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Abstract

Eukaryotic cells depend upon oxygen (O₂) for their survival and elaborate mechanisms have evolved in multicellular animals, especially vertebrates, to monitor the availability of environmental O₂, the efficiency of O₂ extraction from the environment, ensure adequate O₂ delivery to tissues and even to regulate cellular metabolism when O₂ availability is compromised. In vertebrates, specialized O₂ “sensing” cells have developed to carry out many of these processes. Although all O₂ sensing cells ultimately couple low P_{O₂} (hypoxia) to physiological responses, how these cells actually detect hypoxia, i.e., the “O₂ sensor” remains controversial. We have recently proposed that hydrogen sulfide (H₂S) through its O₂-dependent metabolism is a universal and phylogenetically ancient O₂ sensing mechanism. This hypothesis is based on a variety of experimental evidence including; (1) the effects of exogenous H₂S mimic hypoxia, (2) H₂S production and/or metabolism is biochemically coupled to O₂, (3) tissue H₂S concentration is inversely related to P_{O₂} at physiologically relevant P_{O₂}s, (4) compounds that inhibit or augment H₂S production inhibit and augment hypoxic responses, (5) H₂S acts upon effector mechanisms known to mediate hypoxic responses, (6) H₂S was key to the origin of life and the advent of eukaryotic cells and the reciprocal relationship between O₂ and H₂S has been inexorably intertwined throughout evolution. The evidence for H₂S-mediated O₂ sensing is critically examined in this review.

Keywords

Hypoxia • Cardiovascular • Chemoreceptors • Mitochondria

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Abbreviations

3MP	3-Mercaptopyruvate
3-MST	3-Mercaptopyruvate sulfur transferase
AMPK	AMP-activated protein kinase
AOA	Amino-oxyacetate
AOX	Alternative oxidase
Asp	Aspartic acid
CAT	Cysteine aminotransferase
CBS	Cystathionine β -synthase
CDO	Cysteine dioxygenase
CO	Carbon monoxide
CSE	Cystathionine γ -lyase
Cys	Cysteine
DAO	D-amino acid oxidase
DHLA	Dihydrolipoic acid
EC ₅₀	Effective concentration for half-maximal activity
ETHE1	Mitochondrial sulfur dioxygenase
Gly	Glycine
GSH	Reduced glutathione
GSSG	Oxidized glutathione
H ₂ O ₂	Hydrogen peroxide
H ₂ S	Hydrogen sulfide
HA	Hydroxylamine
HIF	Hypoxia-inducible factor
HPC	Hypoxic pulmonary vasoconstriction
HSD	Hypoxic systemic vasodilation
IK _{Ca}	Intermediate conductance potassium channel
K _{ATP}	Adenosine triphosphate sensitive potassium channel
KCl	Potassium chloride
K _i	Inhibition constant
K _v	Voltage-gated potassium channels
NEB	Neuroepithelial bodies
NEC	Neuroepithelial cells
NO	Nitric oxide
O ₂ ⁻	Superoxide
PASMC	Pulmonary artery smooth muscle cells
pB	Pre-Bötzingen respiratory group
PKC ϵ	Protein kinase C epsilon
PLP	Pyridoxal 5'phosphate
Po ₂	Partial pressure of oxygen
PPG	Propargyl glycine

Rde	Rhodanase
RI	Ischemia reperfusion injury
ROS	Reactive oxygen species
R-SO	Sulfenyl
$S_2O_3^{2-}$	Thiosulfate
SO	Sulfur oxidase
SO_3^{2-}	Sulfite
SO_4^{2-}	Sulfate
SQR	Sulfide:quinone oxidoreductase
ST	Sulfur transferase
TASK	Acid-sensitive potassium channel
TR	Thiosulfate reductase, a.k.a. rhodanase
TRD	Thioredoxin reductase
Trx	Thioredoxin
α -Kg	α -ketoglutarate

2.1 Introduction

Specialized O_2 sensing tissues in vertebrates are strategically placed to monitor ambient O_2 , O_2 transport in blood, and to match blood flow with ventilation or tissue demand. Neuroepithelial cells (NEC) are present on the external surfaces of fish gills and monitor water PO_2 (Milsom and Burleson 2007). This is especially important for these aquatic vertebrates because, compared to air, water has considerably less O_2 (1/30), slower rates of O_2 diffusion (Krogh's diffusion coefficients 1/200,000) and higher viscosity (60 times). Even more problematic, aquatic O_2 levels can vary both temporally (minutes to seasons) and spatially within meters (Bickler and Buck 2007). In lungs of newborn mammals, cells similar to neuroepithelial-like cells are found in clusters (called neuroepithelial bodies, NEB) near airway bifurcations and here they may be important in the transition from the relatively hypoxic uterine environment during and shortly after birth (Kemp et al. 2002). External O_2 sensors other than NEB are relatively uncommon in terrestrial vertebrates. Presumably this is because atmospheric O_2 is relatively constant (21 %) and internal O_2 sensors appear to be able to accommodate changes in O_2 availability (such as in borrows or with increasing altitude) if needed. Arterial O_2 sensors that monitor blood PO_2 and O_2 delivery are found in fish as vascular-facing NEC and in higher vertebrates as the type I glomus cells of carotid and aortic bodies. (It is perhaps no coincidence that the first gill arch of fish is the homolog of the mammalian carotid body.) Mammalian adrenal medullary cells and homologous chromaffin cells that line systemic veins in fish secrete catecholamines in response to hypoxemia (Nurse et al. 2006; Perry et al. 2000) and may monitor tissue O_2 extraction. Perhaps the best characterized O_2 sensing tissues are the blood vessels themselves. It has generally been accepted that hypoxia relaxes systemic vessels thereby matching tissue perfusion to metabolic demand, whereas hypoxia

contracts pulmonary vessels to match ventilation to perfusion (Sylvester et al. 2012). However, recent studies have shown that many systemic vessels in non-mammalian vertebrates are contracted by hypoxia (Russell et al. 2008) and hypoxia relaxes pulmonary vessels in diving mammals to prevent pulmonary hypertension that would otherwise occur during a prolonged dive (Olson et al. 2010). Although the vascular response to hypoxia is intrinsic to vascular smooth muscle (Madden et al. 1992) there appears to be considerable plasticity in the functional organization of this response. These atypical responses have been key to evaluating H₂S-mediated mechanisms for acute O₂ sensing as described in this chapter.

There is considerable controversy concerning the actual mechanism with which these cells detect O₂ levels or availability and then transduce this into physiologically relevant signals and of the numerous proposed O₂ sensing mechanisms none have received unanimous support. Our work has suggested that the O₂ dependent metabolism of hydrogen sulfide (H₂S) is an effective and efficient mechanism of H₂S sensing. This review presents the evidence supporting our hypothesis.

