

PROTECTION BY INHALED HYDROGEN THERAPY IN A RAT MODEL OF ACUTE LUNG INJURY CAN BE TRACKED *IN VIVO* USING MOLECULAR IMAGING

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ABSTRACT—Inhaled hydrogen gas (H₂) provides protection in rat models of human acute lung injury (ALI). We previously reported that biomarker imaging can detect oxidative stress and endothelial cell death *in vivo* in a rat model of ALI. Our objective was to evaluate the ability of ^{99m}Tc-hexamethylpropyleneamineoxime (HMPAO) and ^{99m}Tc-duramycin to track the effectiveness of H₂ therapy *in vivo* in the hyperoxia rat model of ALI. Rats were exposed to room air (normoxia), 98% O₂ + 2% N₂ (hyperoxia) or 98% O₂ + 2% H₂ (hyperoxia+H₂) for up to 60 h. *In vivo* scintigraphy images were acquired following injection of ^{99m}Tc-HMPAO or ^{99m}Tc-duramycin. For hyperoxia rats, ^{99m}Tc-HMPAO and ^{99m}Tc-duramycin lung uptake increased in a time-dependent manner, reaching a maximum increase of 270% and 150% at 60 h, respectively. These increases were reduced to 120% and 70%, respectively, in hyperoxia+H₂ rats. Hyperoxia exposure increased glutathione content in lung homogenate (36%) more than hyperoxia+H₂ (21%), consistent with increases measured in ^{99m}Tc-HMPAO lung uptake. In 60-h hyperoxia rats, pleural effusion, which was undetectable in normoxia rats, averaged 9.3 gram/rat, and lung tissue 3-nitrotyrosine expression increased by 790%. Increases were reduced by 69% and 59%, respectively, in 60-h hyperoxia+H₂ rats. This study detects and tracks the anti-oxidant and anti-apoptotic properties of H₂ therapy *in vivo* after as early as 24 h of hyperoxia exposure. The results suggest the potential utility of these SPECT biomarkers for *in vivo* assessment of key cellular pathways in the pathogenesis of ALI and for monitoring responses to therapies.

KEYWORDS—^{99m}Tc-duramycin, ^{99m}Tc-HMPAO, acute respiratory distress syndrome, hyperoxia, SPECT imaging

INTRODUCTION

Acute lung injury (ALI) is one of the most frequent causes of admission to medical intensive care units (1, 2). Acute Respiratory Distress Syndrome (ARDS) occurs in ~250,000 patients/year in the US, carries a mortality rate that may exceed 40%, lacks early detection tools, and has limited therapies (1, 2). The most common therapy is ventilation with high concentrations of oxygen (hyperoxia) (3). However, sustained exposure to high fractions of oxygen causes ARDS (4). Thus, the development of novel diagnostics and therapies for treating patients with ARDS is urgently needed.

Recent preclinical studies have demonstrated that inhaled hydrogen gas (H₂) at a concentration of ~2% provides protection in lung injury animal models of human ALI/ARDS (e.g., ventilation-induced injury, transplant-induced ischemia-reperfusion injury, lipopolysaccharide, and hyperoxic injury)

(5–10), attributed to its potent anti-oxidant, anti-apoptotic, and anti-inflammatory properties. H₂ reduces the most damaging oxidants such as hydroxyl radical and peroxynitrite, but has no effect on superoxide, nitric oxide, or hydrogen peroxide and hence does not interfere with their role in cell signaling and/or immune response (5, 8). Additional studies have shown that the anti-apoptotic properties of H₂ are associated with inhibition of caspase 3 activation (8). Moreover, H₂ is highly diffusible (6, 8), and hence can readily reach subcellular compartments that are targets of oxidative stress, including mitochondria.

