Hypoxia in the Renal Medulla: Implications for Hydrogen Sulfide Signaling

Jerzy Bełtowski
Department of Pathophysiology, Medical University, Lublin, Poland

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ABSTRACT

Hydrogen sulfide (H2S) is enzymatically generated in mammalian tissues from either L-cysteine or L-homocysteine. H2S possesses multiple biological activities, including regulation of vascular tone and blood pressure. Hydrogen sulfide produced in endothelial cells, vascular smooth muscle cells, and perivascular adipose tissue dilates blood vessels by activating ATP-sensitive potassium channels. In addition, H2S produced locally within the kidney stimulates natriuresis and diuresis by increasing glomerular filtration and inhibiting tubular sodium reabsorption. Because H2S is oxidized in mitochondria in pO2-dependent manner and ambient pO2 is physiologically low in the renal medulla, it is expected that the activity of H2S is higher in the medullary region than the cortical region. H2S, accumulating in increased amounts in the renal medulla under hypoxic conditions, may function as an oxygen sensor that restores O2 balance by increasing medullary blood flow, reducing energy requirements for tubular transport, and directly inhibiting mitochondrial respiration. Hypoxia is an important pathogenic factor in many renal diseases, such as ischemia/reperfusion- or nephrotoxin-induced acute renal failure, progression of chronic nephropathies, diabetic nephropathy, and arterial hypertension. Deficiency of endogenous H2S may contribute to the pathogenesis of these pathologies by compromising medullary oxygenation, and administration of H2S donors may be of therapeutic value in these disorders.

Studies performed during the last decade indicate that, apart from NO and CO, H2S is the third “gasotransmitter” involved in the regulation of various physiological functions, including vascular tone and blood pressure, inflammatory reaction, neurotransmission and gastrointestinal system function. H2S is enzymatically synthesized in three metabolic pathways (Fig. 1): 1) desulfhydration of L-cysteine or L-homocysteine by cystathionine γ-lyase (CSE, EC 4.4.1.1), 2) desulfhydration of L-cysteine by cystathionine β-synthase (CBS, EC 4.2.1.22), and 3) transamination of L-cysteine by cysteine aminotransferase (identical with aspartate aminotransferase) to 3-mercaptopyruvate, followed by its desulfhydration to pyruvate by 3-mercaptopyruvate sulfurtransferase (3-MST, EC 2.8.1.2). Hydrogen sulfide activates ATP-sensitive potassium channels (KATP) in various cells, although many other signaling mechanisms have also been described. H2S is inactivated by binding to hemoglobin to form sulfhemoglobin, excretion in exhaled air, and, first and foremost, oxidation in mitochondria. Many studies addressed the role of H2S in the regulation of vascular tone and blood pressure. Indeed, it is suggested that H2S deficiency may contribute to the pathogenesis of arterial hypertension both in experimental animal models and in humans. Recently, renal synthesis and activity of H2S have been characterized (Xia et al., 2009). Because renal sodium handling has a prominent role in the long-term regulation of blood pressure (apart from vascular tone), renal effects of this gas are of great interest for the cardiovascular pharmacologist. In addition, it is well established that renal medulla is a hypoxic environment and that H2S metabolism is O2-dependent. The possible relationship between renal hypoxia and H2S signaling in physiologic and pathologic conditions is addressed in this article.

ABBREVIATIONS: CSE, cystathionine γ-lyase; CBS, cystathionine β-synthase; 3-MST, 3-mercaptopyruvate sulfurtransferase; CO, carbon monoxide; COX-2, cyclooxygenase-2; GFR, glomerular filtration rate; HIF-1, hypoxia-induced factor; HO-1, heme oxygenase-1; H2S, hydrogen sulfide; KATP, ATP-sensitive potassium channels; mTAL, medullary thick ascending limb; NCC, sodium/chloride cotransporter; NKCC, sodium/potassium/chloride cotransporter; NO, nitric oxide; SQR, sulfide/quinone oxidoreductase; GYY4137, morpholin-4-ium-4-methoxyphenyl(morpholino) phosphinodithioate.
Role of \( \text{H}_2\text{S} \) in the Regulation of Vascular Tone and Blood Pressure