2.2 Mechanism(s) of O₂ Sensing

Despite the apparent ubiquity of O₂ sensing tissues in vertebrates there has been little consensus on the mechanism that specifically measures Po₂ or O₂ concentration. Potassium channels have long been a likely candidate (Weir and Archer 1995) although it is now believed that they operate downstream of the actual sensing mechanism. The various theories of O₂ sensing mechanisms have been extensively reviewed Sylvester et al. (2012). Because mitochondria account for most of a cell's O₂ consumption they are central to most O₂ sensing theories and implicit in the three most prevalent theories, the redox hypothesis, the reactive oxygen species (ROS) hypothesis and the energy state/AMPK (AMP-activated protein kinase) hypothesis. In the redox hypothesis, hypoxia suppresses mitochondrial oxidative phosphorylation which further reduces the cytosol and decreases ROS production. Voltage-gated potassium (K_v) channels that were tonically kept open during normoxia by ROS now close and the resulting cell depolarization opens voltage-gated calcium channels and the influx of calcium produces contraction. Essentially the opposite occurs in the ROS hypothesis where hypoxia increases mitochondrial production of ROS, namely superoxide (O₂⁻) and probably more importantly hydrogen peroxide (H₂O₂). The ROS thus produced activate a variety of intracellular signaling cascades that also increase intracellular calcium concentration. In the energy state/AMPK hypothesis, hypoxia decreases mitochondrial ATP production which increases the AMP to ATP ratio and activates AMP kinase. The resulting production of cyclic ADP ribose then brings about an increase in intracellular calcium and contraction. It should be noted, however, that vascular smooth muscle and endothelial cells can and do derive their energy from glycolysis and even though they respond to hypoxia, their ATP levels do not appear to be affected (Dromparis and Michelakis 2013). Other O₂ sensing mechanisms such as heme oxygenase (which generates the gasotransmitter carbon monoxide, CO), plasma

membrane bound NADPH oxidase or a yet identified hemoprotein or mitochondrial complex III and nitric oxide (NO) have also been described for various tissues (Evans et al. 2011; Gonzalez et al. 2010; Haldar and Stamler 2013; Waypa and Schumacker 2010; Wolin et al. 2010).

2.3 H₂S Oxidation as an O₂ Sensing Mechanism

We (Olson et al. 2006) originally proposed that the O₂-dependent metabolism of endogenously generated, and biologically active H₂S functioned as an efficient O₂ sensing mechanism that initiated hypoxic pulmonary vasoconstriction (HPC) and hypoxic systemic vasodilation (HSD). This hypothesis appears to fulfill the criteria for an O₂ sensing mechanism (Olson 2011) in that; (1) the effects of exogenous H₂S mimic hypoxia, (2) H₂S production and/or metabolism is biochemically coupled to O₂, (3) tissue H₂S concentration is inversely related to Po₂ at physiologically relevant Po₂s, (4) compounds that inhibit or augment H₂S production inhibit and augment hypoxic responses, (5) H₂S acts upon effector mechanisms known to mediate hypoxic responses, (6) H₂S-mediated O₂ sensing has an evolutionary precedent and a phylogenetic history. The following sections describe how these criteria have been met.

2.3.1 The Effects of Exogenous H₂S Mimic Hypoxia

2.3.1.1 Cardiovascular System

Mechanical responses to hypoxia are identical to those produced by H₂S in all vessels (Fig. 2.1). Relaxation of rat thoracic aorta and portal vein was one of the first “physiological” effects of H₂S identified (Hosoki et al. 1997) and this mimics the well-known hypoxic vasodilation of mammalian systemic vessels. Similar hypoxic and H₂S vasodilations have been observed in all classes of vertebrates from the most primitive hagfish and lamprey to mammals (cf Russell et al. 2008; Dombkowski et al. 2005). This response has now been observed in over 20 mammalian studies. H₂S also dilates the mouse ductus arteriosus (Baragatti et al. 2013) which would be expected to keep this vessel patent in the relative hypoxic intrauterine environment. H₂S vasodilation of mammalian systemic vessels has also been observed in perfused organs (Cheng et al. 2004) and in vivo (Derwall et al. 2011; Leffler et al. 2010; Mustafa et al. 2009; Yan et al. 2004; Yang et al. 2008). Consistent with hypoxic pulmonary vasoconstriction, H₂S constricts isolated bovine pulmonary arteries (Olson et al. 2006, 2010), increases vascular resistance in perfused fish gills (Skovgaard and Olson 2012) and perfused rat lungs (Madden et al. 2012) and increases pulmonary arterial blood pressure in vivo (Derwall et al. 2011; Sowmya et al. 2010).

Hypoxic responses of non-mammalian vertebrates are considerably more variable in that systemic vessels can be either dilated or contracted by hypoxia and often these effects are multiphasic. Nevertheless, in over 30 animals from all

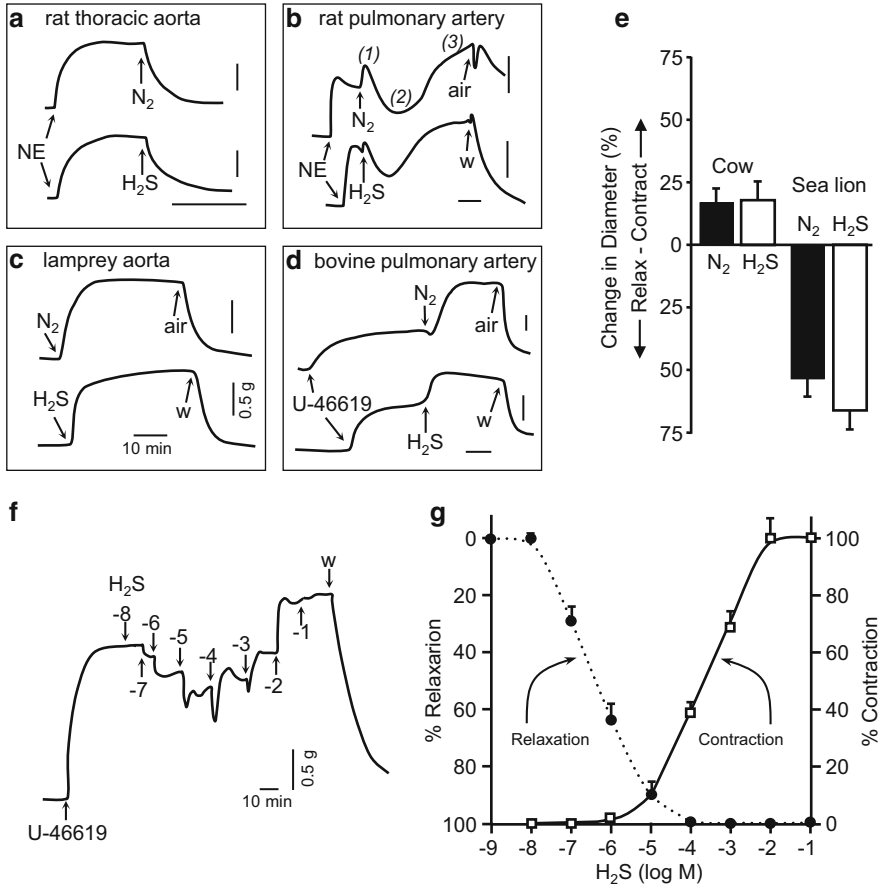


Fig. 2.1 Hypoxia (95 % N₂/5 % CO₂ **a, b, d, e**; or 100 % N₂, **c**) and H₂S (300 μmol/l) produce identical responses in conductance (>500 μm diameter) vessels from rat thoracic aorta (**a**), rat pulmonary artery (**b**), lamprey dorsal aorta (**c**) and bovine pulmonary artery (**d**). Vessels pre-contracted with 1 μmol/l norepinephrine (NE) or U-46619 (thromboxane A₂ mimetic; 0.1 μmol/l); *air* aeration with room air; *w* wash; 1, 2, 3, tri-phasic response. *Horizontal time bar* in **a–d** = 10 min, vertical tension scale = 0.5 g. (**e**), hypoxia (P_{O₂} ~ 50 mmHg) and H₂S (3 × 10⁻⁴ M) produce identical contractions of cow resistance (<500 μm diameter) pulmonary arteries while both stimuli relax sea lion resistance pulmonary arteries. Mean ± SE; *N* (animals, vessels) = cow (9,9), sea lion (3,5). (**f, g**), H₂S has two dose-dependent effects on pre-contracted (0.1 μmol/l U-46619) bovine pulmonary arteries. H₂S appears to produce a dose-dependent relaxation between 10⁻⁸ and 10⁻⁵ mol/l, whereas above 10⁻⁵ mol/l it produces a dose-dependent constriction. The EC₅₀ for relaxation (5.5 ± 1.8 × 10⁻⁷ M) is significantly (*p* < 0.05) different from the EC₅₀ for contraction (3.7 ± 1.5 × 10⁻⁴ M). (**f**) single trace of cumulative doses, *arrows* indicate log M [H₂S]; *w* wash; (**g**) average (+SE) of eight vessels, *filled circles* denote relaxation and *open squares* contraction (values extrapolated where curves overlap ~ 10⁻⁵ M) (**a–d, f, g** Adapted from Olson et al. 2006, with permission; **e** adapted from Olson et al. 2010, with permission)

