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Hydrogen acts as a therapeutic antioxidant by selectively reducing cytotoxic oxygen radicals

Ikuroh Ohsawa¹, Masahiro Ishikawa¹, Kumiko Takahashi¹, Megumi Watanabe^{1,2}, Kiyomi Nishimaki¹, Kumi Yamagata¹, Ken-ichiro Katsura², Yasuo Katayama², Sadamitsu Asoh¹ & Shigeo Ohta¹

Acute oxidative stress induced by ischemia-reperfusion or inflammation causes serious damage to tissues, and persistent oxidative stress is accepted as one of the causes of many common diseases including cancer. We show here that hydrogen (H₂) has potential as an antioxidant in preventive and therapeutic applications. We induced acute oxidative stress in cultured cells by three independent methods. H₂ selectively reduced the hydroxyl radical, the most cytotoxic of reactive oxygen species (ROS), and effectively protected cells; however, H₂ did not react with other ROS, which possess physiological roles. We used an acute rat model in which oxidative stress damage was induced in the brain by focal ischemia and reperfusion. The inhalation of H₂ gas markedly suppressed brain injury by buffering the effects of oxidative stress. Thus H₂ can be used as an effective antioxidant therapy; owing to its ability to rapidly diffuse across membranes, it can reach and react with cytotoxic ROS and thus protect against oxidative damage.

Oxidative stress arises from the strong cellular oxidizing potential of excess reactive oxygen species (ROS), or free radicals^{1–5}. Most of the superoxide anion radical (O₂[•]) produced is generated in mitochondria by electron leakage from the electron transport chain and the Krebs cycle⁶. O₂[•] is also produced by metabolic oxidases, including NADPH oxidase and xanthine oxidase⁷. Superoxide dismutase converts O₂[•] into hydrogen peroxide (H₂O₂)⁸, which is detoxified into H₂O by either glutathione peroxidase or catalase. Excess O₂[•] reduces transition metal ions such as Fe³⁺ and Cu²⁺ (ref. 2), the reduced forms of which in turn can react with H₂O₂ to produce hydroxyl radicals (•OH) by the Fenton reaction. •OH is the strongest of the oxidant species and reacts indiscriminately with nucleic acids, lipids and proteins. There is no known detoxification system for •OH; therefore, scavenging •OH is a critical antioxidant process⁹.

Despite their cytotoxic effects, O₂[•] and H₂O₂ play important physiological roles at low concentrations: they function as regulatory signaling molecules that are involved in numerous signal transduction cascades and also regulate biological processes such as apoptosis, cell proliferation and differentiation^{7,10}. At higher concentrations, H₂O₂ is converted into hypochlorous acid by myeloperoxidase; hypochlorous acid defends against bacterial invasion⁵. Nitric oxide (NO•), another ROS, functions as a neurotransmitter and is essential for the dilation of blood vessels¹¹. Thus, cytotoxic radicals such as •OH must be neutralized without compromising the essential biological activities of other, physiologically beneficial, ROS. Here we demonstrate that molecular hydrogen (dihydrogen, H₂) can alleviate •OH-induced cytotoxicity without affecting the other ROS, and propose that H₂ has potential as an antioxidant for preventive and therapeutic applications.