Initially, it was suggested that, in the blood vessels, \( \text{H}_2\text{S} \) is produced exclusively by CSE expressed in vascular smooth muscle cells and activates \( K_{\text{ATP}} \) channels in these cells, leading to membrane hyperpolarization, reduced voltage-dependent \( \text{Ca}^{2+} \) influx, and, ultimately, vasorelaxation (Zhao et al., 2001). However, more recent studies indicate that the situation is more complex. \( \text{H}_2\text{S} \) is synthesized also by endothelial cells, at least in rodents. In mice aortic endothelial cells, \( \text{H}_2\text{S} \) is synthesized by CSE, and its production is stimulated by cholinergic agonists (Yang et al., 2008). Thus, \( \text{H}_2\text{S} \) is suggested to be one of the endothelium-dependent relaxing factors. CSE is not expressed in rat endothelial cells; however, \( \text{H}_2\text{S} \) is synthesized in these cells in a 3-MST-dependent manner (Shibuya et al., 2009). \( \text{H}_2\text{S} \) is also produced by perivascular adipose tissue (Fang et al., 2009). Moreover, \( \text{H}_2\text{S} \), especially at low concentrations, may trigger some vasoconstrictor mechanisms, such as direct inhibition of endothelial NO synthase or inactivation of NO by binding it to form inactive nitrosothiol (Ali et al., 2006). Nevertheless, arterial hypertension is observed in CSE knockout mice, indicating that the net effect of endogenous \( \text{H}_2\text{S} \) is definitely antihypertensive (Yang et al., 2008).

Plasma \( \text{H}_2\text{S} \) concentration as well as vascular CSE expression and activity are lower in experimental models of hypertension, such as spontaneously hypertensive rat, and hypertension induced by NO synthase inhibitors (Wagner, 2009). On the other hand, chronic administration of CSE inhibitor propargylyglycine, increases blood pressure in normotensive animals (Yan et al., 2004). Recently, it has been demonstrated that plasma \( \text{H}_2\text{S} \) is lower in 25 children with essential hypertension compared with 66 normotensive controls (Chen et al., 2007). Taken together, these data indicate that \( \text{H}_2\text{S} \) is involved in the regulation of blood pressure and that its deficiency may contribute to hypertension.

Renal Effect of \( \text{H}_2\text{S} \)

In addition to vascular tone, blood pressure is regulated by renal sodium handling. Although \( \text{H}_2\text{S} \)-generating enzymes are abundantly expressed in the kidney and \( \text{H}_2\text{S} \) formation by cysteine desulphhydration in the kidney was first described almost 3 decades ago (Stipanuk and Beck, 1982), the renal effect of this gas was completely ignored. Recently, Xia et al. (2009) have reported that \( \text{H}_2\text{S} \) is produced in the kidney and that exogenous \( \text{H}_2\text{S} \) donor, sodium hydrosulphide (NaHS), exerts significant diuretic, natriuretic, and kaliuretic effects. These data suggest that \( \text{H}_2\text{S} \) is antihypertensive, not only by inducing vasodilation but also by affecting renal sodium handling. It is noteworthy that diuresis, natriuresis, and kaliuresis are significantly reduced in animals treated with a mixture of CBS and CSE inhibitors, indicating that endogenous \( \text{H}_2\text{S} \) regulates renal function under baseline conditions. Natriuretic effect of \( \text{H}_2\text{S} \) results from both the increase in glomerular filtration rate (GFR) and the inhibition of tubular sodium reabsorption, as indicated by the increase in fractional Na\(^+\) excretion after administration of NaHS (Xia et al., 2009). Furthermore, tubular effect of \( \text{H}_2\text{S} \) is accounted for, at least in part, by the inhibition of Na\(^{+}\),K\(^{+}\)-ATPase—the major driving force for active Na\(^+\) reabsorption along the nephron. Indeed, NaHS-derived \( \text{H}_2\text{S} \) reduces sodium pump activity in isolated basolateral membranes of tubular cells. In addition, Xia et al. (2009) aimed to elucidate the possible effects of \( \text{H}_2\text{S} \) on Na\(^+/K^{+}/\text{Cl}^{-}\) cotransporter (NKCC) and Na\(^+/\text{Cl}^{-}\) cotransporter (NCC), the major apical Na\(^+\) transporters in the medullary thick ascending limb (mTAL) and distal convoluted tubule, respectively, by studying the interaction between \( \text{H}_2\text{S} \) donor and specific inhibitors of these transporters, furosemide (NKCC inhibitor) and hydrochlorothiazide (NCC inhibitor). It has been demonstrated that natriuretic effect of NaHS is impaired in rats receiving furosemide but not in those treated with hydrochlorothiazide. From these data, authors concluded that \( \text{H}_2\text{S} \) inhibits NKCC but not NCC (Xia et al., 2009). However, the effect of \( \text{H}_2\text{S} \) on these cotransporters was not studied directly. Although this conclusion may be plausible, the alternative explanation should also be considered, i.e., that the interaction between \( \text{H}_2\text{S} \) and diuretics is determined by specific hypoxic environment of the renal medulla.