vertebrate classes, the hypoxic responses of both systemic and respiratory vessels are consistently mimicked by H₂S (summarized in Olson and Whitfield 2010). This includes the signature multiphasic contraction-relaxation-contraction of rat pulmonary arteries (Fig. 2.1b) and the unique hypoxic and H₂S-mediated dilation of sea lion pulmonary resistance vessels (Fig. 2.1e). It is also evident that many of these multiphasic responses such as the initial relaxation followed by constriction in bovine pulmonary arteries are the results of separate, but dose-dependent effects of H₂S (Fig. 2.1f), a hint of which can also be seen during the onset of hypoxia (Fig. 2.1d). Hypoxia and H₂S also relax non-vascular smooth muscle of fish urinary bladder and the gastrointestinal tract and in the gastrointestinal tract both of these stimuli produce a unique and transient increase in spontaneous contraction frequency and amplitude prior to the onset of the inhibitory effects (Dombkowski et al. 2006, 2011). H₂S also relaxes human corpus cavernosum and urinary bladder smooth muscle (d'Emmanuele di Villa Bianca et al. 2009; Fusco et al. 2012).

Involvement of H₂S has also been shown in other hypoxia-related responses. In the cardiovascular system this includes angiogenesis, ischemia reperfusion injury (RI) and pre- and post-conditioning against RI (Bian et al. 2006; Cai et al. 2007; Calvert et al. 2010; Lavu et al. 2010; Liu et al. 2010; Pan et al. 2006; Papapetropoulos et al. 2009; Szabo and Papapetropoulos 2011; Wang et al. 2010a, b; Yong et al. 2008). H₂S also contributes to hypoxia-induced radiation resistance (Zhang et al. 2011) and it is a cryogenic mediator of hypoxia-induced anapnoea (Kwiatkoski et al. 2012).

2.3.1.2 Respiration

Intravascular injection or inhalation of H₂S at low concentrations has long been known to mimic hypoxemia by stimulating respiration in many mammals (Beauchamp et al. 1984; Reiffenstein et al. 1992; Haggard and Henderson 1922; Haouzi et al. 2009 [in mice but not rats], 2011; Haouzi 2012; Van de Louw and Haouzi 2012) and birds (Klantz and Fedde 1978). This may have both a central and peripheral component mediated through the carotid bodies. Intracerebroventricular injection of H₂S produces a K_{ATP} channel-mediated dose dependent bradycardia and hypotension (Liu et al. 2011) akin to the hypoxic diving reflex. In more specific studies it was observed that H₂S increases discharge frequency from the pre-Bötzinger (pB) dorsal inspiratory respiratory group and it may initially produce transient inhibition of the pB by stimulating the nearby parafacial respiratory group (Chen et al. 2013; Hu et al. 2008). H₂S stimulates peripheral chemoreceptors (neuroepithelial cells) in the fish gill (Olson et al. 2008) and mammalian carotid body (Li et al. 2010; Makarenko et al. 2012; Peng et al. 2010) and it stimulates the mammalian adrenal medulla (Peng et al. 2010; Zhu et al. 2012) and homologous fish chromaffin cells (Perry et al. 2009). H₂S may also contribute to the sequela of events in which heart failure, hypertension and renal failure activate the carotid body leading to breathing instability and increased sympathetic nerve activity (Schultz et al. 2012).

2.3.2 H₂S Production and/or Metabolism is Biochemically Coupled to O₂

2.3.2.1 Biosynthesis

Pathways for H₂S synthesis and metabolism are shown in Fig. 2.2. L-cysteine and L-homocysteine account for most H₂S production through the activity of four enzymes, cystathionine β-synthase (CBS), cystathionine γ-lyase (CSE aka CGL) and sequential catalysis by cysteine aminotransferase (CAT) and 3-mercaptopyruvate sulfurtransferase (3-MST). H₂S may be synthesized in the cytosol as CBS and CSE and CAT/3-MST are cytosolic enzymes, or it may be synthesized in the mitochondria as CAT/3-MST are present there as well (Kamoun 2004). 3-MST is especially abundant in the mitochondrial matrix (Mikami et al. 2011a) where it can take advantage of threefold higher cysteine concentration than in the cytosol (Fu et al. 2012). CSE can also be translocated to the mitochondria by a variety of stress-related stimuli (Fu et al. 2012). Initially it was believed that CBS was predominantly found in the brain and CSE in the cardiovascular system (reviewed in Kimura 2010), although a broader distribution is becoming evident, i.e., CBS has been identified in vascular endothelium, CAT and 3-MST in vascular endothelium and brain and MST, but not CAT, in vascular smooth muscle (Kimura 2010; Olson et al. 2010). CBS and CSE have also been identified in human plasma (Bearden et al. 2010). H₂S can be generated from D-cysteine, however, this pathway appears limited to the brain and kidney where it protects the former from oxidative stress and the latter from re-perfusion injury; it may be of limited function elsewhere (Shibuya et al. 2013). CBS, CSE and CAT are pyridoxal 5'phosphate (PLP)-dependent, enzymes. S-adenosylmethionine allosterically activates CBS (Stipanuk 2004). CBS contains a heme group that can be inhibited by presumably physiological levels of carbon monoxide (CO; inhibition constant, K_i = 5.6 μM) and although it is also inhibited by nitric oxide (NO), the K_i is so high (320 μM) that it is of questionable physiological significance; O₂ does not affect CBS activity (Banerjee and Zou 2005). CSE and both cytosolic and mitochondrial CAT activity are inhibited by calcium, independent of calmodulin (Mikami et al. 2011b, 2013).

2.3.2.2 Metabolism (Inactivation)

Mathematical models of H₂S diffusion out of cells versus intracellular metabolism suggest that most H₂S is inactivated intracellularly (Olson 2013), and this is supported by the considerable body of evidence that mitochondria efficiently oxidize H₂S (reviewed in Olson 2012c). Mitochondrial enzymes, sulfide:quinone oxidoreductase (SQR), 3-MST, rhodanase (Rde), thiosulfate reductase (TR), sulfur dioxygenase (ETHE1) and sulfite oxidase (SO) ultimately oxidize H₂S to sulfate (SO₄²⁻) which is then excreted. Sulfite (SO₃²⁻) and thiosulfate (S₂O₃²⁻) are intermediates. SQR is bound to the inner mitochondrial membrane and it is closely associated with the respiratory chain “supercomplex” (Hildebrandt 2011) which provides a hint at its O₂ sensing function as the mitochondrion is a lead candidate for the site of O₂ sensing (Sylvester et al. 2012). Not surprisingly, 3-MST,