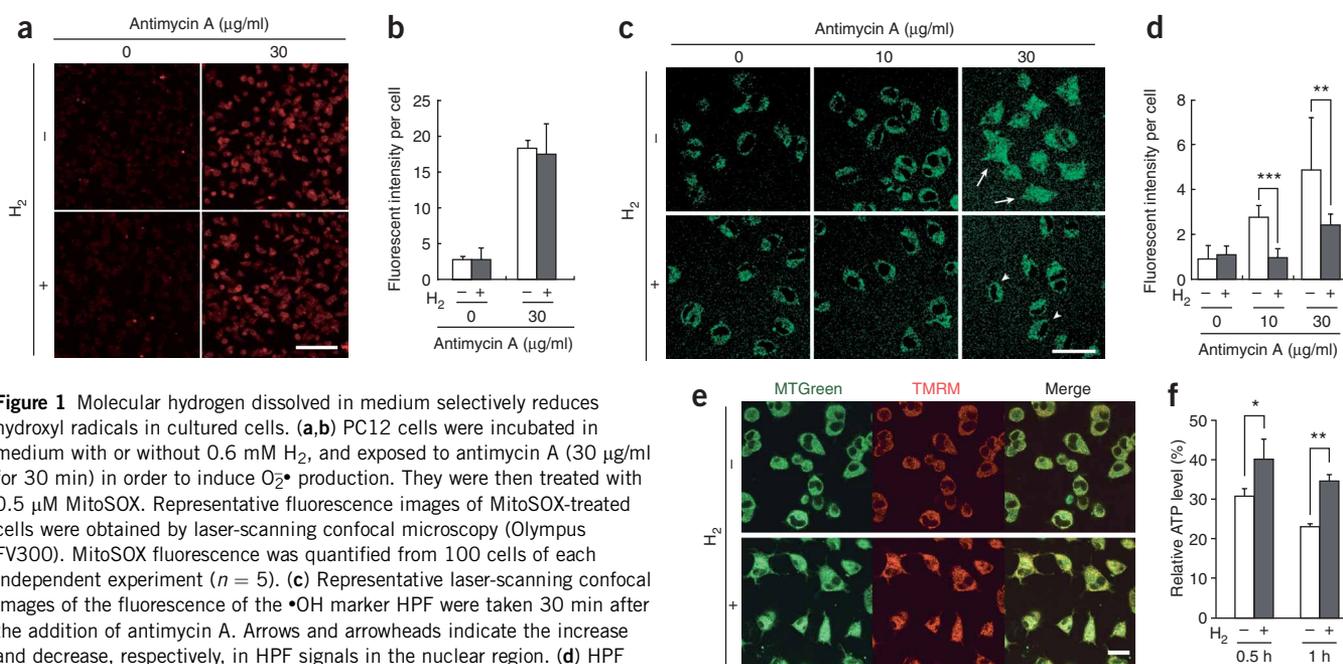
RESULTS

H₂ selectively reduces •OH in cultured cells

H₂ reduces the •OH that is produced by radiolysis or photolysis of water¹²; however, whether H₂ can effectively neutralize •OH in living cells has not been directly investigated. As the cellular damage produced by spontaneous generation of •OH is not sufficient to be detectable, we induced O₂[•] production in PC12 cultured cells. To do this, we treated the cells with a mitochondrial respiratory complex III inhibitor, antimycin A (ref. 13); following such treatment, O₂[•] in these cells is rapidly converted into H₂O₂. The addition of antimycin A increased levels of O₂[•] and H₂O₂, as judged by the fluorescence signals emitted by the oxidized forms of MitoSOX (Fig. 1a) and 2',7'-dichlorodihydrofluorescein (H₂DCF) (Supplementary Fig. 1 online), respectively. We dissolved H₂ and O₂ into medium as described in the Methods, and confirmed the prolonged (24 h long) maintenance of H₂ levels (Supplementary Fig. 2 online). H₂ dissolved in culture medium did not decrease MitoSOX and DCF signals in the cells (Fig. 1a,b and Supplementary Fig. 1). Additionally, H₂ did not decrease the steady-state level of NO• (Supplementary Fig. 1). In contrast, H₂ treatment significantly decreased levels of •OH, as assessed by the fluorescence signal emitted by the oxidized form of 2-[6-(4'-hydroxy)phenoxy-3H-xanthen-3-on-9-yl] benzoate (HPF) (refs. 14,15 and Fig. 1c,d). When we exposed the cells to antimycin A (30 μg/ml) in the absence of H₂, the HPF signals increased in both the nuclear region and the cytoplasm, probably because H₂O₂ diffused from the mitochondria to produce •OH. Notably, H₂ decreased •OH levels even in the nuclear region (Fig. 1c).

¹Department of Biochemistry and Cell Biology, Institute of Development and Aging Sciences, Graduate School of Medicine, Nippon Medical School, 1-396 Kosugi-cho, Nakahara-ku, Kawasaki City 211-8533, Japan. ²Department of Internal Medicine, Nippon Medical School, 1-1-5 Sendagi, Bunkyo-ku, Tokyo 113-8602, Japan. Correspondence should be addressed to S.O. (ohta@nms.ac.jp).

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After antimycin A treatment, H₂ prevented the decline of the mitochondrial membrane potential, as detected by fluorescence of tetramethylrhodamine methyl ester (TMRM), which depends upon the mitochondrial membrane potential, whereas fluorescence levels of MitoTracker Green (MTGreen), which are independent of the membrane potential, were unchanged (Fig. 1e). This suggested that H₂ protected mitochondria from •OH. H₂-treated cells looked normal, whereas H₂-untreated cells were shrunken and had abnormal round shapes (Fig. 1e). Along with this protective effect, H₂ also prevented a decrease in the cellular levels of ATP synthesized in mitochondria (Fig. 1f). The fact that H₂ protected mitochondria and nuclear DNA provided evidence that H₂ penetrated most membranes and diffused into organelles.

H₂ dissolved in medium protects cultured cells against •OH

We placed PC12 cells in culture medium containing H₂ and O₂, and, at the same time, induced oxidative stress by adding antimycin A. At 24 h after the induction of ROS with antimycin A, we observed that H₂ seemed to protect nuclear DNA from oxidation, as shown by decreased levels of oxidized guanine (8-OH-G) (Fig. 2a,b and ref. 16). Moreover, H₂ also decreased levels of 4-hydroxyl-2-nonenal (HNE), an end-product of lipid peroxides (Fig. 2c,d and ref. 17), indicating that it protected lipids from peroxidation. Further, H₂ dissolved in medium protected cells from cell death in a dose-dependent manner (Fig. 2e,f). When we removed H₂ from medium that had been saturated with H₂, the protective effect disappeared (Fig. 2f), suggesting that the observed effect was not due to a reaction of H₂ with the medium. Moreover, we confirmed that H₂ protected cellular viability by using two methods: a modified MTT assay (WST-1 assay) and measurement of cellular lactate dehydrogenase (LDH) leakage from damaged cells (Supplementary Fig. 3 online). To exclude the possibility that the protective effect of H₂ was due to a reaction with

antimycin A, we induced ROS by adding menadione, an inhibitor that acts on mitochondrial complex I, and observed that H₂ protected cells in this system as well (Supplementary Fig. 3).

To verify that H₂ protects against •OH, we pretreated cells with Cu²⁺ and then exposed them to ascorbate, in order to reduce intracellular Cu²⁺ to Cu⁺, which in turn catalyzes the production of •OH from cellular H₂O₂ that is endogenously produced. This treatment primarily induced •OH inside the cells (by the Fenton reaction), thus directly confirming that H₂ protects cells against cellular •OH (Fig. 2g,h).

Spin-trapping identifies a free radical that is reduced by H₂

To identify the free radical species that H₂ reduces, we studied the effects of H₂ on electron spin resonance (ESR) signals of spin-trapping reagents. We produced •OH by the cellular Fenton reaction, and semiquantified the cellular levels of •OH by spin-trapping using 5,5-dimethyl-1-pyrroline *N*-oxide (DMPO). Measurements of ESR indicated that H₂ treatment did indeed decrease signals of •DMPO-OH derived from •OH (Fig. 3a–c).