Hypoxia in the Renal Medulla and Its Role in Local \( \text{H}_2\text{S} \) Signaling

\( \text{H}_2\text{S} \) is oxidized in mitochondria by the sequential action of three enzymes: sulfide/quinone oxidoreductase (SQR), sulfur dioxygenase, and sulfite oxidase (Hildebrandt and Grieshaber, 2008). SQR transfers electrons from \( \text{H}_2\text{S} \) to ubiquinone where they enter the mitochondrial respiratory chain (Fig. 2). Indeed, \( \text{H}_2\text{S} \) is the first and the only currently known inorganic substrate for mitochondria of mammalian cells, and its oxidation may provide energy for ATP synthesis. Mitochondrial \( \text{H}_2\text{S} \) metabolism is highly dependent on oxygen tension. Indeed, several studies have demonstrated that the net \( \text{H}_2\text{S} \) production by various tissues is \( \text{pO}_2 \)-dependent, which is explained by variable degree of mitochondrial oxidation. Net \( \text{H}_2\text{S} \) production can be demonstrated under hypoxic but not under normoxic conditions, because at physiological \( \text{pO}_2 \), most of \( \text{H}_2\text{S} \) is rapidly oxidized (Olson et al., 2006; Whitfield et al., 2008).

It is well established that renal medulla is a hypoxic environment. Indeed, both in the isolated perfused rat kidney and in the rat kidney, in situ \( \text{pO}_2 \) in the renal cortex is close to

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**Fig. 1.** Three pathways of enzymatic \( \text{H}_2\text{S} \) formation: synthesis of L-cystathionine and \( \text{H}_2\text{S} \) from L-cysteine and L-homocysteine by CBS, desulphhydration of L-cysteine by CSE, and transamination of L-cysteine to 3-mercaptopyruvate by cysteine aminotransferase (CAT), followed by its desulphhydration to pyruvate by 3-mercaptopyruvate sulfturtransferase (3-MST).
that in the renal vein (70 mm Hg) but steeply decreases when the electrode is advanced to the renal medulla (Leichtweiss et al., 1969). Oxygen tension in the renal medulla, where mTAL is localized, is between 5 and 15 mm Hg (Epstein, 1997). In most cells in the body, cytochrome c oxidase is almost completely oxidized under physiological conditions because its $K_m$ for oxygen is attained at only 1 to 2 mm Hg in isolated mitochondria and at approximately 10 mm Hg in the whole cells, which is much less than ambient $pO_2$ in these tissues. However, in medullary tubular cells, 20 to 40% of cytochrome c oxidase exists in the reduced state, indicating that local $pO_2$ is close to critical at which mitochondrial respiration might be compromised (Epstein et al., 1982). Due to low $pO_2$, the expression of a major molecular target of hypoxia, hypoxia-induced factor-1 (HIF-1), and its target genes, such as inducible NO synthase, cyclooxygenase-2 (COX-2), and heme oxygenase-1 (HO-1), is much higher in the medulla than in the cortex. In addition, medullary cells possess a high capacity for anaerobic glycolysis to survive in this hypoxic environment.