Recently, we demonstrated the utility of single-photon emission computed tomography (SPECT) biomarker imaging to detect oxidative stress (using ^{99m}Tc-hexamethylpropyleneamine oxime [HMPAO]) and endothelial cell death (using ^{99m}Tc-duramycin) in lungs of rats exposed to high concentrations of O₂ (hyperoxia) or treated with the endotoxin lipopolysaccharide as models of human ALI/ARDS (8, 11–13). Furthermore, we identified a strong correlation between ^{99m}Tc-HMPAO uptake and glutathione tissue content (12), as an indicator of oxidative stress, and between ^{99m}Tc-duramycin uptake and cleaved-caspase 3 as a marker of apoptosis (11, 14). The objective of this study was to evaluate the potential utility of ^{99m}Tc-HMPAO and ^{99m}Tc-duramycin to track the effectiveness of H₂ therapy *in vivo* in the hyperoxia rat model of human ALI/ARDS.

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MATERIALS AND METHODS

Materials

HMPAO (Ceretek) was purchased in kit form from GE Healthcare (Arlington Heights, Ill), and technetium-labeled macroaggregated albumin (^{99m}Tc -MAA, particle sizes 20–40 μm) was purchased from Cardinal Health (Wauwatosa, Wis). Antibodies to 3-nitrotyrosine (3-NT) (Abcam, # ab52309), and keratin 4-hydroxynonenal (4-HNE) (Abcam, # ab46545) were used with appropriate secondary antibodies (mouse 1:3,000 for 3-NT and rabbit 1:3,000) to measure expression of 3-nitrotyrosine (3-NT) and 4-hydroxynonenal (4-HNE) in lung tissue homogenate. Diethyl maleate (DEM) and other reagent grade chemicals were purchased from Sigma–Aldrich (St. Louis, Mo).

Rat model of human ALI/ARDS

All treatment protocols were approved by the Institutional Animal Care and Use Committees of the Zablocki Veterans Affairs Medical Center, the Medical College of Wisconsin and Marquette University.

For normoxia (control) rat studies, adult (68–77 days old) male Sprague–Dawley rats (Charles River; 351 ± 3 (SE) g, $n = 42$) were exposed to room air in chambers side by side with those exposed to hyperoxia. For hyperoxia studies, age- and weight-matched rats (341 ± 3 g, $n = 77$) were housed in a Plexiglass chamber and exposed to 98% $\text{O}_2 + 2\%$ N_2 (pure oxygen mixed with air) for 24, 48, or 60 h as previously described (12). To evaluate the therapeutic effect of 2% H_2 , age-matched rats (344 ± 3 g, $n = 62$) were housed similarly but exposed to 98% $\text{O}_2 + 2\%$ H_2 (Praxair Inc, Danbury, Conn) for 24, 48, or 60 h. For all hyperoxia and hyperoxia+ H_2 experiments, the O_2 concentration in the chamber was measured using a DD103 DrDAQ Oxygen Sensor (Pico Technology, Cambridgeshire, UK) and was determined to be $> 96\%$. For the hyperoxia+ H_2 experiments, the H_2 concentration in the chamber was measured using a portable hydrogen detector (Model # 7200P, US Industrial Products Co, Cypress, Calif) and determined to be $> 1.8\%$.

Lung wet-to-dry weight ratio, weight of pleural effusion

Heart and lungs from a randomly selected subset of each group of rats were isolated as previously described (12). The lungs were dissected free of the heart, trachea and mainstem bronchi, and total lung wet weight was obtained. The left lung lobe was weighed and dried at 60°C for wet-to-dry weight ratio and the remaining lung lobes were used for the histological studies described below (12).

For a subset of rats exposed to hyperoxia or hyperoxia+ H_2 , pleural effusion within the chest cavity was determined by inserting cotton gauze into the chest cavity to absorb any pleural effusion (11). The gauze was weighed before and after use and the difference in weights was used to measure pleural effusion.

