

Cite this: DOI: 10.1039/c3md00323j

The synthesis and functional evaluation of a mitochondria-targeted hydrogen sulfide donor, (10-oxo-10-(4-(3-thioxo-3H-1,2-dithiol-5-yl)-phenoxy)decyl)triphenylphosphonium bromide (AP39)

Sophie Le Trionnaire,^a Alexis Perry,^b Bartosz Szczesny,^c Csaba Szabo,^c Paul G. Winyard,^a Jacqueline L. Whatmore,^a Mark E. Wood^{*b} and Matthew Whiteman^{*a}

Synthesis and bioavailability of the endogenous gasomediator hydrogen sulfide (H₂S) is perturbed in many disease states, including those involving mitochondrial dysfunction. There is intense interest in developing pharmacological agents to generate H₂S. We have synthesised a novel H₂S donor molecule coupled to a mitochondria-targeting moiety (triphenylphosphonium; TPP⁺) and compared the effectiveness of the compound against a standard non-TPP⁺ containing H₂S donor (GYY4137) in the inhibition of oxidative stress-induced endothelial cell death. Our study suggests mitochondria-targeted H₂S donors are useful pharmacological tools to study the mitochondrial physiology of H₂S in health and disease.

Received 26th October 2013

Accepted 5th April 2014

DOI: 10.1039/c3md00323j

www.rsc.org/medchemcomm

1 Introduction

Hydrogen sulfide (H₂S) is now convincingly established as the third gasotransmitter,^{1–3} alongside the more familiar nitric oxide (NO) and carbon monoxide (CO). It is enzymatically produced from amino acids cysteine, homocysteine and cystathionine by two pyridoxal-5'-phosphate-dependent enzymes, namely cystathionine-γ-lyase (CSE) and cystathionine-β-synthase (CBS).^{1–3} A third α-ketoglutarate and cysteine-dependent enzyme, located in the mitochondria of cells, 3-mercaptopyruvate sulfurtransferase (3-MST)⁴ has also been proposed to generate H₂S within the mitochondria.⁵

In the vascular system, H₂S has been proposed as an endothelium-derived vasodilator and genetic knock-out of CSE in animals results in hypertension⁶ and accelerates atherosclerosis.⁷ Similarly, decreased H₂S biosynthesis and/or bioavailability have been observed in various human disease states (and animal disease models)^{1–3} including those with marked mitochondrial and endothelial dysfunction and oxidative stress such as hypertension, diabetes, obesity,⁸ pre-eclampsia⁹ and after myocardial infarction.¹⁰ Collectively, these studies have

highlighted the therapeutic potential of pharmacological strategies to increase H₂S bioavailability in these pathologies.

There is extensive evidence for a role of oxidative stress, and the over-production of detrimental oxidants, in the vascular endothelium of several human disease states including diabetes, obesity, hypertension and stroke.¹¹ Oxidant species such as peroxynitrite (ONOO⁻) and hydrogen peroxide (H₂O₂), as well as the products of biomolecule oxidation such as the lipid-derived aldehyde 4-hydroxynonenal (4-HNE), are well known to induce endothelial and mitochondrial dysfunction and cell death.¹¹

Mitochondria are key intracellular organelles determining cell fate (survival and death) and they are a key source of (and target for) detrimental oxidant production within cells.¹² As such, compounds that can 'target' mitochondria and prevent or limit mitochondria-mediated oxidative stress have received considerable attention. Lipophilic cations such as triphenylphosphonium (TPP⁺) have been extensively used for this purpose.¹³ TPP⁺ derivatives are extensively and rapidly taken up by mitochondria *in vivo*, due to the large negative membrane potential inside the mitochondria (Δψ_m), resulting in a high concentration of the TPP⁺-derivatives within the mitochondria.¹³ The covalent attachment of the lipophilic TPP⁺ cation has become established as a generic and robust method for selectively delivering small, bioactive molecules to mitochondria *in vivo*.¹³

H₂S donor compounds such as GYY4137 **1** (Fig. 1)¹⁴ have been shown to exert prominent vasodilatory activity *in vitro*^{14,15} and in hypertensive animals *in vivo*.^{9,14,15} GYY4137 **1** also

^aUniversity of Exeter Medical School, St. Luke's Campus, Magdalen Road, Exeter EX1 2LU, England, UK. E-mail: m.whiteman@exeter.ac.uk; Tel: +44 (0)1392 722942

^bBiosciences, College of Environmental and Life Sciences, University of Exeter, Geoffrey Pope Building, Stocker Road, Exeter EX4 4QD, England, UK. E-mail: m.e.wood@exeter.ac.uk; Tel: +44 (0)1392 723450

^cDepartment of Anesthesiology, University of Texas Medical Branch, Galveston, TX, USA

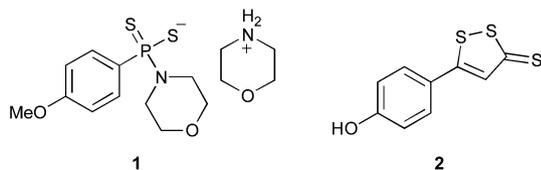


Fig. 1 H₂S donors; GYY4137 **1**, 5-(4-hydroxyphenyl)-3H-1,2-dithiole-3-thione **2**.

inhibited inflammatory signalling in *in vitro*^{16–19} and *in vivo* models of sepsis,¹⁸ arthritis,²⁰ pre-eclampsia⁹ and atherosclerosis.²¹ Furthermore, GYY4137 has also been shown to inhibit oxidative stress-mediated cytotoxicity and loss of mitochondrial function induced by H₂O₂, ONOO[−] and 4-HNE.²² However, GYY4137 is highly water soluble,¹⁴ limiting its cellular permeability, and the above studies have all used high concentrations of GYY4137 (≥100 μM) for anti-inflammatory, vasodilatory, cytoprotective and mitochondrial protective effects to be seen. The need for such high concentrations may further limit its therapeutic potential and alternative strategies for generating potent H₂S donor molecules would be useful.

Dithiolethiones, such as **2**, have been proposed as novel species for H₂S delivery (reviewed in ref. 23) (Fig. 1). Dithiolethione derivatives of non-steroidal anti-inflammatory drugs (*e.g.* naproxen, diclofenac, indomethacin) have been shown to generate H₂S *in vivo*, promote gastro-intestinal blood flow and prevent gastric injury *in vivo*, and exert prominent anti-inflammatory effects with marked additional pharmacological benefit over the parent NSAID alone.^{23–28}

Therefore, with the above observations in mind, we have synthesised a TPP⁺-derivative of dithiolethione **2** to generate a novel mitochondria-targeted H₂S donor molecule. We have then evaluated its effects in a cellular model of oxidative stress and compared its efficacy with the established standard H₂S donor, GYY4137 **1**.