The kidneys receive approximately 20% of cardiac output, and high renal blood flow is mandatory for glomerular filtration. Thus, the whole kidney is well oxygenated, and total renal oxygen extraction is much lower than in other tissues. However, most of blood delivered to the kidney flows through the renal cortex, whereas medullary blood flow is only approximately 10% of total renal perfusion. In addition, medullary descending and ascending vasa recta are arranged in the countercurrent manner, which is essential for maintaining high osmolality in the renal medulla. This countercurrent arrangement allows oxygen to shunt from descending to ascending vasa recta, thus bypassing the inner zone of the renal medulla. Finally, oxygen balance of the renal medulla is compromised by high $O_2$ consumption by the thick ascending limb that uses large amounts of oxygen for active $Na^+/K^+$-ATPase-dependent sodium reabsorption. It is estimated that 60% of renal $O_2$ consumption is accounted for by active $Na^+$ transport in the mTAL. Furosemide, which inhibits $Na^+$ reabsorption in mTAL, reduces oxygen requirement and increase local medullary $pO_2$. In healthy human volunteers, rapid infusion of 20 mg of furosemide increased renal medullary oxygenation measured by blood oxygen level-dependent magnetic resonance imaging by 25%, whereas cortical oxygenation increased only by 10% (Epstein and Prasad, 2000). It is noteworthy that furosemide improves medullary oxygenation while having no effect or even decreasing medullary blood flow, indicating that increase in $pO_2$ results from the inhibition of $Na^+$ reabsorption in the mTAL. By improving local oxygenation, furosemide reduces HIF-1 expression in the outer and inner medulla (Zou et al., 2001). In the isolated perfused rat kidney, furosemide and bumetanide (the other NKCC inhibitor) reduced the amount of cytochrome c oxidase existing in the reduced state from 40 to 20% (Epstein et al., 1982). Likewise, in the intact anesthetized rat, furosemide increased medullary $pO_2$ from 16 to 35 mm Hg (Brezis et al., 1994). In contrast, factors that inhibit proximal tubular reabsorption, such as acetazolamide, inhibitors of gluconeogenesis or fatty acid oxidation, had no effect on the oxygenation of the renal cortex. In addition, the effect of furosemide was not observed in kidneys perfused with hyperoncotic solutions to reduce GFR and $Na^+$ load available for reabsorption. These data indicate that the rate of active $Na^+$ reabsorption in the mTAL is critical for local medullary oxygen balance.

Xia et al. (2009) did not measure $H_2S$ production separately in the cortex and medulla. However, taking into account the above considerations, it is likely that local $H_2S$ concentration is greater in hypoxic medullary microenvironment. In addition, $H_2S$ generated from exogenous NaHS could be more slowly oxidized in the renal medulla and exert more marked effects on medullary nephron segments. It might be hypothesized that, by inhibiting $Na^+$ reabsorption in the mTAL, furosemide reduces $O_2$ consumption and increases local $O_2$ availability, thus accelerating $H_2S$ oxidation.