Moreover, when we induced O₂[•] production by treating cells with antimycin A in the presence of DMPO, we observed multiple ESR signals¹⁸. These signals seemed to consist of those from the •DMPO-OH and •DMPO-H radicals (Fig. 3d–f). The •DMPO-H radical is derived from the hydrogen radical (H•), which can be induced by porphyrins. To visualize the signals decreased by H₂, we obtained the differential spectrum. We found that only •OH-derived signals were decreased by H₂ treatment (Fig. 3e). These results strongly suggest the selective reduction of cellular •OH by H₂ treatment.

H₂ selectively reduces •OH and ONOO⁻ in cell-free systems

Next, we confirmed in a pure solution that HPF fluorescence can be used to monitor the reduction of •OH by H₂ during continuous •OH

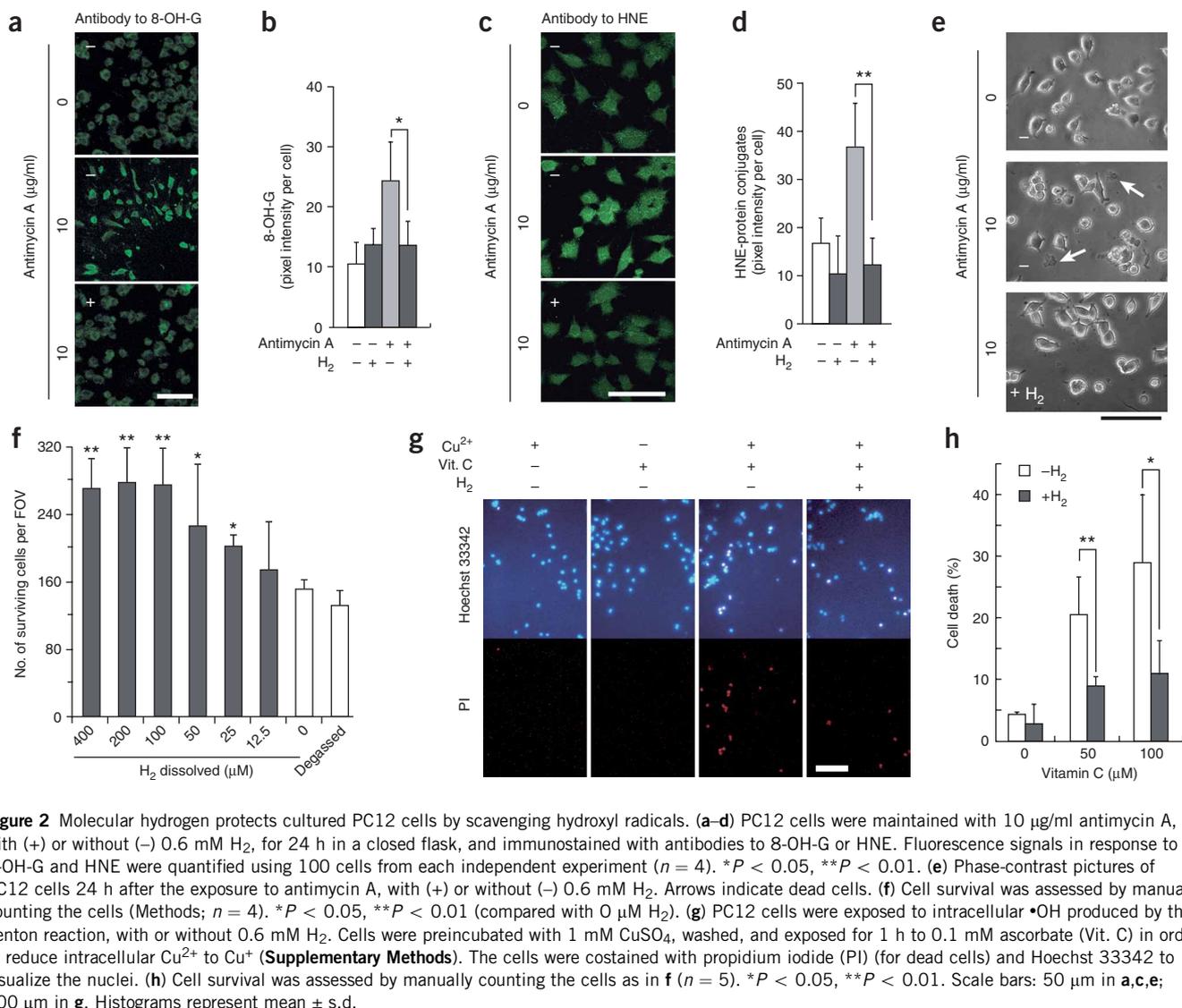


Figure 2 Molecular hydrogen protects cultured PC12 cells by scavenging hydroxyl radicals. (**a–d**) PC12 cells were maintained with 10 µg/ml antimycin A, with (+) and without (–) 0.6 mM H₂, for 24 h in a closed flask, and immunostained with antibodies to 8-OH-G or HNE. Fluorescence signals in response to 8-OH-G and HNE were quantified using 100 cells from each independent experiment ($n = 4$). * $P < 0.05$, ** $P < 0.01$. (**e**) Phase-contrast pictures of PC12 cells 24 h after the exposure to antimycin A, with (+) or without (–) 0.6 mM H₂. Arrows indicate dead cells. (**f**) Cell survival was assessed by manually counting the cells (Methods; $n = 4$). * $P < 0.05$, ** $P < 0.01$ (compared with 0 µM H₂). (**g**) PC12 cells were exposed to intracellular •OH produced by the Fenton reaction, with or without 0.6 mM H₂. Cells were preincubated with 1 mM CuSO₄, washed, and exposed for 1 h to 0.1 mM ascorbate (Vit. C) in order to reduce intracellular Cu²⁺ to Cu⁺ (Supplementary Methods). The cells were costained with propidium iodide (PI) (for dead cells) and Hoechst 33342 to visualize the nuclei. (**h**) Cell survival was assessed by manually counting the cells as in **f** ($n = 5$). * $P < 0.05$, ** $P < 0.01$. Scale bars: 50 µm in **a,c,e**; 100 µm in **g**. Histograms represent mean ± s.d.

production by the Fenton reaction. In this condition, H₂ suppressed increases in HPF signals in a dose-dependent manner (Fig. 4a–c). But when we mixed a solution containing H₂ with HPF preoxidized with •OH, fluorescence signals from oxidized HPF did not decrease (data not shown), supporting the idea that H₂ directly reacts with •OH.