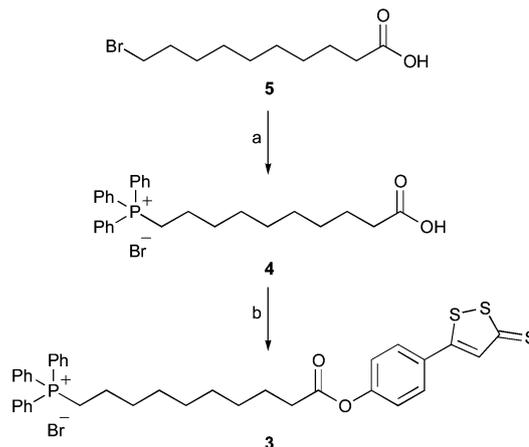
2 Results

2.1 Synthesis

AP39 **3** was prepared in an overall yield of 73% using the two-step process shown in Scheme 1. Phosphonium salt **4** was prepared from 10-bromodecanoic acid **5** and triphenylphosphine under reflux conditions in acetonitrile³³ and coupled, using standard carbodiimide conditions, to 5-(4-hydroxyphenyl)-3H-1,2-dithiole-3-thione **2**.²⁶ Final purification of **3** was achieved using flash chromatography on silica gel (eluting with methanol), the product forming a crisp foam (which could be handled as a solid) on removal of the solvent.

2.2 Intracellular generation of H₂S from AP39

Fig. 2 shows the generation of H₂S from AP39 **3**, detected using two different fluorescence probes selective for sulfide, WSP-1 (ref. 29 and 30) and 7-azido-4-methylcoumarin (AzMC).^{31,32} AP39 induced a concentration-dependent increase in WSP-1 fluorescence, indicative of intracellular H₂S generation²⁹ in human



Scheme 1 Preparation of AP39 **3**. Reagents and conditions: (a) triphenylphosphine (1.0 equiv.), CH₃CN, reflux, 70 h; (b) 5-(4-hydroxyphenyl)-3H-1,2-dithiole-3-thione **2** (1.0 equiv.), *N,N*-dicyclohexylcarbodiimide (1.0 equiv.), 4-dimethylaminopyridine (0.05 equiv.), CH₂Cl₂, room temp., 22 h (73% from **5**).

cerebral microvascular endothelial cells (hCMEC/D3) (Fig. 2A). Furthermore, exposure of bEnd.3 cells to AP39 **3** (100 nM) for 1 hour resulted in an increase in the fluorescence of an alternative H₂S fluorophore AzMC, with significant co-localisation of the signal to mitochondria (Mitotracker) (Fig. 2B).

2.3 Cytotoxicity

Preliminary control experiments were conducted to confirm that the addition of up to 5 μM AP39 and 2 mM GYY4137 for 24 h did not induce significant cytotoxicity compared with vehicle controls (AlamarBlue®; data not shown). Fig. 3 shows concentration-dependent (7–250 nM) inhibition of oxidative stress-mediated toxicity in hCMEC/D3 cells by AP39 **3** and GYY4137 **1** induced by [A] SIN-1 (500 μM), [B] H₂O₂ (50 μM) and [C] 4-HNE (10 μM). The concentration where 50% of cell viability was recovered was estimated to be 25 nM (*vs.* SIN-1), 30 nM (*vs.* H₂O₂) and >125 nM (*vs.* 4-HNE). In order to show that the cytoprotective effects were due to AP39 **3** and not the constituent parts of the AP39 molecule, cells were incubated with 100 nM of the H₂S donor moiety (ADT-OH, **2**), the phosphonium salt containing the mitochondria-targeting motif **4** individually and in combination, and then exposed the cells to SIN-1, H₂O₂ or 4-HNE. Neither ADT-OH **2**, compound **4** (TPP-decanoate) or 100 nM each of ADT-OH **2** with **4**, induced significant cytoprotection against oxidative stress-mediated cytotoxicity (Fig. 3A–C) confirming that cytoprotection was due to AP39 **3**.

We next compared the efficacy of AP39 **3** against an established H₂S donor compound GYY4137 **1**, which has previously been shown to protect human mesenchymal progenitor cells and articular chondrocytes from oxidative stress-mediated toxicity.²² Fig. 3 also shows that when used at the same concentration as AP39 (7–250 nM), GYY4137 **1** was not cytoprotective. However, as expected^{14–20} significant inhibition of oxidative stress-induced cell death was observed with much higher concentrations (*e.g.* ≥100 μM) (Fig. 3D). From these

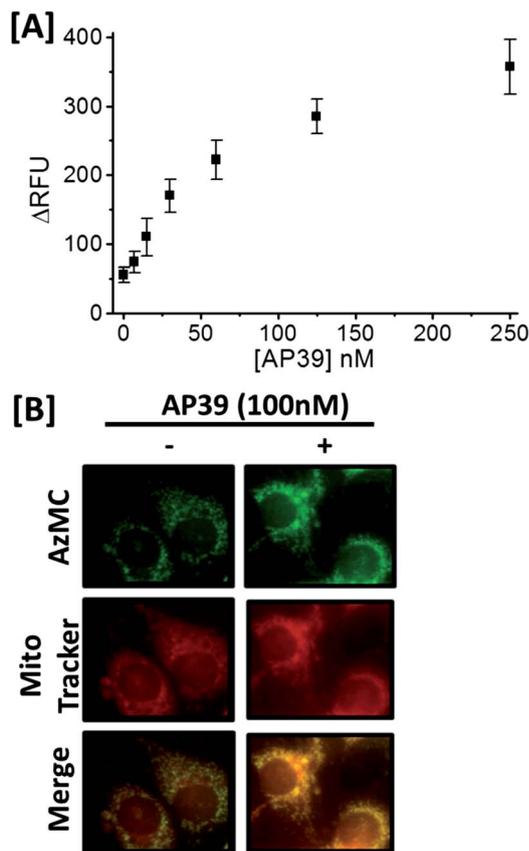


Fig. 2 Intracellular generation of H₂S from AP39. Endothelial cells were treated with 7–250 nM AP39 for 1 hour and intracellular H₂S was detected in human hCMEC/D3 cells using WSP-1 [A]. Co-localisation of mitochondria and H₂S was visualised after 1 hour treatment of murine bEnd.3 cells with AP39 (100 nM) by fluorescence microscopy using MitoTracker Red (for mitochondria) and AzMC (for H₂S) [B]. Images are representative images of three or more independent experiments. Note the concentration-dependent increase in H₂S signal which, at least in part, co-localises within the mitochondrial regions suggesting AP39 generated H₂S mainly in mitochondria.

studies, concentrations of 100 nM AP39 and 100 μM GYY4137 1 were used for subsequent experiments.

2.4 Effects of H₂S donors on mitochondrial membrane potential ($\Delta\Psi_m$), ATP and mitochondrial oxidant production

Fig. 4 shows AP39 3 (100 nM) and GYY4137 1 (100 μM) significantly inhibited oxidative stress-induced loss of mitochondrial membrane potential (Fig. 4A) and inhibited mitochondrial production of reactive oxygen species, detected using MitoSOX Red (Fig. 4B). Incubation of cells with AP39 3 (100 nM) or GYY417 1 (100 μM) alone had no significant effect on mitochondrial membrane potential or mitochondrial oxidant production (data not shown).

Furthermore, AP39 (100 nM) significantly inhibited mitochondrial oxidant production induced by rotenone (5 μM), an inhibitor of mitochondrial respiratory complex I (Fig. 5A) and loss of ATP (Fig. 5B). GYY4137 also prevented rotenone-induced mitochondrial toxicity, albeit when used at a final concentration of 100 μM.

