupled to the phenols to provide 7a–c, azide-bearing precursors to the final 1,2-dioxetanes.45,46 Finally, a [2 + 2] cycloaddition with singlet oxygen was accomplished by bubbling oxygen through a solution of 7a–c and the sensitizer Rose bengal with visible light irradiation, delivering the chemiluminescent probes CHS-1, CHS-2, and CHS-3.

Results and discussion

Design and synthesis of CHS-1, CHS-2, and CHS-3

The CHS probe series was designed such that chemiluminescent emission would be initiated by the H2S-mediated reduction of the azide group, followed by self-immolative carbonate cleavage yielding the free phenolate bearing the 1,2-dioxetane

(Scheme 1). The negatively charged phenolate will emit light spontaneously upon decomposition via an intramolecular chemically initiated electron exchange luminescence (CIEEL) mechanism.39–41 This newly produced light can be observed directly or by transfer of its energy to acceptor molecules like quantum dots, rhodamine, or fluorescein.42 In our studies, we employ a commercially available Emerald II Enhancer solution that consists of a cationic polymer and a dye with similar photophysical properties to fluorescein. The polymer reduces water-induced quenching by providing a hydrophobic environment for the chemiluminescent reaction and the dye effectively red shifts the luminescence emission making it more amenable for biological imaging applications.

By adapting a literature procedure,43 we optimized an efficient and modular synthetic route to access the probes CHS-1, CHS-2, and CHS-3 (Scheme 2). First, unsubstituted, fluorinated, and chlorinated 3-methoxybenzaldehyde derivatives 1a–c were reacted with trimethyl orthoformate in the presence of p-toluenesulfonic acid to give acetals 2a–c. These acetals were subjected to triethyl phosphite and boron trifluoride diethyl etherate at 0 °C, which afforded the diethyl methoxy (3-methoxyphenyl) methyl phosphonates 3a–c. Next, enol ethers 4a–c were obtained through Horner–Wadsworth–Emmons reaction by treating phosphonates 3a–c with nBuLi and 2-adamantanone.44 Nucleophilic demethylation using sodium ethanethiolate provided the phenols 5a–c. The activated ester 6, prepared according to analogous literature procedures, was coupled to the phenols to provide 7a–c, azide-bearing precursors to the final 1,2-dioxetanes.45,46 Finally, a [2 + 2] cycloaddition with singlet oxygen was accomplished by bubbling oxygen through a solution of 7a–c and the sensitizer Rose bengal with visible light irradiation, delivering the chemiluminescent probes CHS-1, CHS-2, and CHS-3.

![Scheme 1](Image)

**Scheme 1** Spiro adamantane 1,2-dioxetanes for chemiluminescent H2S detection at neutral pH.

![Scheme 2](Image)

**Scheme 2** Syntheses of CHS-1, CHS-2, and CHS-3.
Response and selectivity

With the first three CHS probes in hand, we proceeded to measure their luminescent responses to H$_2$S using an F-7000 Hitachi spectrophotometer. At pH 7.4, treatment of the CHS probes with H$_2$S resulted in instantaneous luminescent emission that increased over a course of 10 minutes in a dose-dependent manner (Fig. 1). Addition of the fluorescein-based Emerald II Enhancer provided a red-shifted peak centred at 545 nm compared to the 470 nm emission of the phenolate (Fig. 1, insets). Under these physiologically relevant conditions, we observed an increase in the integrated luminescent response to H$_2$S from CHS-1 to CHS-2 to CHS-3, giving 5-fold, 4-fold, and 12-fold turn-on responses respectively. It should be noted that no background corrections were performed and the values in Fig. 1 are direct instrumental values to provide an accurate comparison between probes. At pH 10, CHS-1 provided the highest chemiluminescence intensity and response, giving a 7-fold increase in photon emission in the first 10 minutes after adding 200 mM H$_2$S (Fig. S1†). Under these alkaline conditions, the H$_2$S-triggered chemiluminescent emissions of the fluorinated CHS-2 and chlorinated CHS-3 were lower than CHS-1. The background signal also increases with CHS-2 and CHS-3, reducing the relative increases over control to 2-fold and 3-fold respectively. A key advantage of these probes is that they display an immediate concentration-dependent emission of light that persists for over an hour (Fig. S2†), an ideal property for the high-throughput detection and imaging of H$_2$S generated in biological environments.