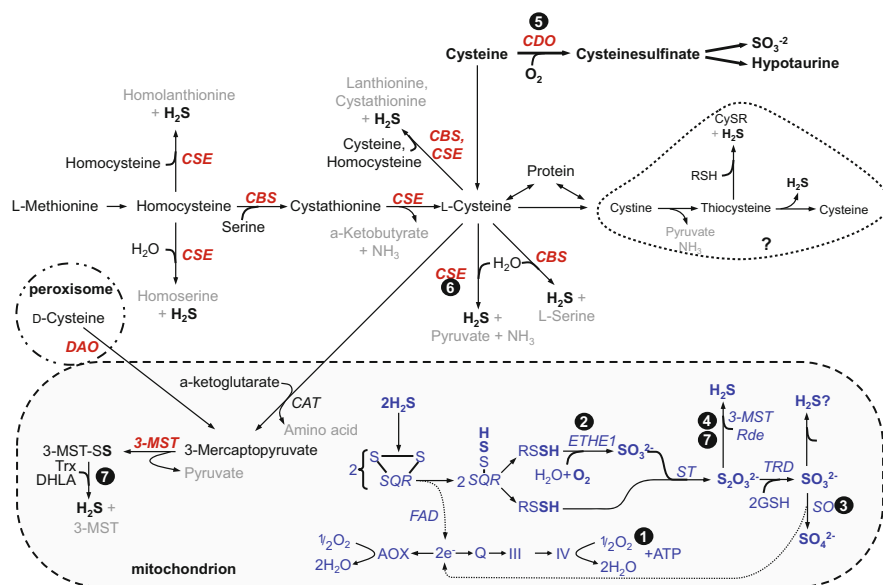


Fig. 2.2 Pathways for H_2S production and degradation. H_2S is synthesized from homocysteine or cysteine by the cytosolic enzymes cystathionine β -synthase (CBS), cystathionine γ -lyase, or the tandem action of cysteine aminotransferase (CAT) and 3-mercaptopyruvate sulfur transferase (3-MST) in both the cytosol and mitochondria. Other potential mechanisms for H_2S biosynthesis have been described in invertebrates (dotted enclosure; Julian et al. 2002) but have yet to be confirmed in mammals. 3-mercaptopyruvate can also be produced from *D*-cysteine in the peroxisome by *D*-amino acid oxidase (DAO). Oxidation of H_2S in the mitochondria (blue letters) is initiated by interaction with the enzyme sulfide:quinone oxidoreductase (SQR) producing two SQR persulfides that are then transferred to a mobile sulfide carrier (RSSH), one of which is oxidized to sulfite (SO_3^{2-}) by mitochondrial sulfur dioxygenase (ETHE1). Sulfur transferase (ST) transfers the other persulfide to form thiosulfate ($\text{S}_2\text{O}_3^{2-}$). H_2S may be regenerated from thiosulfate by 3-MST or rhodanase (Rde), or the thiosulfate may be oxidized to sulfate (SO_4^{2-}) by the sequential actions of thioredoxin reductase (TRD) in combination with glutathione (GSH) and sulfur oxidase (SO). Oxidation of H_2S donates electrons to the respiratory chain (Q, III, IV) that has been shown in invertebrates and mammals to result in ATP production and O_2 consumption. An alternative oxidase (AOX) that oxidizes H_2S without concomitant ATP production has also been observed in invertebrates. H_2S can also be regenerated from thiosulfate by 3-mercaptopyruvate sulfur transferase (3-MST) or rhodanase (Rde) in the presence of other reducing disulfides such as thioredoxin (Trx) or dihydrolipoic acid (DHLA). Circled numbers indicate actual or potential hypoxia-sensitive sites (see text for details) (Modified from Olson et al. (2012c), with permission)

rhodanase and thiosulfate reductase are abundant in the mitochondrial matrix and to a lesser extent the intermembrane space (Koj et al. 1975). H_2S oxidation begins with H_2S binding to the highly conserved Cys-Cys disulfide bridge of SQR. The sulfide is oxidized to elemental sulfur forming SQR persulfide (sulfane sulfur) with the now-reduced SQR cysteine (SQR-SSH). Two H_2S and two SQR are involved, one persulfide sulfur is transferred to sulfur dioxygenase (SDO) where it is oxidized to sulfite while sulfur from the second persulfide is transferred from the SQR to sulfite

by sulfur transferase (ST) producing thiosulfate. One electron from each of the two H_2S are fed via the quinone pool (Q) into the respiratory chain (Marcia et al. 2010) and they ultimately reduce O_2 at complex IV. SQR is bound to the inner mitochondrial membrane and it is believed that sulfur is shuttled from SQR by a mobile carrier such as glutathione (GSH), dihydrolipoate, thioredoxin or even sulfite (Hildebrandt and Grieshaber 2008; Jackson et al. 2012; Theissen and Martin 2008). One of the mobile persulfides is oxidized to sulfite by ETHE1 which consumes molecular O_2 and water in the process. Metabolism of H_2S through SQR appears ubiquitous in tissues although the brain may be an exception (Hildebrandt 2011; Lagoutte et al. 2010; Linden et al. 2011; but see Ackermann et al. 2011). The capacity of cells to oxidize sulfide appears to be greater than the estimated rate of sulfide production (Bouillaud and Blachier 2011; Furne et al. 2008). Thus it is expected that intracellular H_2S concentrations are very low under normoxic conditions.

Under normoxic conditions, most thiosulfate is further metabolized to sulfate by thiosulfate reductase (TR) and sulfite oxidase (SO). Elimination of one sulfur atom as sulfate is accompanied by four atoms of O_2 . Even though sulfur excretion as thiosulfate would conserve O_2 , apparently there is little need for this when O_2 is plentiful and thiosulfate excretion in vertebrates is generally low. In fact, it is not clear why most vertebrates, especially terrestrial ones, would bother with this pathway at all. However, as described below, it may be an important avenue for regeneration of H_2S during hypoxia. Details of H_2S biosynthesis and metabolism can be found in (Kabil and Banerjee 2010; Kimura 2010; Olson 2012c; Stipanuk 2004; Stipanuk et al. 2009).

2.3.2.3 H_2S Oxidation via Electron Transport

In our original mechanism of H_2S -mediated O_2 sensing (Olson et al. 2006) we proposed that H_2S was constitutively produced in the cytosol through transsulfuration and oxidized in the mitochondria. As the amount of O_2 available to the mitochondria determined the rate of H_2S oxidation, and hence H_2S concentration, this was the “ O_2 sensor.” Although this is still likely an integral mechanism, it is now evident that there are a number of other mechanisms with which O_2 can influence H_2S concentration and thereby contribute to O_2 sensing. These mechanisms, some of which are expected to rapidly respond to O_2 while others may provide a longer bias of H_2S concentration, are described in the following paragraphs and shown numerically in Fig. 2.2. While many of these pathways remain to be verified in the context of O_2 sensing, there is accumulating evidence, largely through studies on enzyme deficiencies, that their dysfunction will impact sulfide metabolism and either directly or indirectly increase H_2S concentration.

Rapid Effectors of H_2S Concentration

Electron transport: Disruption of electron flow down the respiratory chain by insufficient O_2 delivery to the mitochondrion at complex IV still remains a very likely and highly effective mechanism to regulate H_2S as it directly couples O_2 availability to H_2S inactivation. This will prevent any further oxidation of H_2S that was derived from

transsulfuration. This pathway of H₂S oxidation has been well-established in the context of ATP synthesis (Goubern et al. 2007; Lagoutte et al. 2010; Modis et al. 2013).

ETHE1: The mitochondrial dioxygenase, ETHE1, uses molecular O₂ and water to oxidize the mobile persulfide from SQR to form sulfite. Inhibition of this pathway will prevent H₂S binding to SQR. Although the effects of O₂ on this pathway have not been examined in detail, they would presumably be similar to the well-characterized ETHE1 deficiencies in experimental animals (ETHE1^{-/-} mice) and humans, the pathology of which is characterized by greatly elevated tissue H₂S and thiosulfate (Di Meo et al. 2011; Drousiotou et al. 2011; Giordano et al. 2011; Tiranti et al. 2009).