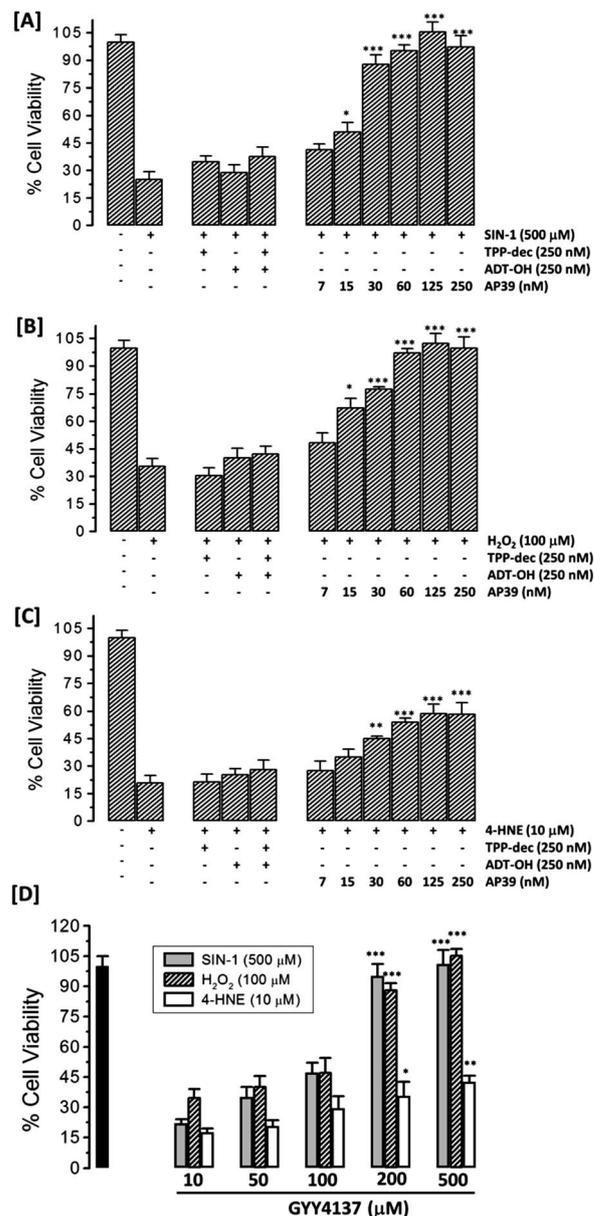


Fig. 3 Concentration-dependent inhibition of oxidative-stress induced cell death by AP39 and GYY4137. hCMEC/D3 cells were incubated with increasing concentrations of AP39 3 and GYY4137 1 (7–250 nM) for 1 hour and [A] SIN-1 (500 μM), [B] H₂O₂ (50 μM) and [C] 4-HNE (10 μM) added. Higher concentrations of GYY4137 1 (10–500 μM) were also examined [D]. Control experiments were also performed using ADT-OH 2, compound 4, alone and in combination [A–C]. Cell viability was assessed by alamarBlue assay after 24 hours. **p* < 0.05, ***p* < 0.01 and ****p* < 0.001 H₂S donors *cf.* oxidant treatment.

3 Experimental

3.1 General synthetic chemistry methods

Starting materials and reagents were obtained from commercial suppliers (Sigma-Aldrich and Fisher Scientific) and were used without further purification. Infrared spectra were recorded using a Perkin Elmer Spectrum BX FT-IR spectrometer. Only major absorbances are quoted, using the abbreviations: (for

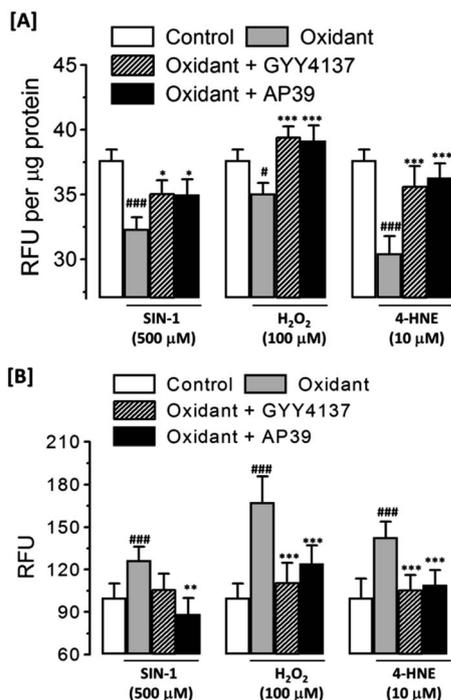


Fig. 4 Inhibition of oxidative-stress induced cell toxicity by H₂S donors. Human hCMEC/D3 endothelial cells were incubated with AP39 **3** (100 nM) or GYY4137 **1** (100 μM) for 1 hour prior to the addition of SIN-1 (500 μM), H₂O₂ (50 μM) or 4-HNE (10 μM). After 24 hours, mitochondrial membrane potential [A] was determined using TMRM and mitochondrial oxidant production [B] determined using MitoSOX. ###*p* < 0.001 oxidant treated cells *cf.* control; **p* < 0.05, ***p* < 0.01, ****p* < 0.001 H₂S donors *cf.* oxidant treatment.

intensity) w, weak; m, medium; and s, strong. Samples were prepared as potassium bromide discs. ¹H NMR spectra were recorded at 300 MHz using a Bruker ACF300 spectrometer. Chemical shifts are quoted in ppm relative to tetramethylsilane, the residual solvent peak being used for referencing purposes. Coupling constants are quoted to the nearest 0.5 Hz with peak multiplicities for single resonances being labelled as: s, singlet; d, doublet; t, triplet; m, unresolved multiplet, AA'BB', AA'BB' pattern and br, broad. Where delineation of individual resonances is not possible, the relevant peaks are grouped together (over a chemical shift range) as complex.

³¹P NMR spectra were recorded at 121 MHz using a Bruker ACF300 spectrometer with external automatic referencing.

¹³C NMR spectra were recorded at 75 MHz using a Bruker ACF300 spectrometer. Chemical shifts are quoted in ppm relative to tetramethylsilane, the solvent peak being used for referencing. Coupling constants are quoted to the nearest 1 Hz with peak multiplicities being labelled using (where appropriate) the abbreviation: d, doublet.

Mass spectra were recorded by the EPSRC National Mass Spectrometry Service Centre, Swansea, UK, in positive ion electrospray (ES⁺) mode.

Analytical thin layer chromatography was carried out using Merck Kieselgel 60 F₂₅₄, coated on aluminium plates, with visualisation of spots by quenching of UV (254 nm) fluorescence or

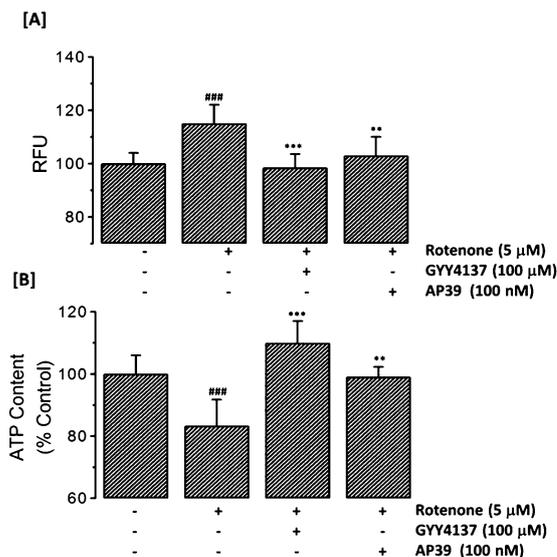


Fig. 5 Inhibition of rotenone induced mitochondrial toxicity by H₂S donors. Human hCMEC/D3 endothelial cells were incubated with AP39 **3** (100 nM) or GYY4137 **1** (100 μM) for 1 hour prior to the addition of rotenone (5 μM). Mitochondrial oxidant production was assessed using MitoSOX (5 μM) [A] and ATP levels determined using firefly lantern luciferase [B]. ##*p* < 0.01 and ###*p* < 0.001 oxidant treated cells *cf.* control; ***p* < 0.01, ****p* < 0.001 H₂S donors *cf.* oxidant treatment.

staining with alkaline potassium permanganate solution as appropriate. Silica gel with particle size 40–63 μm was used for flash chromatography. Solvents and reagents were used as supplied commercially by Sigma-Aldrich and Fisher Scientific without additional purification.

