9-2015

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Recommended Citation

Yueqin Zheng, Xingyue Ji, Kaili Ji, Binghe Wang, Hydrogen sulfide prodrugs—a review, Acta Pharmaceutica Sinica B, Volume 5, Issue 5, 2015, Pages 367-377, ISSN 2211-3835, doi: https://doi.org/10.1016/j.apsb.2015.06.004.

Acta Pharmaceutica Sinica B 2015;5(5):367–377

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Acta Pharmaceutica Sinica B

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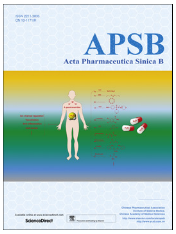

REVIEW

Hydrogen sulfide prodrugs—a review

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Received 5 May 2015; accepted 3 June 2015

Abstract Hydrogen sulfide (H_2S) is recognized as one of three gasotransmitters together with nitric oxide (NO) and carbon monoxide (CO). As a signaling molecule, H_2S plays an important role in physiology and shows great potential in pharmaceutical applications. Along this line, there is a need for the development of H_2S prodrugs for various reasons. In this review, we summarize different H_2S prodrugs, their chemical properties, and some of their potential therapeutic applications.

KEY WORDS

Hydrogen sulfide (H_2S);
Gasotransmitters;
H_2S prodrugs;
H_2S-hybrid nonsteroidal anti-inflammatory drugs;
Controllable H_2S prodrugs;
Hydrolysis-based H_2S prodrugs

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Peer review under responsibility of Institute of Materia Medica, Chinese Academy of Medical Sciences and Chinese Pharmaceutical Association.

http://dx.doi.org/10.1016/j.apsb.2015.06.004

1. Introduction

Hydrogen sulfide (H_2S), a well-known lethal, toxic gas with the smell of rotten eggs, is recognized as one of the three gasotransmitters in mammals, which also include nitric oxide (NO) and carbon monoxide (CO)[1–6]. The literature evidence suggests that hydrogen sulfide possesses the following activities: anti-inflammatory[7–9], anti-tumor[10], ion channel regulation[11–13], cardiovascular protection[14–16] and antioxidation[17]. However, the exact role that hydrogen sulfide plays depends on the specific circumstance, its concentration, and the interplays with other signaling molecules, especially NO and CO[18]. This is a major area of research in developing hydrogen sulfide-based therapeutics, but is beyond the scope of this review. Another major issue is finding appropriate ways of delivering hydrogen sulfide to the relevant location, at the right concentration, and with the appropriate pharmacokinetics. Much of this issue stems from the fact that it is unrealistic to use gaseous hydrogen sulfide itself or its salt such as sodium sulfide in therapeutic applications in human. Thus there is a great deal of interest in searching for appropriate hydrogen-sulfide-releasing agents, which are commonly referred to as H_2S donors or prodrugs. This review provides a summary of developments in this field mostly during the last five years with a focus on the chemistry concepts[19].

1.1. *H_2S chemistry*

H_2S is a weak acid and soluble in water (up to 80 mmol/L at 37 °C[20]). The pK_a values (37 °C) for the first and second dissociation steps are about 6.88 and 19, respectively[21]. Under physiological conditions (pH = 7.4), H_2S largely exists in two forms: the neutral molecular form (H_2S) and an ionic form (HS^-) (Scheme 1). S^{2-} is a very minor component simply because of the second pK_a being very high. However, the bioactive form is still unknown, and the term H_2S is usually used referring to the total sulfide species. Although H_2S has good solubility in water, it is still very unstable in solution. It is easy oxidized in the presence of oxygen. In addition, the volatility of hydrogen sulfide adds complications to experiments. For example, half of the dose of H_2S could be lost in 5 min from open cell culture wells[22]. H_2S concentration can decrease so rapidly that the precise measurement of H_2S concentration is a great challenge in this field[23–28].

1.2. *H_2S biology*

In mammals, three enzymes are involved in sulfur-containing amino acid metabolism and thus responsible for the *in vivo* production of H_2S. Two of them are pyridoxal-5′-phosphate (PLP)-dependent enzymes: cystathionine β-synthase (CBS) and cystathionine γ-lyase (CSE). CBS is expressed predominantly in the central nervous system (CNS)[29]. Relatively high concentrations (47 µmol/L to 166 µmol/L) of H_2S have been observed in the brains of mammals[30–32]. The normal cellular function of CBS is in the trans-sulfuration pathway, catalyzing the condensation of homocysteine with serine to form cystathionine. In the 1980s, CBS isolated from rat liver and kidney was reported to produce H_2S from cysteine[33]. In contrast to CBS, CSE is mainly responsible for the production of H_2S outside of the CNS[7]. CBS and CSE share a common feature of catalytic promiscuity. The relative contributions of CBS and CSE to H_2S generation at low homocysteine concentration are about 7:3. However, CBS activity is confined to chemical transformations at the β-position[34], while CSE is proficient at catalyzing reactions at the β- and γ-carbons of substrates[35]. Furthermore, because homocysteine appears to be unable to bind to the site at which the external aldimine with PLP is formed in CBS, CSE's contribution to the H_2S pool is increased under conditions of moderate and severe hyperhomocysteinemia. A third H_2S-producing enzyme, 3-mercaptopyruvate sulfurtransferase (3MST), was thought to exist, as H_2S was not depleted in *CBS* knockout mouse brain[36]. 3MST, a PLP-independent enzyme, is localized in the neurons in the brain along with cysteine aminotransferase (CAT), while CBS is localized in the astrocytes, a type of glia, in the CNS. 3MST and CAT are also found in the vascular endothelium. CAT catalyzes the reaction of L-cysteine with α-ketoglutarate to form 3-mercaptopyruvate (3MP), which is further catalyzed by 3MST to generate H_2S in the presence of thiol and reducing agents (Fig. 1)[37]. Overall, H_2S production in mammals is intimately connected to the metabolic pathways of sulfur containing amino acids. The PLP-dependent trans-sulfuration pathway, which contains both CBS and CSE for H_2S production, is localized in the cytosol. H_2S synthesis *via* CAT and 3MST occurs in the cytosol and mitochondria.

$$H_2S \underset{}{\overset{Ka_1}{\rightleftharpoons}} H^+ + HS^- \overset{Ka_2}{\rightleftharpoons} 2H^+ + S^{2-}$$

Scheme 1 Hydrogen sulfide disassociation[19], where $pKa_1 = 6.88$, and $pKa_2 = 19$.