Next, we examined the reactivity of H₂ with other ROS or reactive nitrogen species (RNS). We prepared H₂O₂ and peroxyxynitrite (ONOO[–]) by dilution of the respective stock solutions, O₂•[–] by the enzymatic reaction of xanthine oxidase with xanthine, and NO• by the spontaneous reaction of 1-hydroxy-2-oxo-3-(*N*-methyl-3-aminopropyl)-3-methyl-1-triazene (NOC7) in cell-free systems (Supplementary Methods online). H₂ reduced ONOO[–] (Fig. 4d) somewhat, but did not reduce H₂O₂, NO• and O₂•[–] (Fig. 4e–g). In cell-free experiments, we examined whether H₂ reduced the oxidized forms of biomolecules involved in metabolic oxidation-reduction reactions. At room temperature and neutral pH, solutions saturated with H₂ did not reduce the oxidized form of nicotinamide adenine dinucleotide (NAD⁺), the oxidized form of flavin adenine dinucleotide (FAD) or the oxidized form of cytochrome C (data not shown). Thus we infer that H₂ does not affect the metabolism involved in oxidation-reduction

reactions or the levels of O₂•[–], H₂O₂, and NO•, all of which play essential roles in signal transduction.

H₂ protects neurons from *in vitro* ischemia and reperfusion

We also induced oxidative stress in a primary culture of neocortical cells¹⁹ under more physiological conditions. It is known that rapid transition from an ischemic condition to reperfusion results in oxidative stress damage²⁰. To mimic ischemia, we subjected neocortical cells to oxygen glucose deprivation (OGD) under nitrogen or hydrogen gas for 60 min, followed by reperfusion with medium containing O₂ and glucose.

HPF fluorescence showed that 10 min after the completion of OGD followed by reperfusion, •OH levels notably increased when H₂ was absent, but diminished when H₂ was present (Supplementary Fig. 4 online). At 24 h after OGD and reperfusion, H₂ increased neuron survival and vitality (Supplementary Fig. 4), indicating that H₂ protects neurons against oxidative stress-induced cell death.

Inhalation of H₂ gas protects brain injury by reperfusion

To examine the therapeutic applicability of H₂ as an antioxidant, we used a rat model of ischemia. ROS are generated during cerebral

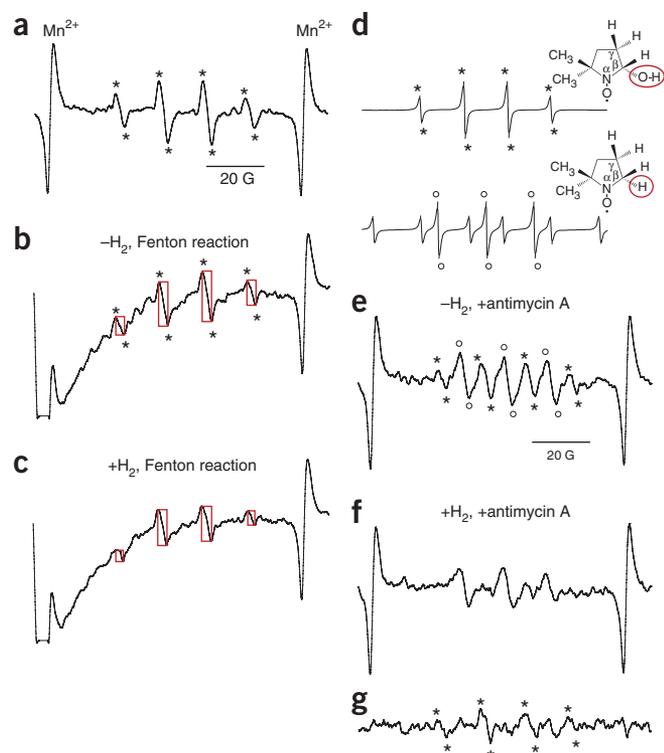


Figure 3 Spin-trapping identifies the free radical species that H_2 reduces. (a) Standard electron spin resonance (ESR) signals of the \bullet DMPO-OH radical were obtained by trapping \bullet OH with a spin-trapping reagent (DMPO; details in **Supplementary Methods**). (b,c) PC12 cells were preincubated with 0.1 M DMPO and 2 mM $CuSO_4$ for 30 min at 37 °C with or without 0.6 mM H_2 . After removal of this medium, the cells were treated with 0.2 mM ascorbate and 0.1 mM H_2O_2 for 5 min at 23 °C to produce \bullet OH and then scraped into a flat cuvette for ESR measurement. Rectangle height reflects signal intensity. (d) The \bullet DMPO-OH and \bullet DMPO-H radicals¹⁸ and their corresponding ESR signals are illustrated. (e,f) PC12 cells were incubated in PBS containing 0.1 M DMPO and 30 μ g/ml antimycin A for 7 min at 23 °C, with or without 0.6 mM H_2 , then scraped into a flat cuvette for ESR measurement. (g) A differential spectrum was obtained by subtracting the spectrum in f from that in e, in order to visualize the signals decreased by H_2 treatment. * indicates \bullet DMPO-OH signals derived from \bullet OH. * and o indicate \bullet DMPO-OH and \bullet DMPO-H signals, respectively (a, b, d, e and g).