A Büchi R110 Rotavapor was used for the removal of solvents under reduced pressure (*ca.* 15 mmHg).

3.2 (10-Oxo-10-(4-(3-thioxo-3H-1,2-dithiol-5-yl)phenoxy)-decyl)triphenylphosphonium bromide (AP39) **3**

A solution of 10-bromodecanoic acid **5** (500 mg, 1.99 mmol) in acetonitrile (5 cm³) was added to a stirred solution of triphenylphosphine (522 mg, 1.99 mmol) in acetonitrile (5 cm³) and the resulting mixture was heated at reflux for 70 h.³³ After cooling to room temperature and evaporation of the solvent *in vacuo*, the residue was triturated with toluene (2 × 10 cm³) and dissolved in dichloromethane (30 cm³). 5-(4-Hydroxyphenyl)-3H-1,2-dithiole-3-thione²⁶ **2** (456 mg, 2.02 mmol), *N,N*-dicyclohexylcarbodiimide (431 mg, 2.09 mmol) and 4-dimethylaminopyridine (12 mg, 0.10 mmol) were added and the resulting solution was stirred at room temperature for 22 h before filtering through a cotton wool plug and evaporation of the filtrate *in vacuo*. A dichloromethane solution of the residue was loaded onto a silica gel flash chromatography column, which was subsequently eluted with ethyl acetate, followed by methanol. The methanol fractions were combined and evaporated *in vacuo* and a dichloromethane solution of the residue was filtered through a filter paper to remove residual silica gel before evaporation *in vacuo* to give the title compound **3** (1.05 g,

73%) as a crisp, orange foam (found $[M - Br]^+$ (ES^+) 641.1766, $C_{37}H_{38}O_2PS_3$ requires 641.1766); ν_{max} (KBr disc)/ cm^{-1} 2925 (m), 2852 (m), 1754 (m) (C=O), 1599 (w), 1521 (w), 1485 (s), 1437 (s), 1410 (m), 1317 (m), 1278 (m), 1185 (s), 1168 (s), 1112 (s), 1026 (s), 996 (m), 896 (w), 839 (w), 747 (m), 722 (m), 690 (m), 535 (m) and 508 (m); 1H NMR (300 MHz, $CDCl_3$) 7.95–7.65 (17H, m, aryl C(2)H, aryl C(6)H and phenyl CH), 7.42 (1H, s, $CHC=S$), 7.23 (2H, part of $AA'BB'$, $J = 8.5$ Hz, aryl C(3)H and C(5)H), 3.85 (2H, m, CH_2P^+), 2.58 (2H, t, $J = 7.5$ Hz, $CH_2C=O$), 1.80–1.55 (6H, m, $3 \times CH_2$) and 1.42–1.19 (8H, m, $4 \times CH_2$); ^{31}P NMR (121 MHz, $CDCl_3$) 25.7 (P^+); ^{13}C NMR (75 MHz, $CDCl_3$) 214.9 (C=S), 183.7 (CH=C-S), 171.7 (C=O), 153.6 (arylC-O), 135.8 (arylC-C=CH), 134.9 (phenylC-H), 133.6 (d, $J = 9$ Hz, phenylC-H), 130.4 (d, $J = 13$ Hz, phenylC-H), 128.9 (C=CH-C(S)), 128.1 (arylC-H), 122.9 (arylC-H), 118.3 (d, $J = 83$ Hz, phenylC- P^+), 34.2 ($CH_2C(O)$), 30.3 (d, $J = 13$ Hz, CH_2), 29.0 (CH_2), 28.9 ($2 \times CH_2$), 28.8 (CH_2), 24.6 (CH_2), 23.0 (CH_2) and 22.5 (d, $J = 18$ Hz, CH_2P^+).

3.3 Morpholin-4-ium-4 methoxyphenyl(morpholino) phosphinodithioate (GY4137)

GY4137 was synthesised as previously described.¹⁴

3.4 Cell culture

Human cerebral microvascular endothelial cells (hCMEC/D3) were isolated from human brain and kindly provided by Dr Pierre-Olivier Couraud, University of Paris Descartes.^{34–36} The bEnd.3 mouse microvascular endothelial cell line was purchased from the American Type Culture Collection (ATCC #CRL-2299, Manassas, VA).^{37,38}

The vascular endothelium is a prime target for oxidative stress *in vivo* and loss of endothelial function and cell death are observed in cardiovascular diseases such as atherosclerosis, hypertension and diabetes.^{39,40} Therefore we used these cells as an *in vitro* model of cellular oxidative stress.

hCMEC/D3 cells were seeded on type I collagen (Sigma, rat tail; dilution 1 : 30) and cultured in endothelial cell media MV2 (PromoCell; C-22221) with a supplement mix (PromoCell; C-39226) diluted to give fetal bovine serum (2.5%), epidermal growth factor (1.25 ng ml^{-1}), basic fibroblast growth factor (2.5 ng ml^{-1}), insulin-like growth factor (5 ng ml^{-1}), vascular endothelial growth factor 165 (0.125 ng ml^{-1}), ascorbate (0.25 μg ml^{-1}) and hydrocortisone (0.05 ng ml^{-1}). hCMEC/D3 cells constitutively express microvascular endothelial cell markers including von Willebrand factor, CD31 (PECAM-1) and CD105 (endoglin) up to passage 35. Cells used in this current study were between passages 25–34. The commercial bEnd.3 mouse microvascular endothelial cell line was cultured as described.^{37,38} Murine bEnd.3 cells were maintained in DMEM containing glucose (1 g l^{-1}) supplemented with 10% fetal bovine serum (10%), non-essential amino acids, (1%) penicillin (100 IU ml^{-1}) and streptomycin (100 μg ml^{-1}) at 37 °C in 10% CO_2 .