**Fig. 2.** Hypothetical role of $H_2S$ as the oxygen sensor in the kidney. Under normoxic conditions (top), $H_2S$ is rapidly oxidized in mitochondria by the sequential action of SQR, sulfur dioxygenase (SDO), and sulfite oxidase (SO). Under hypoxic conditions (bottom), $H_2S$ oxidation is impaired and its level increased; $H_2S$ inhibits active $Na^+$ reabsorption in the mTAL by reducing the activity of NKCC in the apical membrane and $Na^+/K^+$-ATPase (NKA) in the basolateral membrane and thus reduces oxygen consumption. In addition, $H_2S$ decreases $O_2$ consumption by directly inhibiting mitochondrial respiration and increases $O_2$ supply by dilating descending vasa recta (DVR). Decrease in $O_2$ consumption and increase in $O_2$ delivery improve oxygenation status of the renal medulla.
Consequently, impaired natriuretic effect of NaHS in rats receiving furosemide could have resulted not only from the fact that, as suggested by the authors, both H$_2$S and furosemide inhibit NKCC (pharmacodynamic interaction) but also from lower local H$_2$S concentration in furosemide-treated animals (pharmacokinetic interaction). On the contrary, NCC is localized in the distal convoluted tubule in the treated animals (pharmacokinetic interaction). Moreover, the gasotransmitter in the distal tubules of both groups from lower local H$_2$S concentration in furosemide-receiving furosemide-treated animals may result from comparable degrees of H$_2$S oxidation and local levels of the gasotransmitter in the distal tubules of both groups.

**H$_2$S as the Oxygen Sensor in the Kidney?**

It is suggested that H$_2$S functions as an “oxygen sensor” both in the blood vessels (Olson and Whitfield, 2010) and in arterial chemoreceptors (Li et al., 2010). H$_2$S oxidase increases its concentration, leading to vasodilation and stimulation of chemoreceptor afferent neurons, respectively. Indeed, vascular effect of H$_2$S closely resembles the effect of hypoxia (e.g., both induce systemic vasodilation and pulmonary vasoconstriction), and the response of blood vessels and arterial chemoreceptors to hypoxia is abolished by the inhibitors of H$_2$S synthesis. Thus, H$_2$S seems to mediate some effects of hypoxia on the cardiovascular system.

Due to the conflicting needs to simultaneously maintain medullary hyperosmolality for urine concentration and to provide sufficient O$_2$ for tubular transport, renal medullary blood flow must be carefully regulated. Extremely high medullary perfusion will wash out the corticomedullary osmotic gradient and disrupt the ability of the kidneys to concentrate urine, whereas insufficient blood flow might reduce local oxygenation below critical level, leading to the tubular damage. Medullary blood flow is provided by efferent arterioles of juxtamedullary nephrons that proceed toward the medulla as descending vasa recta. Vasa recta are surrounded by pericytes—the smooth muscle-like cells that regulate medullary perfusion by responding to many vasoactive agents. Interestingly, pericytes respond relatively weakly to vasoconstrictors, such as angiotensin II, endothelin-1 and vasopressin, but strongly to vasoconstrictors, including NO, CO, prostaglandin E$_2$, or adenosine (Pallone et al., 2003). It is noteworthy that these vasodilators are generated in great amounts in the renal medulla, partially due to high local expression of enzymes involved in their formation: NO synthases, COX-2, and HO-1. Continuous action of these vasodilators is essential to maintain medullary blood flow and local oxygen balance, and inhibition of their synthesis with, for example, NO synthase or COX inhibitors easily compromises medullary oxygenation and may induce tubular damage. Medullary blood flow must not only be maintained at the precise level but also has to be adjusted to match variable tubular oxygen requirements. Oxygen demand of the mTAL depends on solute load delivered to this segment, which may vary depending on GFR and the fraction of filtrate reabsorbed in the proximal tubule. It is suggested that the “cross-talk” between tubular cells and vascular pericytes adjusts local blood flow to oxygen demand. Indeed, formation of vasa recta vasodilators increases under hypoxic conditions. Nitric oxide is scavenged by reactive oxygen species, in particular superoxide anion radical, which is generated by NADPH oxidase of tubular cells in a pO$_2$-dependent manner. Thus, the level of NO increases at low pO$_2$. Adenosine is produced from ATP in increased amounts under hypoxic conditions. In addition, prolonged hypoxia stimulates the expression of inducible NO synthase, COX-2, and HO-1 by increasing transcriptional activity of HIF-1. NO, prostaglandin E$_2$, CO, and adenosine improve medullary pO$_2$ not only by matching blood flow to the rate of tubular transport but also by reducing oxygen consumption by inhibiting Na$^+$ reabsorption in the mTAL.