Sulfite oxidase: Sulfite oxidase (SO) in the mitochondrial innermembrane space catalyzes the oxidation of sulfite to sulfate by transferring an atom of O₂ from water to sulfite and in the process the enzyme undergoes a 2-electron reduction (Rajapakshe et al. 2012). These electrons are then transferred from SO to cytochrome c and shuttled into the electron transport chain with molecular oxygen as the terminal acceptor. This couples sulfite concentration to O₂ availability and suggests that a hypoxia-induced increase in sulfite would increase thiosulfate concentration and ultimately H₂S production. SO deficiency in a human was first demonstrated in 1967 and, as might be expected, this patient presented with elevated urinary thiosulfate (Mudd et al. 1967).

Thiosulfate reduction: As described above, inhibition of either ETHE1 or SO will prevent further oxidation of thiosulfate and this thiosulfate can now directly produce H₂S under appropriate conditions by reduction. The sulfur atoms on thiosulfate have different oxidation states, the inner sulfur is +5 and the outer (persulfide) sulfur is -1. In the presence of a reducing reagent such as the endogenous mitochondrial reductant, dihydrolipoic acid (DHLA), 3-MST or thiosulfate reductase (TR; aka rhodanase, Rde) can catalyze the removal of the persulfide and generate H₂S (Mikami et al. 2011a; Villarejo and Westley 1963). H₂S generation from thiosulfate under these conditions has been demonstrated in a variety of mammalian and non-mammalian tissues and it is enhanced by hypoxia (Olson et al. 2013). Thiosulfate can also be generated from D-cysteine by D-amino acid oxidase through formation of 3-mercaptopyruvate (Huang et al. 1998) although the biological significance of this pathway is unknown. H₂S generation from thiosulfate will be greatest where thiosulfate concentrations are the highest and when the immediate environment becomes more reduced and the relevant reducing molecules become more available. Thiosulfate concentrations are probably highest in or near the inner mitochondrial membrane, the site of SQR. This is also likely to experience the greatest increase in hypoxia-induced reducing equivalents such as DHLA or thioredoxin because as cells become hypoxic, reactive oxygen species (ROS) increase in both the cytosol and mitochondrial intermembrane space, whereas ROS decrease in the mitochondrial matrix (Waypa et al. 2010). Thus, thiosulfate reduction could significantly contribute to the initial increase in H₂S concentration that activates the O₂ sensing cascade and by recycling sulfur it conserves biologically relevant thiols.

Long-Term Effectors of H₂S Concentration

Cysteine dioxygenase: Cysteine dioxygenase (CDO), a cytosolic enzyme, effectively eliminates sulfur from entering the H₂S pool by irreversibly catalyzing the oxidation of cysteine to cysteinesulfinate which can be further metabolized to hypotaurine, then taurine or sulfite and then sulfate for excretion (Stipanuk et al. 2009). One of the primary functions of CDO is believed to be the detoxification of excess dietary or metabolic cysteine as CDO activity is dynamically regulated by cysteine (as much as 450-fold) whereas cysteine desulfuration, the H₂S-forming transsulfuration pathway is not regulated (Stipanuk et al. 2009). CDO also contributes to degradation of methionine and homocysteine after their conversion to cysteine (Stipanuk and Ueki 2011). Impairment of this pathway, which has been demonstrated in CDO knockout (CDO^{-/-}) mice, redirects sulfur through the desulfuration pathway and increases thiosulfate and H₂S production (Ueki et al. 2011; Roman et al. 2013). As molecular O₂ is the only other substrate in CDO-mediated cysteine oxidation it is likely that hypoxia will impair cysteine oxidation and favor H₂S production. It is not likely that this would contribute to the rapid on/off signaling observed acute hypoxia, but it could place a long-term bias on chronic H₂S-mediated H₂S sensing. An inability of this pathway to handle a large transient cysteine load may partially explain how hypoxic responses are augmented by exogenous cysteine (see below). Ueki et al. (2011) also noted the striking similarities between CDO^{-/-} and ETHE1^{-/-} pathologies and suggested that sulfide/H₂S was the common factor.

CSE translocation to mitochondria: In vascular smooth muscle cells, hypoxia stimulates CSE translocation from the cytosol to the mitochondria where it utilizes the threefold increase in cysteine concentration to generate H₂S which can be subsequently used in ATP synthesis (Fu et al. 2012). It has been proposed that this H₂S improves mitochondrial ATP production and it is protective during hypoxia (Fu et al. 2012). There are, however, several problems with this hypothesis. First, vascular smooth muscle can derive sufficient energy from anaerobic metabolism and does not need oxidative phosphorylation to supply energy, even during hypoxia (Dromparis and Michelakis 2013). Second, because ATP generated from H₂S is ultimately dependent on O₂, it is unclear what the electron acceptor will be in the absence of O₂. However, the H₂S formed by CSE translocation could clearly contribute to O₂ sensing and hypoxic vasodilation.

Indirect O₂ Effects

3-MST and thioredoxin catalytic-site cysteines: Many enzymes contain cysteine in the catalytic site and because these cysteines generally have a low pKa, they are redox active (Nagahara 2011). The catalytic cysteine in 3-MST (Cys²⁴⁷; rat) is one example. The exposed, Cys²⁴⁷ sulfur is readily oxidized to a sulfenyl (R-SO) by O₂, peroxide (H₂O₂) or other oxidants under mild oxidizing conditions; the sulfenyl is also reduced (to R-SH) by reduced thioredoxin (Trx) but not GSH (Nagahara 2012). Monomeric Rat 3-MST can also dimerize by mild oxidation of two other exposed cysteines, Cys¹⁵⁴ and Cys²⁶³; both oxidization of Cys²⁴⁷ and dimerization inactivate the enzyme. A defect in 3-MST activity, presented clinically

as mercaptolactate-cysteine disulfidia, is believed to be associated with deficient H₂S production (Nagahara 2012). While the three external cysteines of 3-MST may well allow it to serve as an effective antioxidant (Nagahara 2012) it could also be a key component of the H₂S-mediated O₂ sensing mechanism. Furthermore, as 3-MST is found in both the cytosol and mitochondrial matrix and during hypoxia ROS in the cytosol increase while ROS in the matrix decrease, in both pulmonary and systemic arterial smooth muscle cells (Waypa et al. 2010), this will favor mitochondrial H₂S production and inhibit it in the cytosol. Parenthetically, the now-oxidized Trx can be reduced by thioredoxin reductase (TRD) using NADPH; which may be an overlooked, but key explanation for why NADPH has been central in many O₂-sensing theories (Gupte and Wolin 2008).