3.5 Detection of hydrogen sulfide in living endothelial cells

Cells were seeded in Lab-Tek II chamber cover glass (Nalgen Nunc International) and incubated overnight at 37 °C and 10% CO_2 humidified incubator. After attachment, the cells were

loaded with 7-azido-4-methylcoumarin (AzMC, SIGMA L511455)^{30,31} and MitoTracker Red CMXRos (Invitrogen M7512) fluorogenic dyes at 10 μM and 50 nM final concentration, respectively, for 30 min. Next, 100 nM of AP39 3 was added with fresh media and cells were further incubated for 1 hour, washed twice with PBS containing calcium and magnesium. 50 μl of PBS was then added to each chamber and micro cover glass was attached. The dye's specific fluorescence was visualized under 40 \times magnification using a Nikon eclipse 80i inverted microscope with Photometric CoolSNAP HQ2 camera and NIS-Elements BR 3.10 software. An additional sulfide-specific fluorophore, WSP-1 (Caymen, 11179-5)^{29,30} was used to determine intracellular generation of H_2S . In these experiments, cells were seeded overnight in black 96 well microplates (Nalgen Nunc International) and incubated at 37 °C with 10 μM WSP-1 for 30 min.³⁰ After this time, cells were washed with pre-warmed phenol-red free culture media and AP39 (10–250 nM) added and WSP-1 fluorescence determined (Ex_{465nm} , Em_{515nm}) using a Molecular Devices M2e microplate reader.

3.6 Cytotoxicity assays

To induce oxidative stress, hCMEC/D3 cells were exposed to either H_2O_2 (100 μM), SIN-1 (500 μM) or the lipid aldehyde product of lipid peroxidation *in vivo*, 4-hydroxynonenal (4-HNE; 10 μM) for 24 hours in the presence or absence of H_2S donors GYY4137 1 (100 μM), AP39 3 (100 nM), ADT-OH 2 (100 nM) or compound 4 (100 nM). After this time cell viability, as an end point for cytotoxicity, was assessed by alamarBlue® assay (AbD Serotec; #BUF012) according to the manufacturer's instructions. Fluorescence was then determined using a Molecular Devices M2e plate reader (fluorescence; Ex_{540nm}/Em_{612nm}) as described. Data are expressed as % of untreated or vehicle treated cells (% viability).

3.7 Assessment of mitochondrial membrane potential ($\Delta\Psi_m$)

Mitochondrial membrane potential ($\Delta\Psi_m$) in whole hCMEC/D3 cells was measured by using the fluorescent potentiometric probe tetramethylrhodamine methyl ester (TMRM; Invitrogen). TMRM is a membrane-permeable cationic fluorophore that electrophoretically accumulates in mitochondria in response to their negative potential and decrease of TMRM fluorescence is indicative of $\Delta\Psi_m$ disruption and mitochondrial and cellular toxicity. Cells were incubated with SIN-1 (500 μM), H_2O_2 (100 μM) or 4-HNE (10 μM) in the presence or absence of H_2S donors for 18 h and after this time, cells were incubated for 30 min with TMRM (200 nM), washed with warm (37 °C) phosphate buffered saline (pH 7.4) and TMRM fluorescence (Relative Fluorescence Units; RFU) determined by fluorimetry (Ex_{548nm}/Em_{573nm}).^{41,42}

3.8 ATP determination

hCMEC/D3 cells were seeded overnight on 24 well plates (Greiner) containing 1.0 ml culture media and treated with the respiratory chain inhibitor rotenone (5 μM), and the oxidants SIN-1 (500 μM), H_2O_2 (100 μM) or 4-HNE (10 μM) in the presence or absence of AP39 (100 nM) or GYY4137 (100 μM) for 18 hours.

After this time, cells were washed twice with ice cold phosphate buffered saline (PBS) and lysed with 100 μ l of ice-cold trichloroacetic acid (TCA; 10% w/v). 5 μ l of TCA lysate was then added to 200 μ l of arsenite buffer (containing 80 mM MgSO₄, 10 mM KH₂PO₄ and 100 mM Na₂HAsO₄, mixed in a 1 : 1 : 1 ratio; pH 7.4) followed by 10 μ l firefly lantern extract (containing luciferase; Sigma).^{41,42} Emitted light was recorded on a GloMax Jr, (Promega) luminescence detector as described. ATP concentrations were determined using a freshly prepared standard curve and samples normalised to cellular protein content using a commercial bicinchoninic acid-based kit (Bio-Rad).

3.9 Intracellular oxidant production

hCMEC/D3 cells were treated with oxidants and H₂S donors (GYY4137 **1**, 100 μ M; AP39 **3**, 100 nM) as described above. The production of mitochondria-derived reactive oxygen species was determined by fluorimetry using the mitochondria-targeted oxidant probe MitoSOX Red™ (Invitrogen, 5 μ M) and fluorescence determined (RFU) Ex₃₉₀/Em_{580nm}.⁴³

3.10 Statistical analysis

All graphs are plotted with mean \pm SEM. In all cases, the mean values were calculated from data taken from at least six separate experiments, performed on separate days using freshly prepared reagents. Where significance testing was performed, an independent *t*-test (Student's; two populations) was used; **P* < 0.1, ***P* < 0.05, ****P* < 0.01.

4 Discussion

H₂S has been proposed as a novel cytoprotective mediator.^{22,44–46} In isolated mesenchymal progenitor cells RNAi-mediated knockdown of CSE potentiated SIN-1, H₂O₂ and 4-HNE-mediated mitochondrial toxicity, an effect reversed with GYY4137.²² Genetic knockout of CSE renders endothelial⁶ and striatal Q111⁴⁷ cells more sensitive to oxidative stress-induced toxicity and blood vessels more prone to atherosclerosis.²¹ However, it should be noted that this is not seen in all models. For example, hepatocytes from CSE^{-/-} mice exposed to galactosamine/lipopolysaccharide were shown to be more sensitive to oxidative injury than wild type animals,⁴⁸ although it is unclear if the effects were mediated by H₂S since CSE knock out did not significantly decrease plasma or liver H₂S levels and markedly increased plasma homocysteine levels.⁴⁸ Nevertheless, in cell culture experiments, H₂S/HS⁻ generated from NaSH (albeit at \geq 100 μ M) has been shown to prevent detrimental cytotoxic effects and oxidative protein modification induced by oxidants such as hydrogen peroxide, superoxide, hypochlorite and peroxynitrite (reviewed in ref. 46). In neuronal cells, NaSH (\geq 100 μ M) also inhibited oxidative stress-mediated cell death after treatment with β -amyloid⁴⁹ or the mitochondrial toxin 1-methyl-4-phenylpyridinium (MPP⁺).⁵⁰ Furthermore, H₂S is also reported to inhibit the expression and activity of NAD(P)H oxidase, a key source of extra-mitochondrial oxidant species⁵¹ and it upregulates the expression of the antioxidant enzyme thioredoxin-1 in

vascular endothelial cells.⁵² However, in each of these studies, the concentrations of H₂S required for each of these studies are often vastly excessive (typically >1–200 μ M) and well beyond that seen in health or extreme pathology. Although the absolute level of free H₂S gas in the vasculature is not known, the most recent analytical techniques have suggested levels of free H₂S are in the nM to low μ M range, suggesting that many of the above cellular studies using NaSH or Na₂S may not reflect the endogenous effects of physiologically relevant concentrations of H₂S found in the vasculature.²

We recently showed RNAi-mediated knockdown of CSE rendered mitochondria more sensitive to oxidative stress-induced mitochondrial toxicity, an effect which was overcome by the H₂S donor GYY4137 **1** (albeit \geq 100 μ M) suggesting that endogenous H₂S may function to preserve mitochondrial integrity.²² This is supported by *in vivo* studies. For example, in a rodent cardiac ischaemia-reperfusion model, both Na₂S infusion and selective cardiac CSE over-expression preserved mitochondrial ultrastructure, preserved ATP generation and respiratory chain function *in vivo*,⁴⁵ possibly *via* a mitochondrial pathway involving the preservation of Bcl-2 signalling, inhibition of Bax, upregulation of PKC and opening of mitochondrial K_{ATP}-channels.^{10,52}