Histology

In a randomly selected subset of rats with normoxia ($n = 4$), 48-h hyperoxia ($n = 5$), 48-h hyperoxia+ H_2 ($n = 5$), 60-h hyperoxia ($n = 5$), and 60-h hyperoxia+ H_2 ($n = 4$) lungs were fixed after inflation in 10% neutral buffered formalin (Fisher Scientific, Pittsburg, Pa) and embedded in paraffin. Whole-mount sections of lung were cut (4 μm thick), processed and stained with hematoxylin and eosin (H&E, Richard Allan, Kalamazoo, Mich). Using high-resolution jpeg images of the slides, an investigator masked to the treatment groups obtained 3 to 4 representative images from preselected areas of the lung on each slide, avoiding large vessels, or airways at $\times 100$ (for neutrophils and edema) and $\times 400$ (for alveolar septum thickness). These images were then scored independently and values for each rat averaged for a single “n.” We used a 0 to 2 scoring system for neutrophil influx, edema, and thickness of the diffusion barrier (Table 1) recommended by Matute-Bello et al. (15).

Western blots

Western blot analysis was carried out as previously described (16) on whole lung tissue homogenate (protein concentration 30 $\mu\text{g}/\mu\text{L}$) to quantify the expressions of 3-nitrotyrosine (3-NT) (17) and (4)-hydroxynonenal (4-HNE)

(18) as indicators of oxidative stress. The following primary antibodies (Abcam) were used: 3-NT ab52309 and 4-HNE ab46545 with appropriate secondary antibodies.

Bronchoalveolar lavage (BAL)

Representative rats from normoxia, 48-h hyperoxia, and 48-h hyperoxia+ H_2 groups were anesthetized with Beuthanasia (40–50 mg/kg i.p.). The trachea was cannulated, the chest opened, and the heart and lungs were removed from the thoracic cavity. The lungs were infused through the trachea with 3 mL of ice-cold, Ca^{2+} -free phosphate-buffered saline *ex vivo* (12). The solution was withdrawn and saved for analysis. The procedure was repeated with a second volume of 3 mL for a total instilled lavage of 6 mL. The returned BAL volume was measured and the cells resuspended by gentle agitation. An aliquot (1 mL) was removed for determination of total cell counts and protein concentration in the cell-free supernatant. The remainder of the sample was used for cytospin preparations. Cell counts were obtained by resuspending cell pellet from 1 mL after centrifugation at 1,000 g for 10 min in a known volume and counting with a hemocytometer (12).

Mitochondrial membrane potential

Representative rats from the normoxia, 48-h hyperoxia, and 48-h hyperoxia+ H_2 groups were anesthetized, and the lungs rapidly exposed and cleared of residual blood with 50 mL cold perfusion solution (physiologic saline buffered with 10 mM HEPES (pH 7.4) and containing 5.5 mM glucose) via the right ventricle. The lungs were then removed from the chest, trachea, large airways, and large vessels were removed, after which the peripheral lung was placed in an ice-cold homogenization buffer (pH 7.4) containing 10 mM HEPES, 200 mM mannitol, 70 mM sucrose, 1 mM EFTA, 2% fatty acid-free BSA, and protease inhibitor cocktail (50 $\mu\text{L}/\text{g}$ lung tissue; set III, Calbiochem) and minced over ice. Lung tissue was homogenized using a Tissue Tearer Homogenizer. The resulting homogenate was then centrifuged (Sorvall Superspeed RC-5B, Norwalk, Conn) at $2,000 \times g$ at 4°C for 15 min. The supernatant was transferred to a clean tube and centrifuged at $17,800 \times g$ at 4°C for 15 min. The resulting supernatant was discarded and the remaining pellet was resuspended in 5 mL ice-cold homogenization solution and centrifuged at $17,800 \times g$ at 4°C for 15 min. The supernatant was discarded and the final pellet was resuspended in 0.3 to 4 mL ice-cold buffer (same as the homogenization buffer without BSA or the protease inhibitor cocktail) and stored on ice to be used for membrane potential studies. Mitochondrial protein was determined using the Pierce BCA protein assay with bovine serum albumin as the standard.