2. H_2S prodrugs

In the past several years, many series H_2S prodrugs have been developed. They could be divided into three general classes: plant-derived natural products, hydrolysis-based H_2S prodrugs, and controlled-release H_2S prodrugs.

2.1. *Plant-derived natural products*

Allium vegetables, represented by garlic and onions, have long been considered as salubrious foods that have anti-inflammatory functions, and their active ingredients have been shown to reduce the risk of diabetes and cardiovascular diseases[38–40]. It was not until 2007 that studies from Kraus' group showed that the

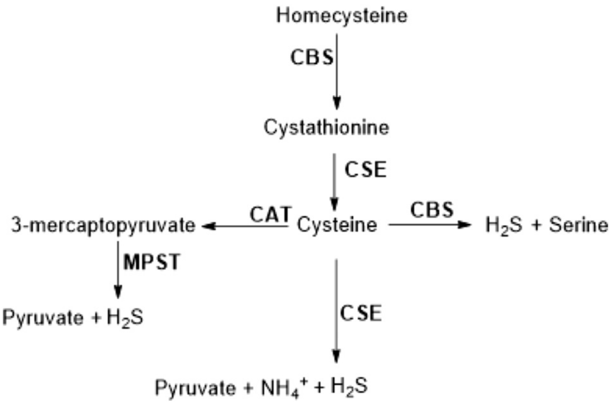


Figure 1 Enzymatic pathways of H_2S production in mammalian cells.

vasoactivity of garlic compounds was correlated with H_2S production[41], which suggested that the major beneficial effects of allium vegetable diets are mediated by the biological production of H_2S from organic polysulfides.

To date, several sulfur-containing components from garlic or garlic preparations have been identified (γ-glutamylcysteines and alliin in the intact garlic; ajoene and allyl mercaptan in the steam-distilled garlic oil; *S*-allyl-cysteine and *S*-allyl-mercaptocysteine in the aged garlic extract; and methiin in the garlic homogenate). Among all the different components, only three of them, *S*-allyl-cystein (SAC), diallyl disulfide (DADS), and diallyl trisulfide (DATS) have been shown to have pharma cological effects, which are correlated with the H_2S signaling pathway[41,42]. DADS and DATS are major components of garlic oil[43], and are derived from allicin, which is unstable in water (Scheme 2).

Organic polysulfides DADS and DATS act as H_2S donors when they react with biological thiols including GSH, or by human red blood cells *via* glucose-supported reactions. It is proposed that DADS undergoes nucleophilic substitution at the α-carbon and yield a key intermediate allyl perthiol to form H_2S (Scheme 3). The chemical conversion of organic polysulfides to H_2S is facilitated by allyl substituents and dependent on the number of tethering sulfur atoms. Another study of DADS found that the hepatocyte cytotoxicity of DADS might be attributed to the inhibition effect of H_2S on cytochrome oxidase[44], suggesting biological production of H_2S from DADS.

The third sulfur-containing compound in allium vegetables related to H_2S production is *S*-allyl-cysteine (SAC), a reduced form of alliin, which is the major component in aged garlic extract. Studies from Zhu′s group[42,45] showed that SAC and CR-SPRC, a cysteine analog of SAC, upregulated CSE expression and increased plasma H_2S concentrations. Rats used in an acute myocardial infarction and heart failure model were treated with SAC or CR-SPRC, respectively. It was found that SAC and its analog significantly lowered mortality and improved cardiac function. The activity of CSE, CAT, GSH, and plasma H_2S concentration were increased in SAC-pretreated and CR-SPRC-treated rats, suggesting its cardioprotection effect *via* a H_2S-mediated pathway. However, there is no report on H_2S production directly from SAC in the biological systems.

Recently, Kondo et al.[46] published a H_2S prodrugs: SG-1002 (Fig. 2), which is a polysulfur mixture containing 92% α sulfur, 7% sodium sulfate and a trace amount of other sulfur derivatives. In one study, SG-1002 was administered to C57BL/6J or *CSE* knockout mice to investigate the effects of genetic modulation of CSE and exogenous H_2S in a pressure overload-induced heart failure model. It was found that *CSE* knockout mice exhibited significantly greater cardiac dilatation and dysfunction than wild-type mice after transverse aortic constriction, and cardiac-specific *CSE* transgenic mice maintained cardiac structure and function after transverse aortic constriction. H_2S afforded by SG-1002 could upregulate the vascular endothelial growth factor (VEGF)-Akt-endothelial nitric oxide synthase (eNOS)-nitric oxide (no)-cGMP pathway with preserved mitochondrial functions, attenuated oxidative stress, and increased myocardial vascular density. The results show oral H_2S therapy prevents the transition from compensated to decompensated heart failure in part *via* upregulation of endothelial nitric oxide synthase and increased nitric oxide bioavailability. However what needs to be noted concerning these studies is that the mechanism of H_2S release from SG-1002 is not described. More studies are needed to prove the correlation of H_2S production and the observed pharmacological effects.