ischemia and reperfusion, and are one of the major causes of brain damage^{21,22}. We produced focal ischemia in rats by occluding the middle cerebral artery (MCA) for 90 min, and then performed reperfusion for 30 min (ref. 23). In three of four conditions, rats inhaled H_2 gas, mixed with nitrous oxide (N_2O) for anesthesia, during the entire 120 min process (proportions of H_2 , O_2 and N_2O (vol/vol/vol) were 1%:30%:69%, 2%:30%:68%, and 4%:30%:66%); in the fourth condition, H_2 was absent, (H_2 : O_2 : N_2O (vol/vol/vol) was 0%:30%:70%). We carefully monitored physiological parameters during the experiments (Methods) and found no significant changes resulting from the inhalation of H_2 (**Supplementary Table 1** online). Additionally, there was no significant influence on cerebral blood flow,

as measured by the Doppler effect (ref. 24 and **Supplementary Fig. 5** online). H_2 dissolved in arterial blood was increased by the inhalation of H_2 in proportion to the concentration inhaled; the amount of H_2 dissolved in venous blood was less than that in artery blood, suggesting that H_2 had been incorporated into tissues (**Fig. 5a**).

At 1 d after MCA occlusion, we sectioned and stained brains with 2,3,5-triphenyltetrazolium chloride (TTC), a substrate for mitochondrial respiration (**Fig. 5b**). We estimated infarct volumes by assessing the staining of brain areas (white indicates infarct, **Fig. 5b,c**), and found a clear H_2 -dependent decrease in infarct volume, with 2–4% of H_2 providing the most substantial effect (**Fig. 5c**). We also noted that H_2 exerted its effect only when it was inhaled during reperfusion; when H_2 was inhaled during ischemia, infarct volume was not significantly decreased (**Fig. 5d,e**). For comparison, we tested two other compounds: edaravone (approved in Japan as an ROS scavenger for the treatment of cerebral infarction²⁵) and FK506 (in clinical trials for cerebral infarction in the United States²⁶). H_2 was more effective than edaravone and as effective as FK506 in alleviating oxidative injury (**Fig. 5c**). These results indicate the potential of H_2 for therapy.

Inhalation of H_2 gas suppresses the progression of damage

At 1 week after MCA occlusion, the difference in infarct volume between untreated and H_2 -treated rats increased, compared to 1d after

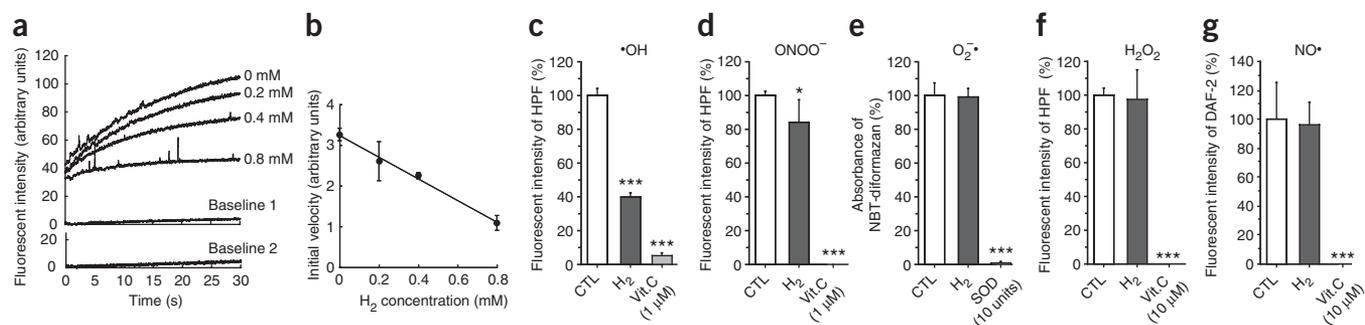


Figure 4 Molecular hydrogen dissolved in solution scavenges hydroxyl radicals at 23 °C and pH 7.4 in cell-free systems. (a,b) The Fenton reaction, which generates hydroxyl radicals, was initiated by adding H_2O_2 (to a final concentration of 5 μ M) in a closed cuvette at 23 °C with gentle stirring (**Supplementary Methods**). Levels of \bullet OH in the presence of various concentrations of H_2 dissolved in the solution were assessed for HPF fluorescence. (a) Representative time course traces of HPF fluorescence at each concentration of H_2 . Baselines 1 and 2 show HPF fluorescence (in the presence of 0.8 mM H_2) in the absence of H_2O_2 (baseline 1) and in the absence of ferrous perchlorate (baseline 2). (b) Mean \pm s.d. of initial rates of increase in HPF fluorescence (four independent experiments). (c–g) Levels of \bullet OH and two reactive nitrogen species (RNS: $NO\bullet$ and peroxynitrite ($ONOO^-$)) remaining after incubation with 0.6 mM of H_2 at 23 °C (details in the **Supplementary Methods**). Vitamin C (Vit. C) and superoxide dismutase (SOD) were used as positive controls. Signals generated in the absence of H_2 (CTL) were set at 100%. Data represent mean \pm s.d. ($n = 6$). * $P < 0.05$, *** $P < 0.001$. NBT-diformazan: oxidized form of nitroblue tetrazolium (NBT, a detector of $O_2\bullet^-$). DAF-2: diaminofluorescein-2 (a detector of $NO\bullet$).