2.3.3 Tissue H₂S Concentration Is Inversely Related to P_{O₂} at Physiologically Relevant P_{O₂}s

If H₂S and O₂ coexist in the environment or in cells it is only transient. In fact, hypoxia, or more often anoxia, is generally (although rarely appreciated) a requisite for all measurements of tissue H₂S production, other than those using polarographic H₂S sensors (Olson 2012a). Using the polarographic sulfide sensor, originally developed by Jeroschewski et al. (1996), Kraus and Doeller (2004) observed that excised gills and gill mitochondria from sulfide-adapted mussel, *Geukensia demissa*, rapidly consumed H₂S in the presence of O₂ and that the rate of H₂S consumption was reduced 50-fold in anoxia and 75 % inhibited by cyanide. The authors estimated the P₅₀ (the partial pressure of O₂ at half maximal rate) for H₂S oxidation in mitochondria of approximately 7.5 mmHg. Both Furne et al. (2008) and Doeller et al. (2005) measured the relationship between O₂ and H₂S production in rat tissues and observed that H₂S production was suppressed at normoxic P_{O₂} and Furne et al. (2008) observed a switch from H₂S production in hypoxia to H₂S consumption in normoxia in mouse liver and brain. Similar observations have been made in a variety of other tissues (Fig. 2.3; Dombkowski et al. 2011; Linden et al. 2011; Madden et al. 2012; Olson et al. 2008, 2010; Olson and Whitfield 2010; Whitfield et al. 2008). A compelling argument for H₂S-mediated O₂ sensing can be made by comparing bovine and sea lion lungs (Olson et al. 2010); while both tissues clearly demonstrate an identical and reciprocal relationship between H₂S production/consumption and O₂ (Fig. 2.3a, b), both hypoxia and H₂S constrict the former and dilate the latter (Fig. 2.1e).

To date, there has only been one study in which the rate of H₂S consumption by tissue has been measured at carefully controlled P_{O₂} (Olson et al. 2010). As shown in Fig. 2.3d, the efficiency of H₂S oxidation by bovine lung homogenate, bovine pulmonary arterial smooth muscle cells, or purified bovine heart mitochondria begins to fail at physiologically relevant P_{O₂}s and at P_{O₂}s routinely encountered during hypoxia H₂S metabolism becomes highly sensitive to O₂ availability. Further demonstration of the physiological relevancy of this process is the observation that the P_{O₂} at which the ability of pulmonary arterial smooth muscle cells to

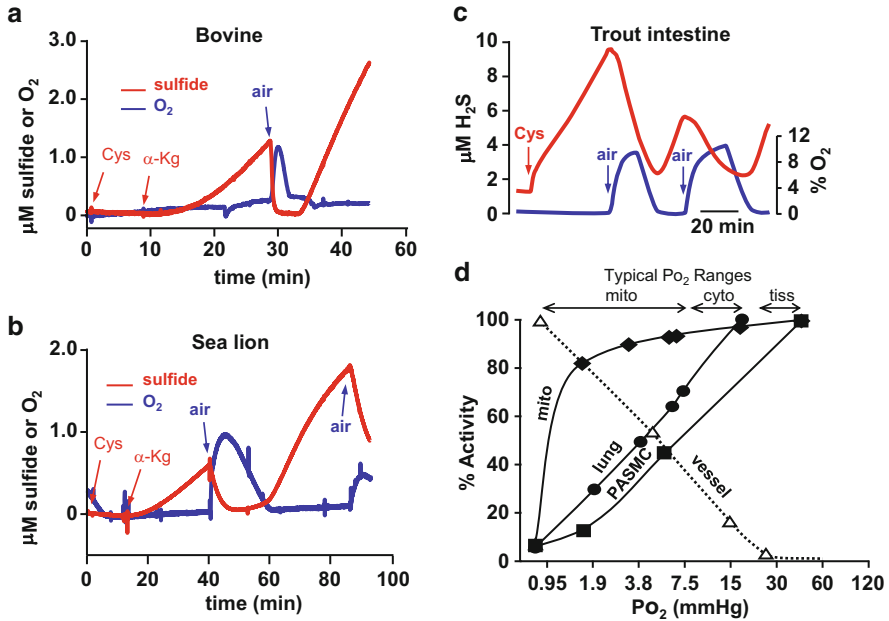


Fig. 2.3 Reciprocal relationship between O_2 and H_2S in tissues. (a–c) Realtime measurements of O_2 and H_2S in homogenized cow lung (a), homogenized sea lion lung (b) and homogenized trout intestine (c) using gas-specific polarographic electrodes. H_2S production increases after addition of 1 mM cysteine (Cys) and α -ketoglutarate (α -Kg) or Cys alone but only in the absence of O_2 . Injection of a small air bubble (air) which increases O_2 concentration immediately reduces H_2S concentration all tissues. When the O_2 is consumed, H_2S concentration again increases. These results show that H_2S production is inversely related to O_2 in a variety of tissues, even though bovine pulmonary arteries are constricted by hypoxia whereas sea lion pulmonary arteries and trout intestines are relaxed. (d) H_2S consumption as a function of O_2 availability (PO_2) by bovine mitochondria (mito), homogenized bovine lung tissue (bovine lung) and bovine pulmonary artery smooth muscle cells (PASMC). H_2S is rapidly metabolized (100 % inactivation rate) until PO_2 falls to ~ 15 mmHg (1–2 mmHg for mito); H_2S metabolism rapidly fails as PO_2 continues to fall. The PO_2 values at which H_2S metabolism is impaired are at the low end of cytosolic and mitochondrial PO_2 and would be expected during hypoxia. The PO_2 at which H_2S metabolism is reduced to half (P_{50}) in lung tissue and PASMC is essentially the same PO_2 that produces half-maximal hypoxic vasoconstriction of bovine pulmonary arteries (vessel). (a, b, d, Modified from Olson et al. 2010, c modified from Dombkowski et al. 2011, with permission)

oxidize H_2S is halved (P_{50}) is identical to the P_{50} of hypoxic pulmonary vasoconstriction. As might be expected, mitochondria function at a PO_2 below the cytosolic PO_2 and it is evident in Fig. 2.3d that the H_2S oxidation curve is left-shifted accordingly. These studies clearly show that the metabolism of H_2S is O_2 dependent, that the ability of tissues to metabolize H_2S fails at physiologically relevant PO_2 s, and this provides a sensitive and efficient mechanism for O_2 sensing.

2.3.4 Compounds that Augment or Inhibit H₂S Production Augment or Inhibit Hypoxic Responses

The ability of sulfur donors especially cysteine to augment hypoxic responses has been well documented (Fig. 2.4). Cysteine increases the magnitude of hypoxic vasoconstriction of isolated lamprey aortas (Olson et al. 2006), bovine pulmonary arteries (Olson et al. 2006, 2010) and it increases vascular resistance in the perfused rat lung (Madden et al. 2012). Both reduced and oxidized glutathione augment hypoxic vasoconstriction in pulmonary arteries and the perfused rat lung and cysteine plus α -ketoglutarate (presumably utilizing the CAT/3-MST pathway) increases hypoxic vasoconstriction in bovine pulmonary arteries (Madden et al. 2012; Olson et al. 2010). Continuous utilization of cysteine to sustain a hypoxic vasoconstriction is evident in Fig. 2.4d where it clearly sustains the hypoxic response. Exogenous cysteine also augments hypoxic relaxation of rat aortas (Bucci et al. 2010), the relaxation component of the perfused trout gill (Skovgaard and Olson 2012) as well as hypoxic relaxation of trout urinary bladder (Dombkowski et al. 2006) and salmon intestine (Dombkowski et al. 2011).

Hypoxic responses of lamprey aorta, bovine pulmonary arteries, rat aorta and the perfused trout gill and rat lung are also inhibited by inhibitors of H₂S synthesis (Fig. 2.5; Olson et al. 2006; Madden et al. 2012; Skovgaard and Olson 2012). Although inhibitors of H₂S are notoriously nonspecific and often poorly absorbed by tissues (Szabó 2007), their application can provide some information on the biosynthetic pathways that are being used to produce H₂S. Not surprisingly, CSE appears to be the major pathway for H₂S production by systemic vessels (Fig. 2.5c). However, in bovine pulmonary arteries inhibition of CBS, but not CSE, reduces the hypoxic response, whereas hydroxyl amine, which inhibits all pyridoxal phosphate dependent enzymes, including CBS, CSE and CAT, completely inhibits hypoxic vasoconstriction (Fig. 2.5b). This suggests that both the CBS and CAT/3-MST contribute to H₂S production in bovine pulmonary vessels. The CAT/3-MST pathway can also be utilized in the rat lung as the competitive inhibitor, aspartate, prevents the augmented hypoxic response produced by exogenous α -ketoglutarate (Fig. 2.5c). There appears to be some species variation in the enzymatic pathways employed as CSE may be a major component of H₂S production mediating hypoxic responses of the perfused rat lung (Madden et al. 2012). Inhibitors of H₂S biosynthesis have also been shown to inhibit hypoxic relaxation of rainbow trout urinary bladder (Dombkowski et al. 2006) and rainbow trout and Coho salmon intestine (Dombkowski et al. 2011).