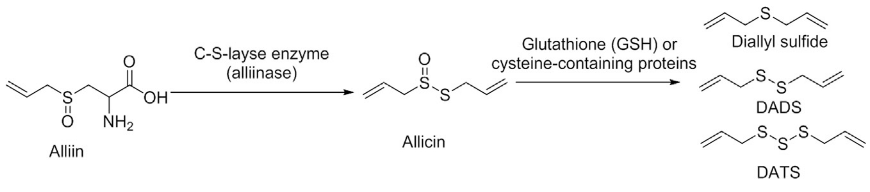
2.2. Hydrolysis-based H_2S prodrugs

Hydrolysis-based H_2S prodrugs primarily consist of four classes of analogs: namely, inorganic sulfite salts including NaHS, Na_2S and CaS; Lawesson's reagent and analogs; 1,2-dithiole-3-thiones (DTTs); and arylthioamides derivatives. For arylthioamides derivatives, some classified them as thiol-activated H_2S donors. Since these compounds are easily hydrolyzed to generate H_2S in PBS buffer, they are summarized in this section.

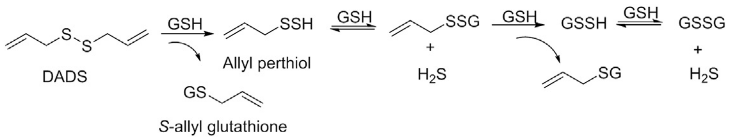
2.2.1. Inorganic sulfite salts

NaHS and Na_2S are two widely used H_2S donors in basic research. Upon hydrolysis, both compounds could generate H_2S quickly in PBS buffer (pH 7.4). In aqueous state under physiological pH, the ratio of HS^-/H_2S is around 3:1[19,47].

NaHS and Na_2S have been extensively used in studying the biological effect of hydrogen sulfide. For example, in an ovalbumin-treated rat model[48], NaHS treatment could increase peak expiratory flow (PEF), and decrease goblet cell hyperplasia, collagen deposition score, the total cells recovered from bronchoalveolar fluid, and influx of eosinophils and neutrophils. Additionally, administration of NaHS also significantly attenuated activation of pulmonary inducible nitric oxide synthase (iNOS). Those results suggested that H_2S possessed anti-inflammatory and



Scheme 2 Sulfur-containing compounds in intact garlic resulting from conversion of amino acid alliin.



Scheme 3 Proposed H_2S production from DADS by reactions involving thiol.

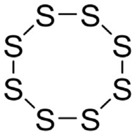


Figure 2 The structure of α sulfur in SG-1002.

anti-remodeling effect in asthma pathogenesis, presumably by the cystathionine-gamma-lyase (CSE)/H_2S pathway. Using NaHS as a H_2S donor, Du et al.[8] examined the possible role of H_2S in the pathogenesis of oleic acid (OA)-induced acute lung injury (ALI) and its regulatory effects on the inflammatory response. Intraperitoneal injection of NaHS (56 μmol/L) into OA-treated rats increased the pressure of oxygen in the arterial blood (PaO_2), reduced the lung wet/dry ratio and alleviated the degree of ALI. Additionally, NaHS decreased inflammatory cytokine such as IL (interleukin)-6 and IL-8 levels and increased anti-inflammatory cytokine IL-10 levels in the plasma and lung tissues. Similarly, Na_2S inhibited IL-1β levels and significantly increased anti-inflammatory cytokine IL-10 levels in an acute lung injury model[49].

In addition to anti-inflammatory effect, NaHS or Na_2S also showed pro-inflammatory[50–52], ion channel regulation[11,12], cardiovascular[53], and neurogenic regulation[54] effects. Although NaHS and Na_2S presented promising biological results both *in vitro* and *in vivo*, the likelihood of their use in clinical applications is small due to reasons such as release kinetics, smell, lack of ability to target, and difficulty in controlling its concentration because of hydrogen sulfide's volatility. Nevertheless, encouragingly, a sodium sulfide solution (IK-1001) for intravenous injection has successfully completed a phase I clinical trial, thus pointing to the possibility of applications in well-defined situations[4].

Another potential inorganic H_2S donor is calcium sulfide (CaS), which is one of the effective components in a traditional medicine, hepar sulphuris calcareum[55]. Compared to NaHS and Na_2S, CaS is chemically more stable. However, there is only limited information on the effectiveness of CaS as H_2S donor[56].

2.2.2. *Lawesson's reagent and analogs*

Lawesson's reagent, which is widely used for sulfurization in organic synthesis[57], also releases H_2S upon hydrolysis, and it has been used as a H_2S donor in some studies. Compared to inorganic sulfide, the release rate with Lawesson's regent is much slower. After incubation of Lawesson's reagent in buffer or rat liver homogenate for 60 min, the conversion to H_2S was about 18% or 11%, respectively[58]. In work by Medeiros et al.[59], Lawesson's reagent was used as H_2S donor to evaluate its protective effect against alendronate (ALD)-induced gastric damage in rats. In this study, Lawesson′s reagent was orally administrated once daily for 4 days. Induction of gastric damage by ALD (30 mg/kg) was seen 30 min after ALD administration. The results showed that pretreatment with Lawesson's reagent (27 μmol/kg) attenuated ALD-mediated gastric damage, reduced TNF-α, IL-1β, and malondialdehyde formation; lowered myeloperoxidase activity; and increased the level of GSH in the gastric tissue. All those results suggested that Lawesson's reagent plays a protective role against ALD-induced gastric damage by activation of ATP-sensitive potassium (K_{ATP}) channels. In another study[60], Lawesson's reagent also attenuated ethanol-induced macroscopic damage in a dose-dependent fashion. However, Lawesson's reagent also releases H_2S spontaneously upon hydrolysis in aqueous solution, and it suffers from poor water solubility, which may pose a limit for its further applications.