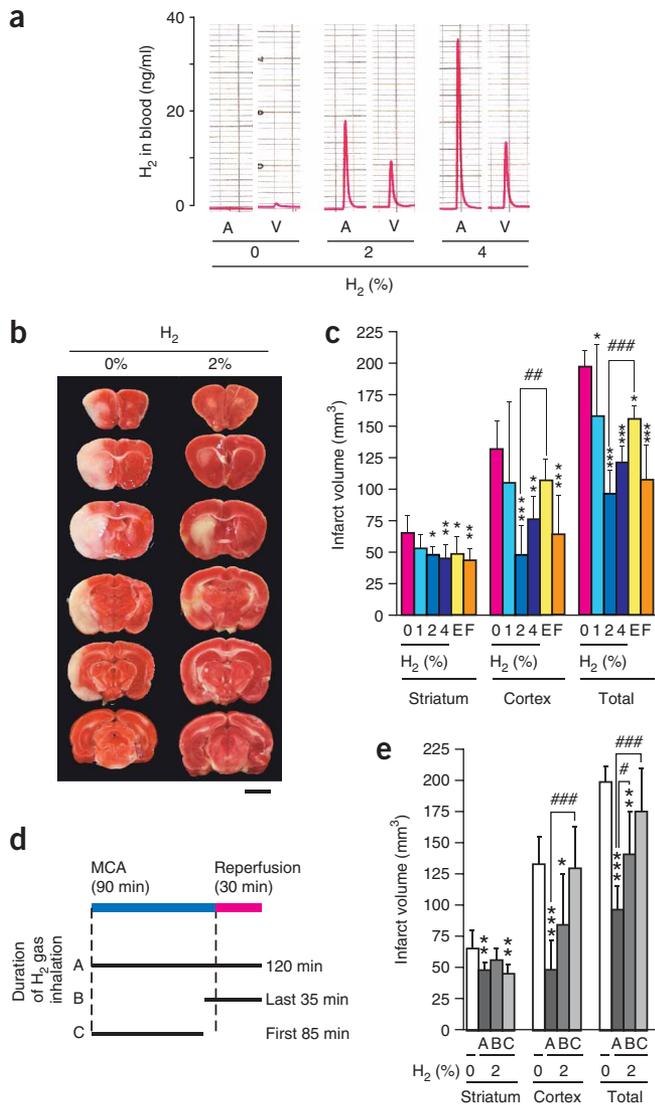


Figure 5 Inhalation of hydrogen gas protects against ischemia-reperfusion injury. **(a)** Rats inhaled H₂ and 30% O₂ for 1 h under the anesthetics N₂O and halothane. Arterial (A) and venous (V) blood were collected, and the amount of H₂ was examined by gas chromatography. **(b)** Rats underwent middle cerebral artery (MCA) occlusion. During the 120-min procedure, the indicated concentration of mixed gas was inhaled. One day after MCA occlusion, the forebrain was sliced into six coronal sequential sections and stained with the mitochondrial respiratory substrate TTC. Scale bar, 5 mm. **(c)** Infarct volumes of the brain were calculated in the brain slices. E and F, treatment with edaravone and FK506 ($n = 6$). * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, compared with 0% of H₂. ## $P < 0.01$, ### $P < 0.001$ compared with 2% of H₂. **(d)** Schematic of experiment with three different durations of hydrogen gas (2%) inhalation. **(e)** Infarct volumes of the brain for different durations of inhalation (calculated as in **c**) ($n = 6$). * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$, compared with 0% of H₂. # $P < 0.05$, ### $P < 0.001$ compared with 120 min of treatment. A, B and C represent the different durations of H₂ gas inhalation (shown in **d**). Histograms represent mean \pm s.d.

DISCUSSION

This study shows that molecular hydrogen can selectively reduce ROS *in vitro*. As $\bullet\text{OH}$ and ONOO^- are much more reactive than other ROS (ref. 14), it stands to reason that H₂ will react with only the strongest oxidants. This is advantageous for medical procedures, as it means that the use of H₂ should not have serious unwanted side effects. It is likely that H₂ is mild enough not to disturb metabolic oxidation-reduction reactions or to disrupt ROS involved in cell signaling—unlike some antioxidant supplements with strong reductive reactivity, which increase mortality, possibly by affecting essential defensive mechanisms²⁹.

H₂ has a number of advantages as a potential antioxidant: it effectively neutralizes $\bullet\text{OH}$ in living cells, and, unlike most known antioxidants, which are unable to successfully target organelles³⁰, it has favorable distribution characteristics: it can penetrate biomembranes and diffuse into the cytosol, mitochondria and nucleus. Despite the moderate reduction activity of H₂, its rapid gaseous diffusion might make it highly effective for reducing cytotoxic radicals. Its ability to protect nuclear DNA and mitochondria suggests that it could reduce the risk of life style-related diseases and cancer.

H₂ markedly decreased oxidative stress and suppressed brain injury caused by ischemia and reperfusion. Inhalation of H₂ gas was more efficacious than a treatment currently approved for cerebral infarction and, furthermore, mitigated hepatic injury caused by ischemia and reperfusion (K. Fukuda, S.A., M.I., Y. Yamamoto, I.O. and S.O., unpublished data). This finding indicates that the beneficial effects of H₂ are not specific to cerebral injury but can be used for injuries in other organs.

This study suggests that H₂ protects cells and tissues against strong oxidative stress by scavenging $\bullet\text{OH}$. However, it remains possible that H₂ also protects from stress by directly or indirectly reducing other strong oxidant species in living cells. For instance, H₂ may induce cytoprotective factors; however, we found no H₂-induced change in the expression of several genes involved in cytoprotection or reduction (K.N., M.I., I.O. and S.O., unpublished data). Further studies will reveal the mechanisms by which H₂ protects cells and tissues against oxidative stress.