H$_2$S emerges as a candidate for a novel oxygen sensor and mediator of tubulovascular cross-talk in the renal medulla. Its level is directly dependent on oxygen tension, and it both inhibits Na$^+$ transport in the mTAL (Xia et al., 2009) and induces vasodilation. Although the effect of H$_2$S on vasa recta has not been studied so far, H$_2$S relaxes various blood vessels in the experimental studies (Zhao et al., 2001), and K$_{ATP}$ channels, the main vascular target for H$_2$S, are expressed in descending vasa recta pericytes (Cao et al., 2005). K$_{ATP}$ channel opener, pinacidil, dilates, whereas their blocker, glibenclamide, constricts descending vasa recta. Because H$_2$S stimulates K$_{ATP}$ channels directly, not through any intermediate signaling mechanisms, it is very likely that locally generated H$_2$S regulates pericyte tone. Apart from increasing blood flow and inhibiting tubular Na$^+$ reabsorption, H$_2$S may improve medullary oxygen status by directly inhibiting mitochondrial respiration (Fig. 2). Indeed, H$_2$S is a potent reversible inhibitor of cytochrome c oxidase. Cytochrome c oxidase is also competitively inhibited by NO in the renal medulla (Palm et al., 2009). However, H$_2$S seems to possess several potential advantages over NO as an oxygen sensor. Formation of NO is dependent on many factors, such as expression of various NOS isoforms, availability of its substrate l-arginine, its cofactor tetrahydrobiopterin, and its inhibitor asymmetric dimethylarginine, and is compromised due to one or more of these mechanisms in many disease states. In addition, NO is rapidly scavenged by reactive oxygen species, even under physiological conditions, and this process is enhanced when oxidative stress exists (Palm et al., 2009). The regulation of H$_2$S-generating enzymes is less understood but it is likely that its level is subjected to less bias by factors other than hypoxia or at least is affected by factors other than those that regulate NO, making the global amount of both gases more directly related to pO$_2$ than either of them alone.

**H$_2$S and Renal Ischemia-Reperfusion Injury**

Ischemia/reperfusion injury is the most common mechanism of acute renal failure. Because of low pO$_2$, even under physiological conditions, mTAL is particularly sensitive to the hypoxic injury and is the segment most commonly affected by ischemic necrosis. Furosemide, as well as other factors that inhibit Na$^+$ reabsorption in the mTAL, such as ouabain or GFR reduction, diminish hypoxic mTAL damage in the hypoperfused kidney (Breizi and Rosen, 1995; Rosenberger et al., 2006). Classically, acute tubular necrosis is classified into that caused by ischemic and toxic insults. However, more recent studies indicate that hypoxia contributes significantly to the tubular damage induced also by various nephrotoxins, such as radiocontrast agents, myoglobin...
bin, hemoglobin, amphotericin B, and nonsteroidal anti-inflammatory drugs (Rosenberger et al., 2006). Inhibitors of mTAL reabsorption reduce tubular damage, at least in some of these disorders, by improving medullary O₂ balance (Heyman et al., 1989).