GYY4137, a water-soluble derivative of Lawesson's reagent, could also release H_2S upon hydrolysis[16]. Compared to Lawesson's reagent and sulfide salts, it can generate H_2S at a slower rate. With the use of the H_2S microelectrode or the DTNB (5, 5-dithiobis-(2-nitrobenzoic acid)) assay, it was found that incubation of GYY4137 in aqueous solution (pH 7.4, 37 °C) resulted in the release H_2S, and the concentration of H_2S peaked at around 6–10 min, and remained at a low level (<10 μmol/L) over a sustained period of 100 min. In one experiment, the administration of GYY4137 (133 μmol/kg i.v. or intraperitoneal) to anesthetized rats could also boost the concentration of H_2S in plasma to around 75 μmol/L at the 30 min point, and the concentration remained elevated (above 40 μmol/L) for more than 180 min. Additionally, GYY4137 did not cause any significant cytotoxic effect, or alter the cell cycle profile or p53 expression of cultured rat vascular smooth muscle cells. However, NaHS was previously reported to induce apoptotic cell death of cultured fibroblasts and smooth muscle cells. The differences in the safety profile between GYY4137 and NaHS may be attributed to the differences in H_2S release rate and the concentration of H_2S generated.

In work published by Liu et al.[61], GYY4137 was employed as a H_2S donor to investigate its effects on CVB3-induced myocarditis and possible underlying mechanisms. The results showed that GYY4137 suppressed CVB3-induced secretion of enzymes implicated in cardiocyte damage including LDH, CK-MB, and decreased the level of pro-inflammatory cytokines, such as TNF-α, IL-1β and IL-6. Moreover, GYY4137 also inhibited the activation of NFκB and the IκBα degradation induced by CVB3. Notably, the phosphorylation of p38, ERK1/2 and JNK1/2 induced by CVB3 was also suppressed by GYY4137. Taken together, GYY4137 exerted its anti-inflammatory effect in CVB3-infected cardiomyocytes, which was possibly associated with H_2S generation by GYY4137. The anti-inflammatory mechanism may be associated with the inhibition of NFκB and the mitogen-activated protein kinase (MAPK) signaling pathway.

Additionally, at a concentration of 400 or 800 μmol/L, GYY4137 also showed some anti-cancer effect with 30%–70% death in seven different human cancer cell lines (HeLa, HCT-116, Hep G2, HL-60, MCF-7, MV4-11 and U2OS)[62] and no effect on the survival of normal human lung fibroblasts (IMR90, WI-38). In contrast, NaHS did not showed any anticancer effect (400 μmol/L), and only showed less potent growth inhibition (15%–30%, 800 μmol/L). The author attributed such difference to the different H_2S release rate between GYY4137 and NaHS. Incubation of GYY4137 (400 μmol/L) in culture medium released low concentrations (<20 μmol/L) of H_2S, with the concentration sustained over a period of 7 days. In contrast, incubation of NaHS (400 μmol/L) in the same way led to much higher concentrations (up to 400 μmol/L) of H_2S with a much shorter duration (1 h). It is well-known that the effect of H_2S is concentration-dependent with high concentrations (above 250 μmol/L) being toxic[63], thus it is easy to understand that release kinetics and peak concentration would make much difference to the overall effect of a H_2S donor. The *in vivo* antitumor effect of GYY4137 was also evaluated. In a xenograft mice model (HL-60 and MV4-11 cells), GYY4137 could significantly inhibit tumor growth at dosages of 100–300 mg/kg/day.

Despite all the success described above, other independent studies sometimes showed opposite effect when NaHS was used as a donor. For example, H_2S in the form of NaHS showed protective effect for colon cancer cells[64], increased proliferation of colon cancer cells, and reduced apoptosis in several cell lines[65]. These disparate observations may be due to the use of different H_2S donors, which release H_2S at different rates, give different byproducts, and have different peak concentrations. Although ZYJ1122 (Fig. 3), an analog of GYY4137 lacking sulfur, was inactive in all cancer cell lines tested, it is unclear what byproducts GYY4137 would generate in cells, because the metabolism for GYY4137 is expected to be complicated. Additionally, it should be kept in mind that the percentage of hydrolysis for GYY4137 is low, which means that the majority of GYY4137 remained in the cells. Since relatively high concentrations of GYY4137 was used (400 and 800 μmol/L), it is entirely possible that the observed anticancer effect may be caused by GYY4137 itself or its metabolism products, and not necessarily the released H_2S. The convoluted situation with the observed effects of "H_2S" is a strong indication that future experiments need to be benchmarked against a standard and standard conditions with careful control and documentation of concentrations.

In order to tune the H_2S release capability of GYY4137, structural modifications on the phosphorodithioate moiety were made to GYY4137 to afford a series of *O*-substituted phosphorodithioate-based H_2S donors (Fig. 3)[66]. Their H_2S releasing properties were evaluated by fluorescence methods. After incubation (100 μmol/L) in PBS buffer (pH 7.4) for 3 h at room temperature, *N*,*O*-diarylated donors and GYY4137 could release H_2S with a final concentration of around 800 nmol/L. However, the *O*-alkylated donors showed very weak H_2S production (data not shown in the paper). The protective effects of *N*,*O*-diarylated donors against H_2O_2-induced oxidative damage in H9C2 cells were investigated. Specifically, the donors were incubated with the cells for 24 h before H_2O_2 was added. Then cell viability was determined by the CCK-8 assay after incubation for another 5 h. The results showed that in the absence of a H_2S donor, cell viability decreased by about 65%. In the presence of H_2S donors (*N*,*O*-diarylated donors, GYY4137 and NaHS), a much higher level cell viability was observed, especially for one *N*,*O*-diarylated donor, which increased the cell viability to about 95% at the concentration of 100 μmol/L. These results suggested that the H_2S donors did present protective effects against oxidative injury. As mentioned above, the biological results obtained for these donors should be carefully associated with the generation of H_2S. Further experiments may be needed to clarify this.