Collectively, these *in vitro* and *in vivo* studies have strongly suggested that mitochondria are key regulatory targets for endogenous and exogenously applied H₂S suggesting that compounds which deliver H₂S to mitochondria could be therapeutically useful. To test this hypothesis *in vitro*, we exposed microvascular endothelial cells to oxidative insult and examined cell viability and mitochondrial toxicity after oxidative insult using a novel mitochondria-targeted TPP⁺-derived dithiolethione (AP39, **3**) and a well established but non-targeted H₂S donor molecule GYY4137 **1**. Concentrations of GYY4137 (100 μ M) were chosen based on Fig. 3D and the cytoprotective effects reported for this compound in a variety of cellular models.^{14–22} In each assay (Fig. 3–5), AP39 **3** significantly inhibited oxidative stress induced toxicity at concentrations more than 1000-fold lower than that of GYY4137 (*e.g.* 100 nM AP39 *cf.* 100 μ M GYY4137). In contrast, incubation of cells with TPP⁺-decanoate (compound **4**) which targets mitochondria, but cannot generate H₂S or the H₂S donor moiety ADT-OH alone (*e.g.* lacking TPP⁺), did not prevent oxidant-induced cell death (Fig. 3A–C). Similarly, incubation of cells with compound **4** and ADT-OH **2** together also failed to show cytoprotective effects indicating that the whole AP39 molecule (*i.e.* mitochondria-targeted H₂S delivery) was required for cell preservation (Fig. 3A–C). Whilst our study clearly shows inhibition of oxidative stress-induced cellular toxicity and mitochondrial preservation by AP39, it is not possible to determine from these data whether mitochondrial protection was the cause or a consequence of cytoprotection. Nevertheless, TPP⁺-derivatised H₂S donor compounds such as AP39 may be useful tools in studying mitochondria–H₂S interactions.

Although further work is required to define the precise biomolecular pathways by which AP39 **3** prevents cellular injury, the pathways for endogenous mitochondrial generation of H₂S have recently been uncovered.^{5,52–56} The mitochondrial enzyme

3-MST generates low levels of H₂S and 3-MST-derived H₂S concentrations in the nanomolar range were very recently shown to contribute electrons to the Krebs cycle and enhance mitochondrial electron transport and bioenergetics,⁵ an effect blocked during oxidative stress⁵⁴ but reversed with exogenous H₂S.⁵⁴ Recently, CSE⁵³ and CBS^{54,55} have been shown to translocate from the cytosol in cells to the mitochondrial matrix in response to hypoxic and calcium stress, to generate H₂S within the mitochondria, possibly acting as an electron acceptor in the mitochondrial respiratory chain, resulting in increased cellular ATP production and cell preservation.^{53–56} It is possible that these effects were also mediated by AP39-derived H₂S, contributing to the overall cytoprotective effects of this compound since we observed co-localisation of H₂S generation with mitochondria (Fig. 2B), preservation of ATP levels (Fig. 5B) and mitochondrial $\Delta\psi_m$ (Fig. 4A), and decreased mitochondrial oxidant production (Fig. 4B and 5A). Therefore, it appears that the endogenous enzymes responsible for H₂S generation are either located within or translocate to the mitochondria in response to cellular stress and mitochondria-derived H₂S contributes to overall cellular bioenergetics and cellular health. Since mitochondrial production of H₂S is perturbed by oxidative stress, whilst mitochondrial dysfunction and oxidative stress are key pathological events in several human disease states (including hypertension, stroke, neurodegenerative disease, arthritis, hepatitis *etc.*; reviewed in ref. 1–3), it is likely that mitochondrial H₂S delivery may represent a novel approach to study mitochondrial function in health and disease. This potentially reveals a novel therapeutic strategy to treat (or limit) mitochondrial dysfunction in human disease.

5 Conclusions

Our current study shows that coupling H₂S generating dithiolethione (AP39) to a moiety well characterised to enable selective targeting of intracellular mitochondria (TPP⁺) greatly increased the cytoprotective potency of H₂S relative to a standard and non-targeted H₂S donor compound GYY4137. Selective pharmacological manipulation of mitochondrial H₂S may represent a novel approach to preserve mitochondrial function and prevent oxidative stress-induced cellular injury *in vivo*.

Acknowledgements

The authors are grateful to the EPSRC National Mass Spectrometry Service Centre (Swansea, UK) for determination of mass spectra and to Ms Srijana Rai for her technical support. We are also grateful to the American Diabetes Association (#7-12-BS-184) and the Medical Research Council (UK; G0800107) for their generous research support.

References

- 1 R. Wang, Physiological implications of hydrogen sulfide: a whiff exploration that blossomed, *Physiol. Rev.*, 2012, 971–896.

- 2 M. Whiteman, S. Le Trionnaire, M. Chopra, B. Fox and J. Whatmore, Emerging role of hydrogen sulfide in health and disease: critical appraisal of biomarkers and pharmacological tools, *Clin. Sci.*, 2011, 121, 459–488.
- 3 M. S. Vandiver and S. H. Snyder, Hydrogen sulfide: a gasotransmitter of clinical relevance, *J. Mol. Med.*, 2012, 90, 255–263.
- 4 N. Shibuya, M. Tanaka, M. Yoshida, Y. Ogasawara, T. Togawa, K. Ishii and H. Kimura, 3-Mercaptopyruvate sulfurtransferase produces hydrogen sulfide and bound sulfane sulfur in the brain, *Antioxid. Redox Signaling*, 2009, 11, 701–714.
- 5 K. Módis, C. Coletta, K. Erdélyi, A. Papapetropoulos and C. Szabo, Intramitochondrial hydrogen sulfide production by 3-mercaptopyruvate sulfurtransferase maintains mitochondrial electron flow and supports cellular bioenergetics, *FASEB J.*, 2013, 27, 601–611.
- 6 G. Yang, L. Wu, B. Jiang, W. Yang, J. Qi, K. Cao, Q. Meng, A. K. Mustafa, W. Mu, S. Zhang, S. H. Snyder and R. Wang, H₂S as a physiologic vasorelaxant: hypertension in mice with deletion of cystathionine gamma-lyase, *Science*, 2008, 322, 587–590.
- 7 S. Mani, H. Li, A. Untereiner, L. Wu, G. Yang, R. C. Austin, J. G. Dickhout, S. Lhoták, Q. H. Meng and R. Wang, Decreased endogenous production of hydrogen sulfide accelerates atherosclerosis, *Circulation*, 2013, 25(127), 2523–2534.
- 8 M. Whiteman, K. M. Gooding, J. L. Whatmore, C. I. Ball, D. Mawson, K. Skinner, J. E. Tooke and A. C. Shore, Adiposity is a major determinant of plasma levels of the novel vasodilator hydrogen sulphide, *Diabetologia*, 2010, 53, 1722–1726.
- 9 K. Wang, S. Ahmad, M. Cai, J. Rennie, T. Fujisawa, F. Crispi, J. Baily, M. R. Miller, M. Cudmore, P. W. Hadoke, R. Wang, E. Gratacós, I. A. Buhimschi, C. S. Buhimschi and A. Ahmed, Dysregulation of hydrogen sulfide producing enzyme cystathionine- γ -lyase contributes to maternal hypertension and placental abnormalities in preeclampsia, *Circulation*, 2013, 127, 2514.
- 10 M. Lavu, S. Bhushan and D. J. Lefer, Hydrogen sulfide-mediated cardioprotection: mechanisms and therapeutic potential, *Clin. Sci.*, 2010, 120, 219–229.
- 11 B. Halliwell and J. Gutteridge, *Free radicals in biology and medicine*, Oxford University Press, 2007, ISBN-10: 019856869X.
- 12 M. P. Murphy, How mitochondria produce reactive oxygen species, *Biochem. J.*, 2009, 417, 1–13.
- 13 R. A. Smith, R. C. Hartley, H. M. Cocheme and M. P. Murphy, Mitochondrial Pharmacology, *Trends Pharmacol. Sci.*, 2012, 341–352.
- 14 L. Li, M. Whiteman, Y. Y. Guan, K. L. Neo, Y. Cheng, S. W. Lee, Y. Zhao, R. Baskar, C. H. Tan and P. K. Moore, Characterisation of a novel, water-soluble hydrogen sulfide-releasing molecule (GYY4137). New insights into the biology of hydrogen sulfide, *Circulation*, 2008, 117, 2351–2360.
- 15 H. Robinson and S. Wray, A new slow releasing, H₂S generating compound, GYY4137 relaxes spontaneous and