Acute oxidative stress may be caused by several factors, including inflammation, intense exercise, cardiac infarction, cessation of blood flow and organ transplantation. For treatment, H₂ dissolved in saline could easily be delivered intravascularly. For prevention, H₂ saturated in water could be administered. Inhalation of H₂ has already been used in the prevention of decompression sickness in divers and has shown a

occlusion (Fig. 6a,b). The behavior of each rat, graded according to a neurological score²⁷, revealed that the inhalation of H₂ during ischemia and reperfusion improved movement (Fig. 6c). Moreover, although body weight and body temperature of H₂-untreated rats gradually declined, those in H₂-treated rats eventually recovered (Fig. 6d,e). Thus H₂ suppressed not only the initial brain injury, but also its progressive damage.

We examined H₂-mediated molecular changes at 12 h, 3 d or 7 d after occlusion, by staining brain sections with antibodies to 8-OH-G in order to assess the extent of nucleic acid oxidation (Supplementary Fig. 6 online), and with antibodies to HNE to assess lipid peroxidation (Supplementary Fig. 6). For both of these oxidative markers, staining was substantially reduced in H₂-treated rats as compared to untreated rats. We also stained identical regions of the brain with antibodies to Iba1 (ref. 28) and antibodies to GFAP, which are specific to activated microglia and to astrocytes, respectively (Fig. 6f,g and Supplementary Fig. 6). We found a distinct H₂-dependent decrease in the accumulation of microglia, indicative of inflammation and remodeling. Taken together, these results indicate that H₂ can markedly decrease oxidative stress and suppress brain injury.

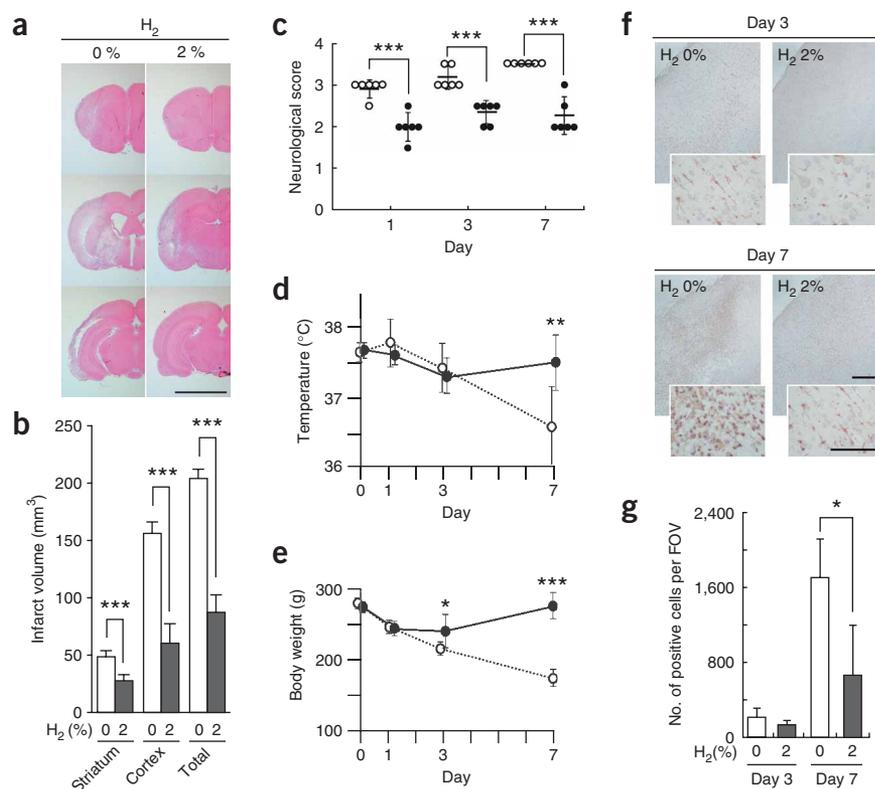


Figure 6 Inhalation of H₂ gas improved brain injury after 1 week. Rats inhaled 2% of hydrogen gas during the 120-min ischemia and reperfusion procedure and were maintained for 1, 3 or 7 d. **(a)** One week after MCA occlusion, the brains were sliced and stained with hematoxylin and eosin. Three representative slices are shown. Scale bar, 5 mm. **(b)** Infarct volumes (light-pink regions in **a**) were calculated ($n = 6$). $***P < 0.001$. **(c)** Neurological scores were graded on a scale of 0 to 5, as described previously²⁷; score 0, no neurological deficit; 1, failure to fully extend the right forepaw; 2, circling to the right; 3, falling to the right; 4, unable to walk spontaneously; and 5, dead. When a rat's neurological score was judged to be between 1 and 2, 2 and 3, or 3 and 4, the score was set at 1.5, 2.5 and 3.5, respectively. Closed and open circles represent treatment with or without H₂ ($n = 6$). $***P < 0.001$. **(d,e)** Body weights and temperature were monitored with (closed circles) or without (open circles) inhalation of 2% hydrogen gas ($n = 6$). $*P < 0.05$, $**P < 0.01$, $***P < 0.001$. **(f)** On days 3 or 7 after MCA occlusion, coronal 6- μ m sections from the ischemic core area in the temporal cortex were stained with antibody to Iba1 (a microglial marker). Scale bar, 200 μ m (100 μ m in the inset). **(g)** Cells positive for the Iba1 antibody²⁸, per field of view (FOV), were counted in the ischemic core area, as indicated in **f** ($n = 6$). $*P < 0.05$. Data represent mean \pm s.d.

good safety profile³¹. Notably, H₂ has no risk of flammability or explosion at a concentration of less than 4.7% in air. We propose that H₂, one of the most well-known molecules, could be widely used in medical applications as a safe and effective antioxidant with minimal side effects.