2.2.3. *Arylthioamides derivatives*

A series of arylthioamides were synthesized by Vincenzo Calderone et al.[67], and their H_2S release properties were evaluated. The synthesized compounds were incubated with or without L-cysteine in PBS buffer at 37 °C, and H_2S release was recorded by amperometry. The results showed that compounds **1**–**3** (Fig. 4) did not generate a detectable level of H_2S (<2 μmol/L) in the absence of L-cysteine; however, they did release H_2S in the presence of L-cysteine with $C_{\max}$ of about 10 μmol/L. For compounds **4** and **5** with strong electron-withdrawing substituents, no detectable levels of H_2S were observed with or without L-cysteine. Based on those results, it seems that the H_2S release mechanism for arylthioamides is thiol-activated, and Xian et al.[68] did classify arylthioamides as thiol-activated H_2S donors. However, some analogs in this series also generated detectable amounts of H_2S in the absence of L-cysteine, especially compound **12**, which did not show any difference in the amount of H_2S released with or without L-cysteine. It is well characterized that hydrolysis of thioacetamide would lead to H_2S formation. So it could be concluded that the hydrolysis of arylthioamides could also give H_2S. Actually, Wallace et al.[69] classified these compounds as hydrolysis-based H_2S donors. It may be more reasonable to say that both mechanisms contribute to H_2S generation because there is no clear evidence to exclude either.

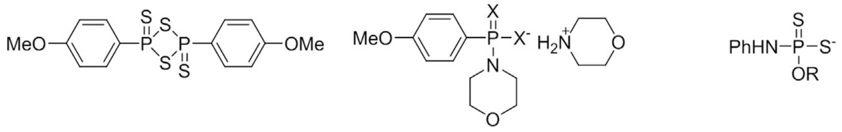
After confirmation of H_2S release from arylthioamides, compound **1** was chosen for further pharmacological studies. It strongly abolished the noradrenaline-induced vasoconstriction in isolated rat aortic rings and hyperpolarized the membranes of human vascular smooth muscle cells in a dose-dependent fashion. After oral administration of compound **1**, the systolic blood pressure of the animals was significantly reduced. These findings make arylthioamides promising H_2S donors for further study.

No matter what the H_2S release mechanism for arylthioamides is, it should be noted that incubation of 1 mmol/L of the donors only release H_2S with a $C_{\max}$ value of about 10 μmol/L, which means that the major species in solution is still the donor itself. Thus it is still premature to associate the observed bioactivities with the generation of H_2S alone, because the bioactivities may be caused by the donor itself or a combination of various species. Actually, this issue is quite common among the organic H_2S donors. More detailed and well-designed control experiments are needed to address this issue.

2.2.4. *1,2-Dithiole-3-thiones and H_2S-hybrid nonsteroidal anti-inflammatory drugs*

1,2-Dithiole-3-thiones (DTT) has also been used as a H_2S donor. Although its H_2S-release mechanism is still not fully clarified, it is widely accepted that hydrolysis is part of the underlying mechanism for the generation of H_2S from DTT[57].

The use of nonsteroidal anti-inflammatory drugs (NSAIDs) suffers from unacceptable risk of gastrointestinal ulceration and bleeding[70–73]. In order to reduce such side effects, DTTs have been conjugated to NSAIDs to form HS-hybrid NSAIDs (HS-NSAIDs, Fig. 5), which showed significant reduction of gastrointestinal damage compared to the parent NSAIDs[73,74]. In addition, HS-NSAIDs also boosted the anti-inflammatory effect of their NSAIDs counterparts. In a work by Fiorucci et al.[75], DTT was conjugated to diclofenac to afford a HS-NSAID-hybrid ATB337, and its anti-inflammatory effect was investigated along with diclofenac in rats. In a rat air pouch model, orally



Lawesson's reagent

GYP4137: X = S;
ZYJ1122 : X = O;

Phosphorodithioate

Figure 3 The chemical structures for Lawesson's reagent-based H_2S donors.

administrated ATB-337 dose-dependently suppressed the activity of both COX-1 and COX-2, and the efficiency was comparable to that of the diclofenac. Additionally, pretreatment with ATB-337 and diclofenac led to a reduction of carrageenan-induced paw swelling volume. Notably, pretreatment with ATB-337 at 10 μmol/kg achieved a reduction in edema formation comparable to that seen with diclofenac at 30 μmol/kg. This enhanced potency was probably associated with the generation of H_2S from ATB-337.

An enhanced anti-inflammatory effect was also observed for ATB-429[76]. In addition to their anti-inflammatory effect, other HS-NSAIDs including HS-sulindac (HS-SUL), HA-aspirin (HS-ASA), HS-ibuprofen (HS-IBU), and HS-naproxen (HS-NAP), were also reported to exhibit anti-proliferative effect against human colon, breast, pancreatic, prostate, lung, and leukemia cancer cell lines. The conjugation with 5-(4-hydroxyphenyl)-1,2-dithiol-3-thione (ADT-OH) significantly increased the growth inhibitory effect of NSAID by 28- to >3000-fold[77].