It is well established that hydrogen sulfide protects from ischemia/reperfusion injury of myocardium, liver, small intestine, neurons, and the lung. Several recent studies indicate that H₂S is protective also in renal ischemia reperfusion. H₂S applied in the breathing air increased survival of mice subjected to bilateral renal ischemia reperfusion, attenuated renal dysfunction (reduced plasma urea and creatinine concentrations), reduced morphological indices of acute tubular necrosis, decreased elevated caspase-3 activity, and attenuated the expression of proapoptotic protein Bax (Bos et al., 2009). In addition, H₂S reduced renal infiltration with monocytes/macrophages and granulocytes. Likewise, NaHS improved renal function, ameliorated oxidative stress, and reduced cell damage in the rat and mouse models of renal ischemia reperfusion (Tripatara et al., 2009; Xu et al., 2009). In contrast, CSE inhibitor propargylglycine impaired the recovery of renal function after reperfusion and worsened morphological tubular damage (Tripatara et al., 2008). Various mechanisms may contribute to the protective effect of H₂S in renal ischemia, such as amelioration of tubular cell apoptosis (Bos et al., 2009), anti-inflammatory effect (Tripatara et al., 2008; Bos et al., 2009), reduction of oxidative stress (Xu et al., 2009), and inhibition of proapoptotic protein kinases p38 mitogen-activated protein kinase, extracellular signal-regulated kinase, and c-Jun N-terminal kinase (Tripatara et al., 2008). Reduction of oxygen consumption and improvement of medullary oxygenation may also play a prominent role in the protective effect of H₂S against renal ischemic damage. It should be noted that, in ischemic acute renal failure, hypoxia is not confined to the renal medulla and mTAL; renal cortex and other tubular segments, such as S3 segment of the proximal tubule, experience severe hypoxia as well. It is likely that H₂S concentration also increases in other regions apart from the mTAL and is involved in their protection from the ischemic damage.

It is unclear whether renal ischemia reperfusion affects the level of endogenous H₂S in the kidney. In the rat kidney, ischemia reperfusion decreased CBS activity, resulting in the reduction of CBS-dependent H₂S production and accumulation of homocysteine in the kidney (Xu et al., 2009). Decrease in CBS activity results from both acidosis (an optimal pH for CBS is above 7) and overproduction of NO, which inactivates CBS by binding to its heme iron. Unlike CBS activity, CSE activity was not changed. In contrast, in the mouse model of in vivo renal ischemia reperfusion, CSE expression and H₂S production in the kidney are increased (Tripatara et al., 2009). It is possible that intrarenal H₂S deficiency, due to other factors such as nephrotoxic agents, may predispose the kidney to the subsequent ischemic insult. For example, because H₂S avidly binds to heme-containing proteins, its deficiency is likely to occur in hemoglobin- or myoglobin-induced nephropathy.

**H₂S, Hypoxia, and Chronic Kidney Disease**

Many studies suggest that aggravated medullary hypoxia exists in patients with chronic kidney disease and is involved in the progression of renal damage. Several factors contribute to aggravation of medullary hypoxia in these patients, including reduction of peritubular capillary density, decrease in medullary blood flow due to glomerular hypoperfusion, altered regulation of vascular tone of the descending vasa recta due to reactive oxygen species-mediated NO deficiency, anemia, increased oxygen demand of the surviving nephrons because of both the increase in single nephron GFR, and reabsorption and degradation of filtered proteins (Heyman et al., 2008). Hypoxia promotes progression of renal disease by stimulating extracellular matrix accumulation, endothelial damage, tubulointerstitial injury, transdifferentiation of proximal tubule cells to myofibroblasts, and stimulation of tumor necrosis factor α and adhesion molecule ICAM-1 (intercellular adhesion molecule-1) in tubular cells (Tanaka and Nangaku, 2010). Of note, treatment strategies that reduce tubular oxygen consumption or improve renal oxygenation, such as low-salt and low-protein diet, erythropoietin, or renin-angiotensin system inhibitors, retard the progression of kidney disease.

Chronic kidney disease is associated with hyperhomocysteinemia due to impaired metabolism of this amino acid in the kidney through the trans-sulfuration pathway. Several lines of evidence suggest that H₂S deficiency may be involved in the pathogenesis of chronic kidney disease. First, renal dysfunction and proteinuria are aggravated in CBS-deficient uninephrectomized mice compared with wild-type uninephrectomized mice (Sen et al., 2009). Second, NaHS normalizes augmented expression of metalloproteinases 2 and 9, reduces glomerular cell apoptosis, decreases the expression of podocyte injury marker perinectin, corrects deficiency of glomerular slit diaphragm protein, nephrin, and reduces proteinuria in these mice. Third, chronic administration of CSE inhibitor propargylglycine induces nephropathy. Finally, blood H₂S and sulhemoglobin levels, as well as CSE expression in blood mononuclear cells, are reduced in end-stage renal disease patients compared with healthy controls, indicating that chronic renal failure is a state of H₂S deficiency (Perna et al., 2009).