- oxytocin-stimulated contractions of human and rat pregnant myometrium, *PLoS One*, 2012, 7, e46278.
- 16 S. Merighi, S. Gessi, K. Varani, D. Fazzi and P. A. Borea, Hydrogen sulfide modulates the release of nitric oxide and VEGF in human keratinocytes, *Pharmacol. Res.*, 2012, **66**, 428–436.
 - 17 M. M. Perry, C. K. Hui, M. Whiteman, M. E. Wood, I. Adcock, P. Kirkham, C. Michaeloudes and K. F. Chung, Hydrogen sulfide inhibits proliferation and release of IL-8 from human airway smooth muscle cells, *Am. J. Respir. Cell Mol. Biol.*, 2011, **45**, 746–752.
 - 18 L. Li, M. Salto-Tellez, C. H. Tan, M. Whiteman and P. K. Moore, GYY4137, a novel; hydrogen sulfide-releasing molecule, protects against endotoxic shock in the rat, *Free Radicals Biol. Med.*, 2009, **47**, 103–113.
 - 19 M. Whiteman, L. Li, P. Rose, C. H. Tan, D. B. Parkinson and P. K. Moore, The effect of hydrogen sulfide donors on lipopolysaccharide-induced formation of inflammatory mediators in macrophages, *Antioxid. Redox Signaling*, 2010, **12**, 1147–1154.
 - 20 L. Li, B. Fox, J. Keeble, M. Salto-Tellez, P. G. Winyard, M. E. Wood, P. K. Moore and M. Whiteman, The complex effects of the slow-releasing hydrogen sulfide donor GYY4137 in a model of acute joint inflammation and in human cartilage cells, *J. Cell. Mol. Med.*, 2013, **17**, 365–376.
 - 21 Z. Liu, Y. Han, L. Li, H. Lu, G. Meng, X. Li, M. Shirhan, M. T. Peh, L. Xie, S. Zhou, X. Wang, Q. Chen, W. Dai, C. H. Tan, S. Pan, P. K. Moore and Y. Ji, The hydrogen sulfide donor, GYY4137, exhibits anti-atherosclerotic activity in high fat fed apolipoprotein E(–/–) mice, *Br. J. Pharmacol.*, 2013, **169**, 1795–1809.
 - 22 B. Fox, J.-T. Schantz, R. Haigh, M. E. Wood, P. K. Moore, N. Viner, J. P. Spencer, P. G. Winyard and M. Whiteman, Inducible hydrogen sulfide synthesis in chondrocytes and mesenchymal progenitor cells: is H₂S a novel cytoprotective mediator in the inflamed joint?, *J. Cell. Mol. Med.*, 2012, **16**, 896–910.
 - 23 G. Caliendo, G. Cirino, V. Santagada and J. L. Wallace, Synthesis and biological effects of hydrogen sulfide (H₂S): development of H₂S-releasing drugs as pharmaceuticals, *J. Med. Chem.*, 2010, **53**, 6275–6286.
 - 24 M. E. Wood, M. Whiteman and A. Perry, Hydrogen sulfide releasing compounds and their use, Patent application WO2013045951, 2013.
 - 25 J. L. Wallace, Hydrogen sulfide: a rescue molecule for mucosal defence and repair, *Dig. Dis. Sci.*, 2012, **57**, 1432–1434.
 - 26 L. Li, G. Rossoni, A. Sparatore, L. C. Lee, P. Del Soldato and P. K. Moore, Anti-inflammatory and gastrointestinal effects of a novel diclofenac derivative, *Free Radicals Biol. Med.*, 2007, **42**, 706–719.
 - 27 M. V. Chan and J. L. Wallace, Hydrogen sulfide-based therapeutics and gastrointestinal disease: Translating physiology to treatments, *Am. J. Physiol.: Gastrointest. Liver Physiol.*, 2013, **305**, G467–G473.
 - 28 M. Campolo, E. Esposito, A. Ahmad, R. Di Paola, J. L. Wallace and S. Cuzzocrea, A hydrogen sulfide-releasing cyclooxygenase inhibitor markedly accelerates recovery from experimental spinal cord injury, *FASEB J.*, 2013, **27**, 4489–4499.
 - 29 C. Liu, J. Pan, S. Li, Y. Zhao, L. Y. Wu, C. E. Berkman, A. R. Whorton and M. Xian, Capture and visualization of hydrogen sulfide by a fluorescent probe, *Angew. Chem., Int. Ed.*, 2011, **50**, 10327–10329.
 - 30 M. M. Cortese-Krott, B. O. Fernandez, J. L. Santos, E. Mergia, M. Grman, P. Nagy, M. Kelm, A. Butler and M. Feelisch, Nitrosopersulfide (SSNO(–)) accounts for sustained NO bioactivity of S-nitrosothiols following reaction with sulfide, *Redox Biol.*, 2014, **2**, 234–244.
 - 31 M. K. Thorson, T. Majtan, J. P. Kraus and A. M. Barrios, Identification of cystathionine β-synthase inhibitors using a hydrogen sulfide selective probe, *Angew. Chem., Int. Ed.*, 2013, **52**, 4641–4644.
 - 32 B. Chen, W. Li, C. Lv, M. Zhao, H. Jin, J. Du, L. Zhang and X. Tang, Fluorescent probe for highly selective and sensitive detection of hydrogen sulfide in living cells and cardiac tissues, *Analyst*, 2013, **138**, 946–951.
 - 33 S. Thurnhofer and W. Vetter, Synthesis of (S)-(+)-enantiomers of food-relevant (n-5)-monoenoic acid saturated anteiso-fatty acids by a Wittig reaction, *Tetrahedron*, 2007, **63**, 1140–1145.
 - 34 S. Ohtsuki, C. Ikeda, Y. Uchida, Y. Sakamoto, F. Miller, F. Glacial, X. Decleves, J. M. Scherrmann, P. O. Couraud, Y. Kubo, M. Tachikawa and T. Terasaki, Quantitative targeted absolute proteomic analysis of transporters, receptors and junction proteins for validation of human cerebral microvascular endothelial cell line hCMEC/D3 as a human blood-brain barrier model, *Mol. Pharm.*, 2013, **10**, 289–296.
 - 35 H. Mkrtchyan, S. Scheler, I. Klein, A. Fahr, P. O. Couraud, I. A. Romero, B. Weksler and T. Liehr, Molecular cytogenetic characterization of the human cerebral microvessel endothelial cell line hCMEC/D3, *Cytogenet. Genome Res.*, 2009, **126**, 313–317.
 - 36 B. Weksler, I. A. Romero and D. Couraud, The hCMEC/D3 cell line as a model for the human blood brain barrier, *Fluids Barriers CNS*, 2013, **10**, 16.
 - 37 T. Watanabe, S. Dohgu, F. Takata, T. Nishioku, A. Nakashima, K. Futagami, A. Yamauchi and Y. Kataoka, Paracellular barrier and tight junction protein expression in the immortalized brain endothelial cell lines bEND.3, bEND.5 and mouse brain endothelial cell 4, *Biol. Pharm. Bull.*, 2013, **36**, 492–495.
 - 38 T. Y. Park, E. J. Baik and S. H. Lee, Prostaglandin E₂-induced intercellular adhesion molecule-1 expression is mediated by cAMP/Epac signalling modules in bEnd.3 brain endothelial cells, *Br. J. Pharmacol.*, 2013, **169**, 604–618.
 - 39 S. M. Davidson and M. R. Duchon, Endothelia mitochondria: Contributing to vascular function and disease, *Circ. Res.*, 2007, **100**, 1128–1141.
 - 40 H. Cai and D. G. Harrison, Endothelial dysfunction in cardiovascular disease: The role of oxidative stress, *Circ. Res.*, 2000, **87**, 840–844.