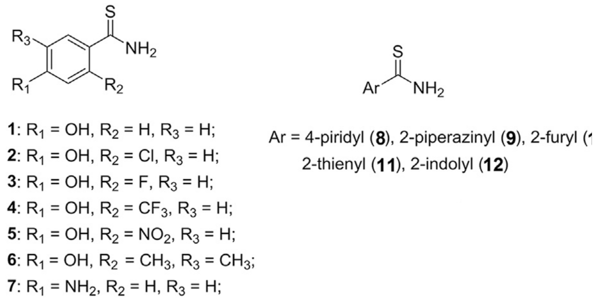


Figure 4 The chemical structures for arylthioamides.

Along the line of NSAID's antiproliferation effect, Kashfi et al.[78] prepared a compound NBS-1120 (Fig. 6), which could release NO, H_2S and aspirin at the same time. NBS-1120 inhibited HT-29 colon cancer growth with IC_{50} values of 45.5 ± 2.5, 19.7 ± 3.3, and 7.7 ± 2.2 nmol/L at 24, 48, and 72 h time points, respectively. This is the most potent NSAID-based anticancer agent so far. Mechanistic studies showed that NBS-1120 induced apoptosis, and arrested the cells at G0/G1 phase. NBS-1120 also showed promising *in vivo* antitumor effect. It significantly inhibited tumor growth by 85% in mice bearing a human colon cancer xenograft.

Accumulating evidence supports that H_2S plays a vital role in the modulation of mitochondrial cell death pathways and in the regulation of cellular bioenergetics[3,4,80]. Multiple studies revealed that H_2S donors help maintain mitochondrial integrity, reduce the release of mitochondrial death signals, and attenuate mitochondrially-regulated cell death responses of various types[79,81,82]. Szabo et al.[83] prepared a compound AP39 (Fig. 6) with two moieties: ADT-OH for H_2S generation and triphenylphophinium (TPP) for mitochondrial targeting. Cell imaging studies confirmed that AP39 was primarily internalized in mitochondria[84]. After confirming the mitochondria-targeting H_2S delivery, compound AP39 was employed to investigate its effect on bioenergetics, viability, and mitochondrial DNA integrity in bEnd.3 murine microvascular endothelial cells *in vitro*. At a

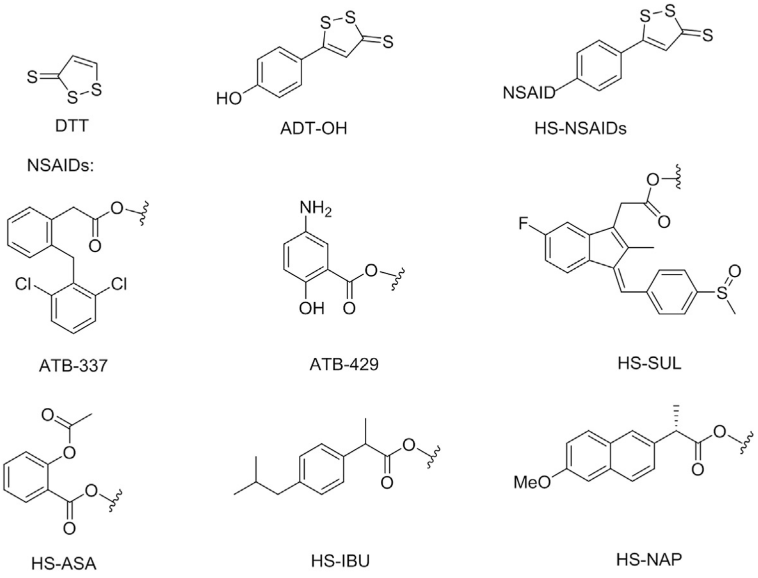


Figure 5 The chemical structures for HS NSAID hybrids.

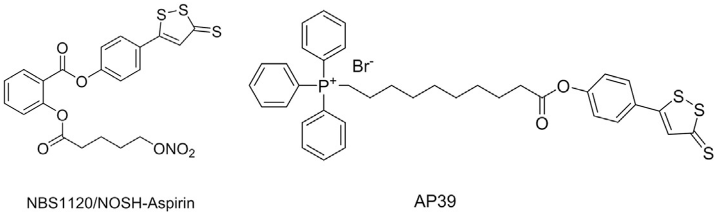


Figure 6 The chemical structure for NBS1120[79] and AP39.

concentration of 100 nmol/L, incubation of AP39 with bEnd.3 cells caused an increase in basal oxygen consumption rate (OCR), which represented respiratory reserve capacity, a key bioenergetic parameter. Meanwhile, AP39 (30 and 100 nmol/L) could also induce an increase in FCCP (carbonyl cyanide 4-(trifluoromethoxy) phenylhydrazone)-stimulated OCR. However, when the concentration of AP39 was increased to 300 nmol/L, an inhibitory effect was observed instead. AP39 could also attenuate the loss of cellular bioenergetics during oxidative stress caused by glucose oxidase. Additionally, Co-treatment of ADT-OH with TPP targeting moiety did not show any antioxidant or cytoprotective effect in oxidatively stressed endothelial cells even at a concentration of 300 nM, which is attributed to its inability to enter mitochondrial compartment. In contrast, ADT-OH without the TPP targeting moiety did not show any antioxidant or cytoprotective effect in oxidatively stressed endothelial cells even at a concentration of 300 nmol/L, which is attributed to its inability to enter mitochondrial compartment. In summary, the various mitochondrial effects observed for AP39 are consistent with the role of H_2S in the regulation of mitochondrial function.