We next tested the selectivity of CHS-1, CHS-2, and CHS-3 for H$_2$S against other biologically relevant reactive sulphur, oxygen, and nitrogen (RSON) species. The response of CHS-1 to 200 mM Na$_2$S in 20 mM HEPES buffered to pH 7.4 was tested against other RSON species by adding 5 mM reduced glutathione (GSH), 1 mM l-cysteine and homocysteine, and 200 mM of S-nitrosoglutathione, sulfi te (SO$_3$$^-$), hydrogen peroxide (H$_2$O$_2$), hypochlorite (OCl$^-$), tert-butyl hydroperoxide (tBuOOH), nitroxyl (HNO), nitric oxide (NO), and nitrite (NO$_2$$^-$). None of the species tested displayed significant increases in luminescence intensity over the blank control (Fig. 2a). Additionally, the response to Na$_2$S was minimally perturbed by the presence of physiological levels of GSH, l-cysteine, and homocysteine. We observed similar results when CHS-2 and CHS-3 were evaluated for their selectivity in 20 mM HEPES at pH 7.4 (Fig. 2b and c). These response and selectivity data demonstrate that CHS-1, CHS-2, and CHS-3 are able to detect H$_2$S at physiologically relevant pH with minimal interference from competing analytes.

Mechanistic studies of chemiluminescent H$_2$S detection

We next sought to understand the factors that lead to increased light production and optimized response for 1,2-dioxetane chemiluminescent probes. First, we investigated the role of the phenol/phenolate equilibrium. Since the measurement of the pK$_a$ of the phenolate dioxetane products of the CHS probes is complicated by their rapid chemiluminescent decomposition, we used the reported experimental values of phenol, 2-fluorophenol, and 2-chlorophenol (Fig. 3c and d). The H$_2$S-stimulated emission intensity at pH 7.4 displays an increasing trend with increased phenol acidity, indicating that ionization of the phenol is critical to attaining good luminescence response under these conditions (Fig. 3c). On the other hand, there is no clear correlation with phenol pK$_a$ and the chemiluminescent response at pH 10 (Fig. 3d). We further investigated the nature of the chemiluminescent emission by performing quantum chemistry calculations on the phenolate structures released from CHS-1, CHS-2, and CHS-3 after reaction with Na$_2$S (Tables S1–S3†). Geometries were optimized using density functional theory (DFT) at the B3LYP/6-311+G(d,p) level of theory, and the charge on each atom was...
calculated using an electrostatic potential (ESP) model at the M06/6-31+G(d,p) level of theory. All calculations were carried out with the integral equation formalism polarizable continuum model (IEF-PCM) in water as solvent using the Gaussian 09 program package. While we found no correlation between the charge on the phenolic oxygen (O8) and the chemiluminescent response at pH 7.4 (Fig. 3f), an excellent correlation ($R^2 > 0.99$) was observed at the response at pH 10 (Fig. 3f). ESP charge calculations performed with B3LYP and ωB97XD functionals also provided good correlations ($R^2 > 0.97$) of the O8 charge and the chemiluminescent response at pH 10 (Fig. S3f). These data indicate that at lower pH, the chemiluminescent emission is governed by the equilibrium between the protonated phenol and unprotonated phenolate oxygen, and are in agreement with previous observations.49 CHS-3 is the most readily ionized and therefore shows the highest chemiluminescent emission. On the other hand, at pH 10 the phenolate species dominates for all three deprotected dioxetanes and the efficiency of chemiluminescent emission is predicted by the more negative O8 charge density, probably due to an increased propensity towards initiation of the first intramolecular electron transfer step of CIEEL.49,50 These data reveal trends that, when taken together, provide a powerful predictive model for the design of improved chemiluminescent reagents.