Inhibiting CBS in the mouse carotid body decreases hypoxia-stimulated afferent nerve activity *in vitro* and blunts the hypoxic hyperventilation *in vivo* (Li et al. 2010). Conversely, Peng et al. (2010) observed an inverse PO₂-dependent increase in H₂S production by rat carotid bodies and both H₂S production and sinus nerve activity could be blocked by inhibiting CSE; in a mouse CSE knockout (CSE^{-/-}) hypoxic responses of glomus cells were significantly reduced. Hypoxia-evoked catecholamine

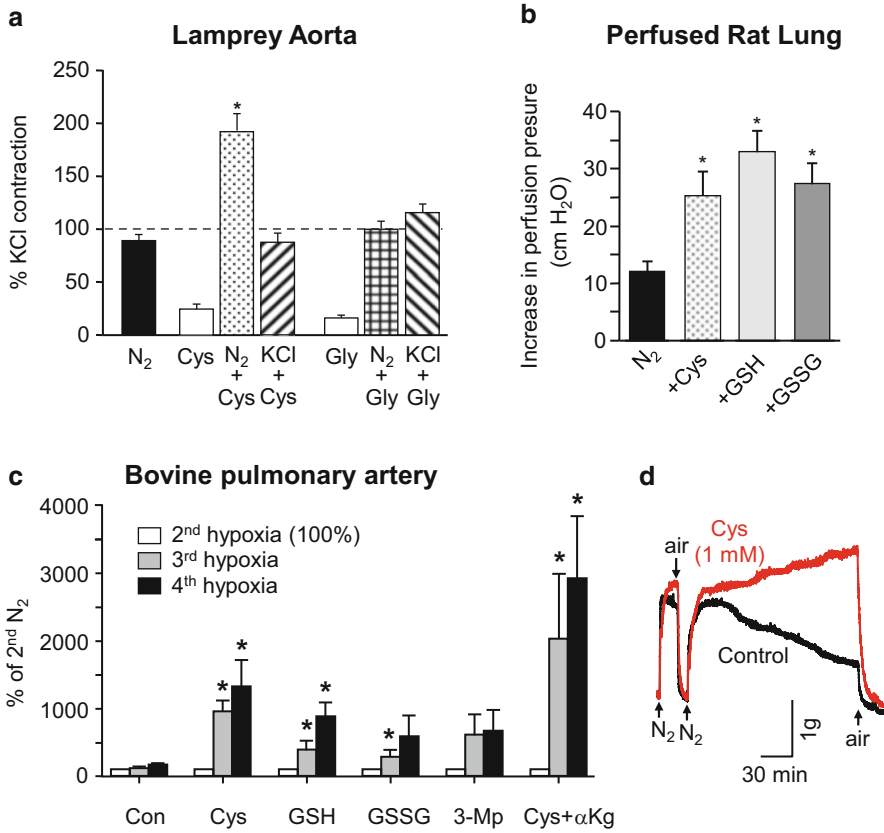


Fig. 2.4 Substrates for H₂S biosynthesis augment hypoxic responses. **(a)** In the lamprey aorta cysteine (Cys, 1 mM) nearly doubles a hypoxic contraction but does not affect a KCl (80 mM) contraction. Both Cys and glycine (Gly, 1 mM) had a slight effect but Gly does not affect the hypoxic response. **(b)** Cys (1 mM), reduced glutathione (GSH, 1 mM) and oxidized glutathione (GSSG, 1 mM) all significantly increase perfusion pressure in the perfused rat lung. **(c)** Cys (1 mM), GSH (1 mM), GSSG (1 mM) and Cys plus α-ketoglutarate (Cys + αKg, 1 mM) enhance consecutive hypoxic contractions of bovine pulmonary arteries. **(d)** Representative myograph traces illustrating the ability of Cys (1 mM) to prolong a hypoxic contraction in an isolated bovine pulmonary artery (Modified from Olson 2012b, with permission)

secretion from adrenal glands was also inhibited in CSE^{-/-} mice or by inhibiting CSE in rats Peng et al. (2010). Clearly additional studies are needed so sort out the specific metabolic pathways for H₂S production in the glomus cells, but nevertheless, a strong case can be made for the involvement of H₂S in hypoxic signal transduction.

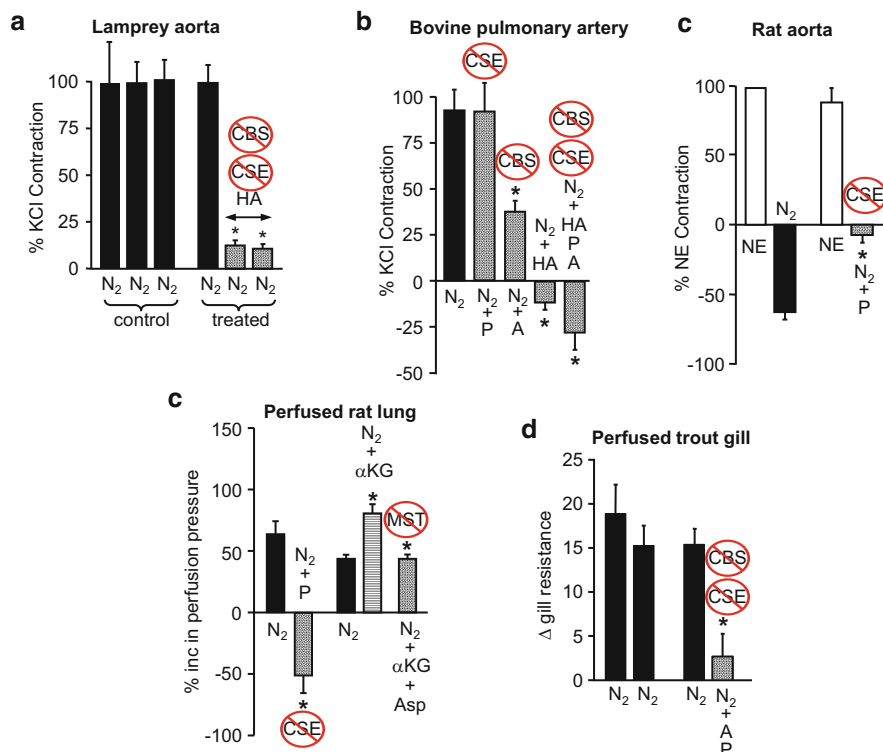


Fig. 2.5 Inhibitors of H₂S biosynthesis inhibit hypoxic vasoconstriction in the lamprey aorta (a), and bovine pulmonary artery (b) and hypoxic vasodilation of the norepinephrine (NE, 1 μM) precontracted rat aorta. Inhibiting H₂S biosynthesis also inhibits hypoxic vasoconstriction in the perfused rat lung (c) and perfused trout gill (d). *CBS* cystathionine β-synthase, *CSE* cystathionine γ-lyase, *A* amino-oxyacetate a CBS inhibitor (1 mM), *P* propargyl glycine a CSE inhibitor (10 mM), *HA*, *CBS* and *CSE* inhibitor hydroxylamine (1 mM), *α-Kg* α-ketoglutarate a substrate for mercaptopyruvate sulfur transferase (*MST*), *Asp* aspartic acid, an inhibitor of *MST* (10 mM) (From Olson 2012b, with permission)

2.3.5 H₂S Acts Upon Effector Mechanisms Known to Mediate Hypoxic Responses

The recent identification of H₂S signaling through sulfhydrylation of protein cysteine molecules (Mustafa et al. 2009) has not only contributed to our overall understanding of H₂S signaling pathways, but it has shed some light on the mechanisms of H₂S signaling in hypoxia. Because many proteins such as enzymes and structural proteins are regulated through active-site cysteines (Nagahara 2011) it is also evident that H₂S signaling is most likely an autocrine activity and that even within the cell it must be highly spatially regulated. This is supported by the models predicting that hypoxic signaling proceeds in the immediate mitochondrial environment (Olson 2013).