Although DTT and its NSAID hybrids showed promising H_2S-related bioactivities both *in vitro* and *in vivo*, it is still unclear how those agents release H_2S *in vivo*. Hydrolysis for sure partially contributes to the release of H_2S from DTT. Because of the presence of disulfide bonds in DTT, thiols could also activate DTT through reduction to release H_2S. Therefore, further experiments are needed to elucidate its H_2S release mechanism.

2.3. *Controllable H_2S prodrugs*

The goal of controllable H_2S prodrugs was to develop H_2S prodrugs, which are stable in aqueous solutions and during sample preparation[85]. The prodrugs can release H_2S in the presence of triggers, which could be enzymes, pH, biomolecules, UV-light, and others. However, this is still a great challenge in this field. Currently, there are three examples: thiol activation, light activation, and bicarbonate activation.

2.3.1. *Thiol activation*

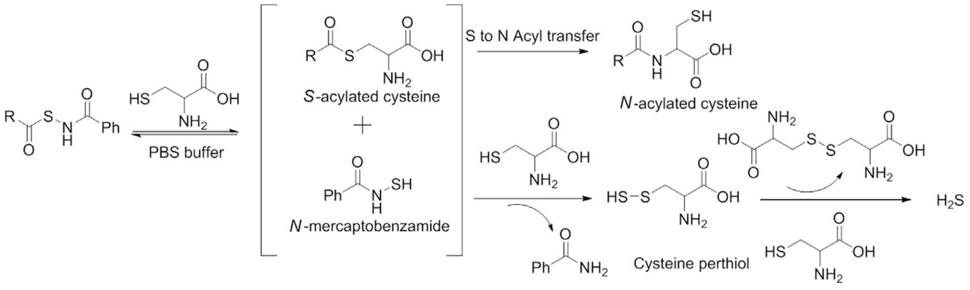
In 2011 Xian's group[85] developed the first thiol activated H_2S prodrugs: *N*-mercapto (N-SH)-based derivatives. The strategy was based on the instability of the N-SH bond. The thiol group was first protected with acyl groups, and then the protected nitrogen-sulfur bond could be stable to some degree. In the presence of thiol species in the biological system, H_2S release can be triggered through reduction. A detail mechanism is shown in Scheme 4. The prodrug is first activated by thiol exchange between a thiol species (cysteine or GSH) and the prodrug to generate *S*-acylated cysteine and *N*-mercaptobenzamide. Then one of the intermediates, *N*-mercaptobenzamide, reacts with cysteine to form cysteine perthiol, which is followed by interaction with cysteine to release H_2S. In this mechanistic study, the Xian's group found that perthiol could also be a key intermediate in H_2S generation. In 2013, Xian's lab[86] published a series of perthiol-based H_2S prodrugs, with a release mechanism similar to that of the previous example. Briefly, thiol exchange initiates the reaction to form penicillamine perthiol intermediate, which is followed by thiol attack again to produce either a disulfide and H_2S (Scheme 5, pathway a,), or a new perthiol, which would interact with another thiol species to release H_2S (Scheme 5, pathway b).

To show the therapeutic potential of perthiol H_2S prodrugs, Xian's laboratory also tested the protective effect of these prodrugs against myocardial ischemia/reperfusion (MI/R) injury in a murine model system, since H_2S was proven to show such effects. In these experiments, mice were subjected to 45 min left ventricular ischemia followed by 24 h reperfusion. Then prodrugs or vehicles were administered into the left ventricular lumen at 22.5 min of myocardial ischemia. Compared to vehicle-treatment alone, mice treated with prodrugs displayed a significant reduction in circulating levels of cardiac troponin I and myocardial infarct size per area-at-risk, suggesting that perthiol H_2S prodrugs indeed exhibit cardiac protection in MI/R injury. It should be noted that the reaction between prodrugs and cysteine yields many reactive sulfane sulfur species. Therefore, further studies on H_2S-related and sulfane sulfur-related mechanisms are still needed.

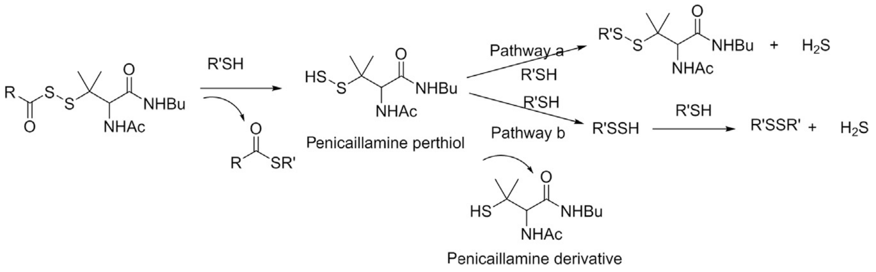
Based on similar strategies, Calderone and coworkers[87] reported dithioperoxyanhydride as a thiol-activated H_2S prodrugs in 2013. The acylpersulfides were proposed to be key intermediates. The H_2S-releasing mechanism is the same as that of perthiol H_2S prodrugs (Scheme 6).