Mitochondrial membrane potential ($\Delta\psi_m$) studies were performed at room temperature using a Photon Technology International (PTI) QuantaMaster fluorometer (HORIBA Scientific, Edison, NJ) that monitored and recorded the rhodamine (R123) emission signal (503/527 nm excitation/emission wavelength) continuously over time (19). Briefly, a cuvette containing 1 mL of the reaction buffer (pH 7.2), R123 (200 nM), and either pyruvate (10 mM) + malate (5 mM) or succinate (7 mM) was placed on the stage of the fluorometer. After 2 min, mitochondrial protein (1 mg/mL) was added, and then once the R123 emission signal reached steady-state (state 2), ADP (100 or 50 μM) was added to evaluate the ADP-stimulated depolarization of $\Delta\psi_m$. The uncoupled $\Delta\psi_m$ was then determined by adding carbonyl cyanide-4-(trifluoromethoxy) phenylhydrazone (FCCP, 10 μM). The emission signal was then normalized to its final value reached after the addition of FCCP (19).

Glutathione (GSH) content

Lungs of randomly selected normoxia, 48-h hyperoxia, and hyperoxia + H_2 rats were isolated, connected to a ventilation-perfusion system, and washed free of blood using Krebs–Ringer bicarbonate perfusate containing (in mM) 4.7 KCl, 2.51 CaCl_2 , 1.19 MgSO_4 , 2.5 KH_2PO_4 , 118 NaCl, 25 NaHCO_3 , 5.5 glucose, and 5% bovine serum albumin as previously described (12, 20). Total lung wet weight was obtained and then a portion of the lung was used for the glutathione assay. The 48-h time point was chosen since at this time the increase in HMPAO lung uptake is large enough to evaluate the impact of H_2 on GSH content without significant cellular infiltration observed at the 60-h time point.

TABLE 1. Endpoints for histological injury grading on a scale of 0–2 for each of the indices of injury, including neutrophilic influx, edema, and thickness of the alveolar septum

Histology injury endpoint/score	0	1	2
Neutrophilic influx	None to very rare	Perivascular or peribronchiolar only	Intra-alveolar and widely distributed
Edema	None to very rare	Proteinaceous material in $< 5\%$ and $< 20\%$ field	Proteinaceous material in $> 20\%$ field
Thickness of alveolar septum	$\leq 1.8 \times$ control thickness	> 1.8 but $< 2.5 \times$ control thickness	$> 2.5 \times$ control thickness

Lung tissue was dissected free from large airways and connective tissue, and weighed. The tissue was then placed into 10 volumes (per lung wet weight) of 4°C sulfosalicylic acid (5%), minced, and homogenized. The homogenate was centrifuged (10,000 × g) at 4°C for 20 min, and the supernatant was used to determine lung GSH content as previously described (12, 20).

Imaging studies

In vivo imaging studies described below were conducted on randomly selected subsets of rats from each exposure condition group. Sample sizes were chosen to achieve a power ≥85% using power analysis (ANOVA power) based on previously published means and standard deviations of the lung uptake of ^{99m}Tc-HMPAO and ^{99m}Tc-duramycin (11–13).

^{99m}Tc-HMPAO and ^{99m}Tc-duramycin were constituted and labeled according to kit directions as previously described (11, 12), while ^{99m}Tc-macroaggregated albumin (MAA) was obtained in its labeled form. Rats were anesthetized with sodium pentobarbital (40–50 mg/kg, i.p.) and a femoral vein was cannulated. The rat was then placed supine on a plexiglass plate (4 mm) positioned directly on the face of a parallel-hole collimator (hole diameter = 2 mm, depth = 25 mm) attached to a modular gamma camera (Radiation Sensors, LLC) for planar imaging (11, 12). An injection (37–74 MBq) of ^{99m}Tc-HMPAO or ^{99m}Tc-duramycin was administered via the femoral vein catheter. Both agents reach steady state in the lung by 20 min postinjection, at which time a 1-min planar image of ^{99m}Tc-HMPAO or ^{99m}Tc-duramycin was acquired (11, 12).

To investigate the role of the anti-oxidant GSH in the lung retention of ^{99m}Tc-HMPAO, a random subset of rats that were injected with ^{99m}Tc-HMPAO were then treated with DEM (1 g/kg body wt i.p.) (12). DEM depletes GSH by conjugating with it to form a thioether conjugate via a reaction catalyzed by the enzyme glutathione-S-transferase (12). Forty-five minutes after DEM treatment and without relocation of the rat, a second injection of ^{99m}Tc-HMPAO was made and the animal reimaged 20 min later.