**H₂S and Renal Oxygenation in Hypertension**

Abnormal renal oxygenation is also observed in experimental models of hypertension. Oxygen tension in the proximal and distal tubules, as well as in the superficial cortical tissue, is lower in spontaneously hypertensive than in normotensive Wistar-Kyoto rat (Welch et al., 2001). Hypoxia in the hypertensive kidney is attributed to oxidative stress-mediated NO deficiency and the resulting abnormalities of vascular tone and tubular Na⁺ transport. In addition, NO, by inhibiting mitochondrial oxygen consumption, increases O₂ efficiency of tubular transport, i.e., reduces the amount of O₂ consumed per unit of reabsorbed Na⁺. Reduced transport efficiency is observed in hypertensive rats and is improved by superoxide scavenger, tempol, which increases renal NO availability (Adler and Huang, 2002; Welch 2006).

Arterial hypertension is observed in H₂S-deficient CSE(−/−) mice (Yang et al., 2008). Although blood pressure elevation in these animals is attributed to abnormal regulation of vascular tone, it cannot be excluded that impaired H₂S effects in the kidney, including its effects on renal oxygenation, contribute to the observed phenotype. Although renal H₂S pro-
duction was not measured in other models of hypertension. CBS expression and activity are markedly reduced in the kidney of Dahl salt-sensitive hypertensive rats (Li et al., 2006). It should be noted that deficiency of other vasodilators in the renal medulla induced by local infusion of NO synthase, cyclooxygenase, or HO-1 inhibitors induces hypertension in experimental animals by increasing tubular Na+ reabsorption.

Conclusions

Hydrogen sulfide is produced in the kidney by both CBS and CSE and stimulates diuresis and natriuresis by increasing glomerular filtration and inhibiting active tubular reabsorption. Because H$_2$S is oxidized in mitochondrial respiratory chain in a Fo$_2$-dependent manner and ambient Fo$_2$ is much lower in the renal medulla than in the renal cortex, it is likely that renal medulla is a principal target tissue for H$_2$S in the kidney. In addition, H$_2$S may function as the oxygen sensor that maintains local oxygen balance under hypoxic conditions by increasing medullary blood flow and reducing tubular O$_2$ consumption. Hypoxia plays an important role in the pathogenesis of renal ischemia/reperfusion injury, chronic renal disease, and arterial hypertension, and both endogenous and exogenous H$_2$S may exert a significant protective effect by improving medullary oxygenation in these states. Currently available H$_2$S donors such as NaHS are not suitable for therapy because they release H$_2$S rapidly and in high amounts. However, attempts are being made to obtain more appropriate H$_2$S precursors for therapeutic purposes. Recently, the first water-soluble nontoxic H$_2$S donor, GYY4137 [morpholin-4-ium-4-methoxyphenyl(morpholinophosphinodithioate), which releases H$_2$S slowly in vitro and in vivo, has been characterized. Such compounds may become useful in the future treatment of renal diseases. In addition, several H$_2$S-releasing derivatives of nonsteroidal anti-inflammatory drugs have been synthesized, which are less toxic for the gastrointestinal system than their parent compounds (Wallace, 2007). Given the possible role of H$_2$S in the regulation of renal oxygenation, as well as the compromising effect of classic nonsteroidal anti-inflammatory drugs on renal medullary circulation and their nephrotoxicity, H$_2$S-releasing derivatives may be a useful alternative for the renal patients.

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Address correspondence to: Jerzy Beltowski, Department of Pathophysiology, Medical University, Jazewskiego 8, 20-090 Lublin, Poland. E-mail: jerzy.beltowski@um.lublin.pl