METHODS

Hydrogen and oxygen measurements. We measured molecular hydrogen (H₂) and oxygen (dioxygen, O₂) dissolved in solution by using a hydrogen electrode (ABLE) and an oxygen electrode (Strathkelvin Instruments), respectively. We determined hydrogen gas concentration by gas chromatography (Teramecs). For measuring H₂ levels in blood, we pretreated rats with heparin to avoid blood clotting, collected arterial and venous blood (5 ml each) in test tubes, and then immediately injected the blood samples into closed aluminum bags containing 30 ml of air. After complete transfer of the H₂ gas from the blood to the air in the closed bag, we subjected 20 ml of the air to gas chromatography using standard H₂ gas, in order to quantify the amount of H₂.

Hydrogen treatment of cultured cells. Over a 2-h period, we dissolved H₂ beyond saturation levels into DMEM medium under 0.4 MPa pressure. We dissolved O₂ into a second medium by bubbling O₂ gas at the saturated level (42.5 mg/l), and CO₂ into a third medium by bubbling CO₂ gas. All three media were maintained at atmospheric pressure. We then combined the three media (H₂ medium:O₂ medium:CO₂ medium) in the proportion 75%:20%:5% (vol/vol/vol) and added fetal bovine serum (FBS) to achieve a final concentration of 1%. For culture, we put the combined medium into a culture flask and immediately examined H₂ or O₂ concentration with an H₂ or O₂ electrode. Then we filled the culture flask with mixed gas consisting of 75% H₂, 20% O₂ and 5% CO₂ (vol/vol/vol) and cultured cells in the closed culture flask. We prepared degassed medium lacking H₂ by stirring the medium, which had been saturated with H₂, in an open vessel for 4 h, and checked the concentration of H₂ with a hydrogen electrode. In the experiments on the dose dependence of H₂ (results shown in Fig. 2f), we diluted the combined medium with a fourth medium containing 1% FBS equilibrated with air containing 5% CO₂, in order

to obtain the desired concentration of H₂; we then filled the culture flasks with the mixed gas diluted with air containing 5% CO₂.

Induction of oxidative stress by antimycin A and menadione. We maintained PC12 cells at 37 °C in DMEM medium containing 1% FBS with or without 0.6 mM H₂ in a closed flask filled with mixed gases as described above. We treated the cells with menadione or antimycin A, which inhibit complex I or complex III, respectively, of the mitochondrial electron transport chain, and thus produce O₂[•] (by accelerating the leakage of electrons). After exposure to antimycin A for 24 h, we assessed cell survival by manually counting the cells double-stained with 1 μ M propidium iodide (dead cells labeled pink) and 5 μ M Hoechst 33342 (dead and living cells labeled blue) under a fluorescent microscope. To examine the protective effect by H₂ on mitochondria, we pretreated cells with 4.5 g/l 2-deoxy-D-glucose (an inhibitor of glycolysis) and 1 mM pyruvate (a substrate of oxidative phosphorylation) for 30 min, exposed them to antimycin A with or without 0.6 mM H₂ and then quantified cellular ATP levels using a cellular ATP measurement kit (TOYO B-Net).

Cerebral infarction model. Animal protocols were approved by the Animal Care and Use Committee of Nippon Medical School. We anesthetized male Sprague-Dawley rats (body weight: 250–300 g) with halothane (4% for induction, 1% for maintenance) in a mixture of nitrous oxide and oxygen (70%:30%, vol/vol). We maintained temperature (37.5 \pm 0.5 °C) using a thermostatically controlled heating blanket connected to a thermometer probe in the rectum, and, at the same time, monitored physiological parameters (using a cannula in the tail artery), including blood gases (pCO₂ and pO₂), pH, glucose level and blood pressure. We attempted to maintain constant levels of pH and pO₂ by regulating the amount of halothane and the N₂O:O₂ ratio. We produced focal ischemia by performing intraluminal occlusion of the left middle cerebral artery (MCA), using a nylon monofilament with a rounded tip and a distal silicon rubber cylinder as previously described²³. The rats underwent MCA occlusion for 90 min and then reperfusion for 30 min; they inhaled H₂ gas during the entire process except in the experiments corresponding to Figure 5d,e. We treated rats with edaravone and FK506 using the most effective concentrations (refs. 25, 23 and Fig. 5c). After the rats recovered from anesthesia, they were maintained at 23 °C.

At 24 h after MCA occlusion, we removed brains under anesthesia and sliced them into six coronal sequential sections (2 mm thick). We stained the sections with 2,3,5-triphenyltetrazolium chloride (TTC) (3%), and then measured infarct and noninfarct areas using an optical disector image analysis system (Mac SCOPE, Mitsuya Shoji). We outlined the border between infarct and noninfarct tissues, and obtained the area of infarction by subtracting the nonlesioned area of the ipsilateral hemisphere from that of the contralateral side. We calculated the volume of infarction as infarct area \times thickness. At 12 h, 3 d or 7 d after MCA occlusion, we quickly removed brains under anesthesia, and fixed them with 10% formalin. We sliced paraffin-embedded brains into a series of 6- μ m sections, and stained sections with hematoxylin and eosin (H&E). We then quantified the pink areas with a graphic analyzer system (Mac Scope). For immunostaining, we stained the sections with antibodies by using VECTASTAIN ABC reagents according to the supplier's instructions.

Statistical analysis. We used StatView software (SAS Institute) for the statistical analyses. For single comparisons, we performed an unpaired two-tailed Student's *t*-test; for multiple comparisons, we used an analysis of variance (ANOVA) followed by Fisher's exact test. We performed experiments for quantification in a blinded fashion.

Note: Supplementary information is available on the Nature Medicine website.

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AUTHOR CONTRIBUTIONS

S.O. conceived the experiments. S.O., I.O., K.K. and Y.K. designed the experiments. I.O., S.A. and S.O. performed data analysis. I.O., M.I., K.T., M.W., K.N., K.Y., S.A. and S.O. performed the experiments. S.O. and I.O. wrote the paper.

COMPETING INTERESTS STATEMENT

The authors declare no competing financial interests.

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