2.3.2. *Photo-induced H_2S prodrugs*

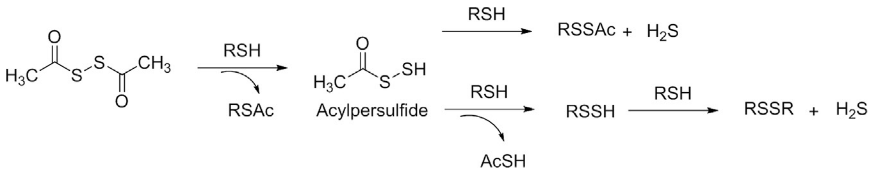
The second type of controllable H_2S prodrugs is light-activated H_2S prodrugs. Recently, there have been two example published. The first one is *gem*-dithiol-based-H_2S prodrugs. In 2013, Xian and coworkers[88] identified geminal-dithiol (*gem*-dithiol) as a structure, which could release H_2S in aqueous solution. Then a photo-cleavable structure (a 2-nitrobenzyl group) was introduced to protect the *gem*-thiols group. When the molecules were exposed to UV-light, *gem*-dithiols were regenerated. Subsequent hydrolysis leads to H_2S release. Based on this strategy, several *gem*-dithiol-based H_2S prodrugs were prepared. Methylene Blue assay indicated that 200 μmol/L prodrugs could generate a peak concentration of 36 μmol/L H_2S under UV irradiation (365 nm). However, there are two



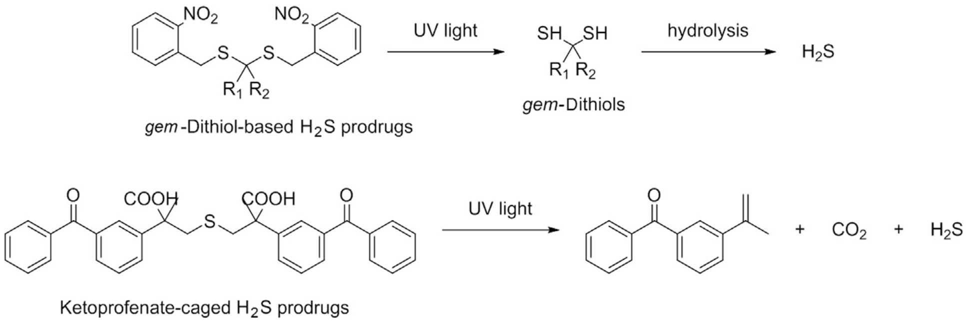
Scheme 4 Proposed N-SH H_2S prodrugs H_2S releasing mechanism.



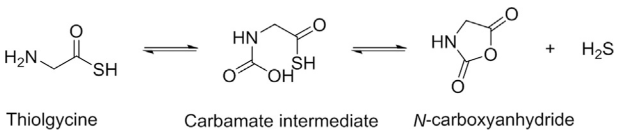
Scheme 5 Proposed perthiol H_2S prodrugs H_2S releasing mechanism.



Scheme 6 Proposed dithioperoxyanhydride H_2S releasing mechanism.



Scheme 7 H_2S release from photo-induced H_2S prodrugs.

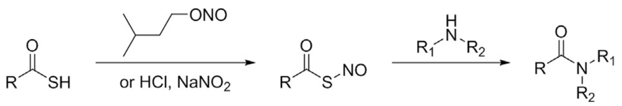


Scheme 8 Proposed mechanism of H_2S release from thiolamino acids.

obvious drawbacks of these prodrugs. First, H_2S release rate depends on the hydrolysis of *gem*-dithol, which is nearly fixed. Second, the reactive byproducts 2-nitrosobenzaldehyde can react with H_2S, which results in diminishing H_2S generation. Later, Nakagawa's group[89] investigated another type of photo-induced H_2S prodrugs: ketoprofenate-caged H_2S prodrugs (Scheme 7). Upon UV irradiation (300–350 nm) for 10 min, 500 μmol/L of the prodrug would generate 30 μmol/L of H_2S in fetal bovine serum together with 2-propenylbenzophenone and CO_2. These two photo-induced H_2S prodrugs successfully demonstrated the photo-triggering concept, but the cytotoxicity induced by UV-light could limit their applications.

2.3.3. *Thiolamino acid*

Thiolamino acids as the third class of controllable H_2S-releasing prodrugs were first reported by Giannis and coworkers[90] in 2012. Thioglycine and thiovaline were shown to release H_2S in the presence of bicarbonate under physiological conditions. The mechanism is shown in Scheme 8.



Scheme 9 Amidation of thiolacid.

The thioamino acids interacted with bicarbonate to form carbamate intermediates, which undergoes a cyclization reaction leading to *N*-carboxyanhydride and H_2S release (Scheme 8). ^{1}H NMR spectroscopy studies were carried out to measure the decomposition of thioglycine in the presence of $NaHCO_3$. In a 40 mmol/L bicarbonate solution at 40 °C, 35% *N*-carboxyanhydride were formed in 72 h. Since there is a high bicarbonate concentration (27 mmol/L) in blood at physiological pH, thiolamino acids can be an H_2S prodrug candidate. Giannis and coworkers[91] compared the H_2S-releasing capacities of thiolamino acids with that of GYY4137. About 50 μmol/L H_2S from 100 μmol/L of thioglycine could be detected by a fluorescent probe dibromobimane, while GYY4137 liberated less H_2S at the same condition. Giannis and coworkers also tested the pharmacological benefits of such H_2S prodrugs. Results showed that thioglycine and thiovaline could enhance intracellular cyclic guanosine monophosphate (cGMP) concentration and promote vasorelaxation. One possible limit of the bicarbonate activated H_2S prodrugs stems from the reactivity of thiolamino acids, which could quickly undergo amidation reaction under aerobic conditions (Scheme 9)[91].

3. Conclusions

The review gives a brief summary of the current state of H_2S prodrugs. These prodrugs not only play an important role as research tools but also are promising candidates for the development of therapeutic agents. All prodrugs have their advantages, and also limitations. The most challenging in this field is still the development of prodrugs with precise control of the release kinetics so that they mimic endogenous H_2S generation. The effects of prodrugs themselves and the byproducts need to be taken into consideration in all the biological experiments. Thus, new hydrogen sulfide prodrugs with improved control of release kinetics are needed in this field.

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