Then in all rats, a final injection of ^{99m}Tc-MAA (37 MBq) was made via the same femoral cannula and the rat re-imaged. The ^{99m}Tc-MAA injection provided a planar image in which the lung boundaries were clearly identified, since >95% of ^{99m}Tc-MAA lodged in the lungs. After imaging, the rats were euthanized with an overdose of pentobarbital. For a subset of the imaged rats, the lungs were removed, fixed inflated with paraformaldehyde, and then following ^{99m}Tc decay for 72 h (~12 half-lives), used for histological studies described above.

Image analysis

Images were analyzed using MATLAB-based software developed in-house. The boundaries of the upper portion of the lungs were identified in the high-sensitivity ^{99m}Tc-MAA images and manually outlined to construct a lung region of interest (ROI) free of liver contribution (12). The ^{99m}Tc-MAA lung ROI mask was then superimposed on the ^{99m}Tc-HMPAO or ^{99m}Tc-duramycin images yielding a lung ^{99m}Tc-HMPAO or ^{99m}Tc-duramycin ROI. No registration was required since the animal was maintained in the same location throughout the imaging study. Background regions in the upper forelimbs were also identified in the ^{99m}Tc-HMPAO or ^{99m}Tc-duramycin images to normalize lung activity for injected ^{99m}Tc-HMPAO or ^{99m}Tc-duramycin specific activity, dose, and decay (11, 12). Mean counts/sec/pixel/injected dose within both the lung and forelimb-background ROIs were then determined and decay corrected. The ratio of the lung and background ROI signals averaged over the 15 to 20 min time interval, when the ^{99m}Tc-HMPAO or ^{99m}Tc-duramycin signal within the ROIs had reached steady state, was used as the measure of lung ^{99m}Tc-HMPAO or ^{99m}Tc-duramycin uptake (11, 12). ^{99m}Tc-HMPAO images acquired after DEM treatment were analyzed in the same way except that the pre-injection baseline activity level within each ROI was subtracted from the corresponding post-injection activity level to account for residual ^{99m}Tc-HMPAO from the first injection (12).

Statistical analysis

Statistical evaluation of data was carried out using SigmaPlot version 12.0 (Systat Software Inc, San Jose, Calif). The level of statistical significance was set at 0.05. Results are expressed as means ± SE unless stated otherwise. To evaluate differences between means of groups at different exposure times with the same treatment (hyperoxia, hyperoxia + DEM, hyperoxia + H₂, or hyperoxia + H₂ + DEM), one-way ANOVA followed by Tukey range test or Kruskal–Wallis one-way ANOVA on Ranks was used. To evaluate differences pre and post DEM for a given group, a paired two-tailed *t* test was used. To evaluate differences between hyperoxia and hyperoxia+H₂ at a given exposure time, an unpaired two-tailed *t* test was used. For histology, scores of two graders were averaged, then performance of the groups compared by Kruskal–Wallis one-way ANOVA on Ranks.

RESULTS

Body weights, lung wet weight, lung wet/dry weight ratios, and pleural effusion

Treatment with H₂ had no effect on the hyperoxia-induced increase or decrease in body weight at 24 or 60 h (Table 2). However, the loss in body weight after 48 h of exposure was smaller (0.98 ± 0.34%) with hyperoxia+H₂ as compared with hyperoxia alone (2.12 ± 0.32%).

Rat exposure to hyperoxia for 48 or 60 h increased left lobe wet weight/body weight ratio by 35% and 79%, respectively, as compared with that of normoxia rats (Table 3). Inclusion of H₂ in the chamber gas mixture did not have a significant effect on this increase. The wet-to-dry weight ratio at 24 h was greater with hyperoxia+H₂ than with hyperoxia alone, but not at 48 or 60 h.

No measurable pleural effusion was observed in any of the groups of rats except for 60-h hyperoxia and 60-h hyperoxia+H₂. Table 4 shows that inclusion of H₂ in the chamber gas mixture reduced by pleural effusion within the chest cavity at this time point.