- 41 M. Whiteman, J. S. Armstrong, N. S. Cheung, J. L. Siau, P. Rose, J.-T. Schantz, D. P. Jones and B. Halliwell, Peroxynitrite mediates calcium-dependent mitochondrial dysfunction and cell death *via* activation of calpains, *FASEB J.*, 2004, **18**, 1395–1397.
- 42 M. Whiteman, P. Rose, J. L. Siau, N. S. Cheung, G. S. Tan, B. Halliwell and J. S. Armstrong, Hypochlorous acid induced mitochondrial dysfunction and apoptosis in human hepatoma HepG2 and fetal liver cells: role of mitochondrial permeability transition, *Free Radicals Biol. Med.*, 2005, **38**, 1571–1584.
- 43 K. M. Robinson, M. S. Janes, M. Pehar, J. S. Monette, M. F. Ross, T. M. Hagen, M. P. Murphy and J. S. Beckman, Selective fluorescent imaging of superoxide *in vivo* using ethidium based probes, *Proc. Natl. Acad. Sci. U. S. A.*, 2006, **103**, 15038–15043.
- 44 K. Suzuki, G. Olah, K. Modis, C. Coletta, G. Kulp, D. Gerö, P. Szoleczky, T. Chang, Z. Zhou, L. Wu, R. Wang, A. Papapetropoulos and C. Szabo, Hydrogen sulfide replacement therapy protects the vascular endothelium in hyperglycemia by preserving mitochondrial function, *Proc. Natl. Acad. Sci. U. S. A.*, 2011, **108**, 13829–13834.
- 45 K. Kondo, S. Bhushan, A. L. King, S. D. Prabhu, T. Hamid, S. Koenig, T. Murohara, B. L. Predmore, G. Gojon Sr, G. Gojon, R. Wang, N. Karusula, C. K. Nicholson, J. W. Calvert and D. J. Lefer, H₂S protects against pressure overload induced heart failure *via* upregulation of endothelial nitric oxide synthase, *Circulation*, 2013, **127**, 1116–1127.
- 46 M. Whiteman and P. K. Moore, Hydrogen sulfide and the vasculature: a novel vasculoprotective entity and regulator of nitric oxide bioavailability?, *J. Cell. Mol. Med.*, 2009, **13**, 488–507.
- 47 B. D. Paul, J. I. Sbodio, R. Xu, M. S. Vandiver, J. Y. Cha, A. M. Snowman and S. H. Snyder, Cystathionine- γ -lyase deficiency mediates neurodegeneration in Huntington's disease, *Nature*, 2014, DOI: 10.1038/nature13136.
- 48 K. Shirozu, K. Tokuda, E. Marutani, D. Leferm, R. Wangm and F. Ichinose, Cystathionine γ -lyase deficiency protects mice from galactosamine/lipopolysaccharide-induced acute liver failure, *Antioxid. Redox Signaling*, 2014, **20**, 204–216.
- 49 Y. Y. Liu and J. S. Bian, Hydrogen sulfide protects amyloid- β induced cell toxicity in microglia, *J. Alzheimer's Dis.*, 2010, **22**, 1189–1200.
- 50 W. L. Yin, J. Q. He, B. Hu, Z. S. Jiang and X. Q. Tang, Hydrogen sulfide inhibits MPP(+)-induced apoptosis in PC12 cells, *Life Sci.*, 2009, 269–275.
- 51 Z. S. Xu, X. Y. Wang, D. M. Xiao, L. F. Hu, M. Lu, Z. Y. Wu and J. S. Bian, Hydrogen sulfide protects MC3T3-E1 osteoblastic cells against H₂O₂-induced oxidative damage-implications for the treatment of osteoporosis, *Free Radicals Biol. Med.*, 2011, **50**, 314–323.
- 52 T. P. Vacek, W. Gillespie, N. Tyagi, J. C. Vacek and S. C. Tyagi, Hydrogen sulfide protects against vascular remodeling from endothelial damage, *Amino Acids*, 2010, **39**, 1161–1169.
- 53 M. Fu, W. Zhang, L. Wu, G. Yang, H. Li and R. Wang, Hydrogen sulfide (H₂S) metabolism in mitochondria and its regulatory role in energy production, *Proc. Natl. Acad. Sci. U. S. A.*, 2012, **109**, 2943–2948.
- 54 K. M. Modis, A. Asimakopoulou, C. Coletta, A. Papapetropoulos and C. Szabo, Oxidative stress suppresses the cellular bioenergetic effect of the 3-mercaptopyruvate sulfurtransferase/hydrogen sulfide pathway, *Biochem. Biophys. Res. Commun.*, 2013, **433**, 401–407.
- 55 C. Szabo, C. Coletta, C. Chao, K. M. Modis, B. Szczesny, A. Papapetropoulos and M. R. Hellmich, Tumor-derived hydrogen sulfide, produced by cystathionine- β -synthase, stimulates bioenergetics, cell proliferation, and angiogenesis in colon cancer, *Proc. Natl. Acad. Sci. U. S. A.*, 2013, **110**, 12474–12479.
- 56 H. Teng, B. Wu, K. Zhao, G. Yang, L. Wu and R. Wang, Oxygen-sensitive mitochondrial accumulation of cystathionine β -synthase mediated by Lon protease, *Proc. Natl. Acad. Sci. U. S. A.*, 2013, **110**, 12679–12684.