Using CHS-3 to detect cellular H$_2$S

Our results show that CHS-3 provides the most robust light emission at physiological pH when compared to CHS-1 and CHS-2. We therefore examined the ability of CHS-3 to detect cellular H$_2$S production in human lung adenocarcinoma epithelial cells (A549). These cells express the enzyme cystathionine γ-lyase (CSE),51 which can utilize homocysteine (Hcy) as a substrate for H$_2$S production. We first demonstrated the ability of CHS-3 to detect exogenous Na$_2$S in a multi-well plate reader format (Fig. 4a), and determined an estimated detection limit (blank control + 3 S.D.) of 5.4 μM. We then incubated A549 cells with Hcy, a substrate for the enzyme CSE. This resulted in
In vivo imaging of H$_2$S using CHS-3

We next investigated the ability of CHS-3 to image H$_2$S at physiological pH using an IVIS Spectrum. An opaque 96-well plate was loaded with 0, 25, 50, 100, and 200 µM Na$_2$S in 20 mM HEPES buffer (pH 7.4) containing 20% Emerald II Enhancer. CHS-3 was added at 40 µM and imaged to reveal a clear increase in luminescence intensity with increasing H$_2$S concentrations (Fig. 5a). Averages of repeated experiments provide a good linear response in the range of 0–200 µM when imaged 30 s after exposure to H$_2$S (Fig. 5b). We next applied a mouse carcass model to determine if CHS-3 would have sufficient light output to be observable through mammalian tissue. The carcasses of sacrificed SCID/BALB-C mice were injected with CHS-3 and either a vehicle control (Fig. S4a and b†) or 0.4 µmol H$_2$S (Fig. S4c and d†) into the peritoneal cavity. An increase in luminescence could be clearly observed in the peritoneum of the carcass injected with H$_2$S versus the carcass injected with the vehicle control.

Confident that light emission from CHS-3 was capable of significant tissue penetration, we finally sought to establish the ability of CHS-3 to image H$_2$S in living animals. C6 brown mice were administered i.p. injections on one side of their peritoneal cavity. The skin was raised during injections to avoid puncturing internal organs. Images were acquired 30 s after injecting 0.08 µmol CHS-3 and either 0.4 µmol Na$_2$S or a vehicle control (H$_2$O) in 100 µL HEPES buffered at pH 7.4 containing 20% Emerald II Enhancer. The final concentration of Na$_2$S in the injection was 4 mM. While vehicle control experiments produced modest signal (Fig. 5c), the mice that received Na$_2$S treatments displayed robust emission of light that was easily detected through their tissue (Fig. 5d). Quantification of the total photon flux from replicate experiments (Fig. S5†) revealed ~4-fold increase ($n = 3$, $p = 0.025$) in the luminescence response in the Na$_2$S treated mice versus vehicle controls (Fig. 5e). The agents were well tolerated and the mice showed no immediate outward signs of malaise. Taken together, these data provide a key milestone towards the development of a new class of in vivo imaging tools for investigating biological hydrogen sulphide.

Conclusions

We have designed and synthesized three 1,2-dioxetane chemiluminescent reaction-based H$_2$S probes, CHS-1, CHS-2, and
CHS-3 that display immediate light emission upon reacting with H2S at physiological pH, a significant advance for H2S detection technology. These reagents provide a sensitive and selective detection platform for H2S using spectrophotometers, multi-well plate readers, and IVIS Spectrum instruments. We have provided a computational and experimentally supported mechanistic framework that serves as a predictive model for designing sterically hindered 1,2-dioxetanes with improved light emission based on the pKa of the phenol released after reacting with H2S and the relative atomic charge densities of these structures. Finally, we demonstrated that CHS-3 was not only capable of detecting cellular H2S produced by A549 cells treated with homocysteine at neutral pH, but also has the rare ability to image H2S in living animals. While CHS-3 provides an exciting proof of principle for in vivo chemiluminescence imaging, we are currently engaged in improving the sensitivity and biocompatibility of chemiluminescent 1,2-dioxetane reagents for diverse applications, and anticipate that these new optimized systems will provide powerful whole animal imaging tools across a range of biological analytes and parameters.

Acknowledgements

This work was supported by Southern Methodist University (start-up funds to A.R.L.) and the Center for Drug Design, Discovery, and Delivery (CD4 seed money to A.R.L.). Imaging was facilitated by the SW-SAIR, a Resource of the Simmons Cancer Center supported in part by NIH P30 1CA142543 and used an IVIS Spectrum, which was purchased under NIH 1S10RR024757. The Texas Advanced Computing Center (TACC) at the University of Texas at Austin and Southern Methodist University’s Center for Scientific Computation provided computing resources. We thank Maciej Kukula of the Shimadzu Center for Advanced Analytical Chemistry at the University of Texas at Arlington for acquiring high-resolution mass spectrometry data. The authors would also like to thank Dr Son’s research group for use of the irradiation lamp.

Notes and references