As would be expected, the mechanisms with which inhibits or activates H₂S cells is commensurate with the intended outcome of H₂S signaling.

It is well-known that hypoxic vasodilation is mediated in part by K_{ATP} channels (Weir and Archer 1995) and these channels were one of the first targets identified for H₂S signaling (Zhao et al. 2001). Since then a variety of channels in vascular smooth muscle and endothelial cells have been shown to be affected by H₂S leading to vasodilation. These include K_{ATP}, intermediate conductance (IK_{Ca}) and K_v7 potassium channels (Jiang et al. 2010; Liang et al. 2011; Martelli et al. 2013; Mustafa et al. 2011). H₂S also relaxes newborn piglet cerebral arteries by increasing [Ca²⁺] in the sarcoplasmic reticulum. This stimulates Ca²⁺ sparks, increases current through K_{Ca} channels and hyperpolarizes the cells thereby lowering global intracellular [Ca²⁺] (Liang et al. 2012). H₂S did not directly affect K_{Ca} channels in these studies. H₂S activates the Kir 6.1 subunit of K_{ATP} channel through sulfhydrylation of specific cysteine residues, especially Cys-34, this decreases the inhibitory effect of ATP on these channels while increasing binding of the activator phosphatidylinositol (4,5)-bisphosphate (PIP2)28 to Kir 6.1; other channels such as the endothelial intermediate conductance (IK_{Ca}) channel and other cysteine residues such as Cys⁶ and Cys²⁶ may also be sulfhydrated and contribute to H₂S relaxation (Jiang et al. 2010; Mustafa et al. 2011). Intermittent hypoxia down regulates CSE and increases vascular tone via the loss of H₂S activation of BK_{Ca} channels (Jackson-Weaver et al. 2011) suggesting a longer time-scale of vascular regulation.

H₂S can also activate cells. We (Sudhahar et al. 2013) have recently shown that H₂S induces membrane trafficking of protein kinase Cε (PKCε) through specific sulfhydrylation of Cys-13 and Cys-74 in the C2 domain. This is consistent with the well known role of PKCε activation in hypoxic pulmonary vasoconstriction (Sylvester et al. 2012). H₂S also activates the carotid body through inhibition of large-conductance calcium activated potassium (BK_{Ca}) channels (Li et al. 2010; Telezhkin et al. 2009, 2010) and/or inhibition of background (TASK) potassium channels (Buckler 2012); both lead to membrane depolarization and voltage-gated Ca²⁺ entry. Although specific channels were not identified, inhibition of potassium channels is consistent with hypoxia- and H₂S-mediated depolarization of zebrafish neuroepithelial cells (Olson et al. 2008), bovine pulmonary arteries (Olson et al. 2006) and lamprey aortas (Madden and Olson, unpublished). H₂S stimulates catecholamine release from rat adrenal cells via H₂S inhibition of I_{K(Ca)} current (Zhu et al. 2012). In other cells, H₂S directly increases BK channel activity in rat GH(3) pituitary tumor cells through its reducing action on sulfhydryl groups of the channel protein (Sitdikova et al. 2010). A direct link between H₂S signaling and hypoxia has been shown by Tao et al. (2012) where the Cys1045-Cys1024 disulfide bond of VEGFR2 is targeted by H₂S and serves as a specific molecular switch for hypoxia mediated migration of vascular endothelial cells.

It is not too surprising that the acute hypoxia signal, H₂S, interacts with the long-term hypoxia signaling hypoxia-inducible factors (HIFs). In general, H₂S decreases HIF-1α expression in a variety of mammalian tissues (Kai et al. 2012; Si et al. 2013; Wu et al. 2012). H₂S inhibits HIF-1α protein accumulation during hypoxia (1 % O₂) or hypoxia-mimetic conditions by enhancing HIF2α phosphorylation independent of

protein synthesis or ubiquitin-proteasomal degradation (Kai et al. 2012; Wu et al. 2012). Hypoxic pre- (and post-)conditioning, which appears to involve H₂S signaling (Bian et al. 2006; Lavu et al. 2010; Pan et al. 2006; Yong et al. 2008) is also associated with a decrease in HIF1- α expression (Sims et al. 2012). Interestingly, H₂S has the opposite effect on the nematode, *Caenorhabditis elegans*, where it increases HIF-1 activity, although this effect appears to be independent of hypoxia-mediated HIF-1 expression (Budde and Roth 2010). Other effectors of H₂S-mediated cellular protection from hypoxia include heat shock protein 90 (Meng et al. 2011), inhibition of ROS-activated pathways such as NF- κ B/COX-2 (Yang et al. 2011) and ERK1/2 and p38MAPK (Lan et al. 2011).

Direct competition between hypoxia and H₂S for the same effector response, seen as the inability of one stimulus to produce a response when the tissue is activated by the other, has been demonstrated in a variety of blood vessels (Olson et al. 2006; Skovgaard and Olson 2012). This provides additional, albeit indirect, evidence that H₂S is involved in hypoxic signaling.

2.3.6 H₂S-Mediated O₂ Sensing Has an Evolutionary Precedent and a Phylogenetic History

H₂S was likely an important energy source and structural entity in the origin of life and for the first 500 million years after the origin of eukaryotes, the latter occurring in sulfidic and anoxic environments (reviewed in Olson 2012c). Thus, there is a long evolutionary history of H₂S in intracellular energy trafficking and signaling. Some of these facets are retained today as SQR, the initial enzyme in H₂S oxidation, is an integral component of the mitochondrial electron transport chain, as is SO (Hildebrandt 2011). It is evident in the present day, however, that H₂S and O₂ are not mutually compatible either in the environment, or in cells. Thus, as the Earth's O₂ levels began to rise some 800 million years ago, environmental H₂S fell and H₂S was no longer available as a substrate for energy production. However, it is clear that cells retained much of their metabolic capabilities and with an ironic, but well established metabolic twist, they now use H₂S as a reporter of O₂ availability.

Conclusions

There is now considerable evidence that the reciprocal relationship between H₂S and O₂ provides cells with an effective and accurate mechanism with which to couple O₂ availability to a variety of effector responses in O₂ sensing and perhaps all cells. This hypothesis is supported by the ubiquitous similarity between the effects of hypoxia and H₂S on a variety of tissues, that net tissue H₂S is exquisitely controlled by O₂ availability at physiologically relevant O₂ levels, that factors that augment or inhibit H₂S production have a similar effect on hypoxic responses and that the downstream effectors for hypoxia and H₂S appear to be identical. This mechanism appears to have originated early on in

evolution and it is likely widespread in the animal kingdom. The next step in evaluating this signaling mechanism will be to determine how, and where, this mechanism operates at the sub-cellular level.

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