Indices of oxidative stress

Table 4 shows that expression of 3-NT, as an indicator of oxidative stress, was elevated following 60 h of exposure to hyperoxia alone. This increase was reduced by 50% in the animals exposed to hyperoxia+H₂. The expression of another indicator of oxidative stress (4-HNE) was not elevated following rat exposure to hyperoxia or hyperoxia+H₂.

Histology

Images of representative lung sections stained with H&E appear in Figure 1. Lung histology from rats exposed to hyperoxia for 24 or 48 h was indistinguishable from normoxia rats including scores for neutrophilic influx, edema, or thickness of the diffusion barrier (Table 5; 48 h data not shown). Samples from lungs of rats exposed to hyperoxia for 60 h exhibited variable degrees of edema, neutrophilic influx and, by high power, an increase in the width of the alveolar septum (diffusion barrier) relative to controls. Samples from rats exposed to hyperoxia+H₂ for 60 h were not different from

TABLE 2. Body weight (BW) pre- and post-treatment

Groups (n)	Pre-BW (g)	Post-BW (g)	% change in BW
24-h: hyperoxia (8)	346 ± 3	350 ± 3	1.04 ± 0.73
24-h: hyperoxia + H ₂ (7)	347 ± 3	351 ± 3*	1.33 ± 0.53
		(P = 0.047)	
48-h: hyperoxia (45)	339 ± 4	332 ± 4*	−2.12 ± 0.32
		(P < 0.001)	
48-h: hyperoxia + H ₂ (41)	344 ± 5	341 ± 5*	−0.98 ± 0.34 [‡]
		(P < 0.001)	(P = 0.018)
60-h: hyperoxia (24)	344 ± 4	325 ± 4 [†]	−5.36 ± 0.57
		(P < 0.001)	
60-h: hyperoxia + H ₂ (14)	340 ± 4	321 ± 4*	−5.52 ± 0.64
		(P < 0.001)	

*Different from corresponding prebody weight (paired Student *t* test).

[†]Different from corresponding prebody weight (Wilcoxon Signed Rank test).

[‡]Different from 48 h hyperoxia (unpaired Student *t* test).

n indicates number of rats.

TABLE 3. Lung weights

Group	Left lobe wet weight/body weight (mg/g) (n)	Left lobe wet/dry ratio (n)
Normoxia	1.23 ± 0.02 (18)	5.36 ± 0.07 (18)
24-h: hyperoxia	1.22 ± 0.05 (5)	4.82 ± 0.07 (5)
24-h: hyperoxia + H ₂	1.30 ± 0.03 (4)	5.31 ± 0.05 [†] (4)
		(<i>P</i> = 0.001)
48-h: hyperoxia	1.55 ± 0.07* (15)	5.55 ± 0.08 (18)
	(<i>P</i> < 0.001)	
48-h: hyperoxia + H ₂	1.45 ± 0.04* (22)	5.55 ± 0.10 (23)
	(<i>P</i> < 0.001)	
60-h: hyperoxia	2.16 ± 0.09* (10)	5.87 ± 0.24 (12)
	(<i>P</i> < 0.001)	
60-h: hyperoxia + H ₂	2.22 ± 0.14* (12)	6.14 ± 0.23* (12)
	(<i>P</i> < 0.001)	(<i>P</i> = 0.014)

Kruskal–Wallis one-way ANOVA on Ranks followed by Dunn test.

*Different from normoxia.

[†]Different from 24 h hyperoxia (unpaired Student *t* test).

n indicates number of rats.

those of normoxia rats and were different from hyperoxia alone with respect to neutrophilic influx and barrier thickness. These data support protection by H₂ relative to injury of rats exposed to 60-h hyperoxia alone.

BAL protein and cell counts

Protein concentration in BAL was greater, compared with normoxic controls, in 48-h hyperoxia (150%) and 48-h hyperoxia+H₂ (63%) rats (Table 6). Total cell count in BAL was higher in 48-h hyperoxia rats than in hyperoxia+H₂ rats (Table 6).

Mitochondrial membrane potential ($\Delta\psi_m$)

We quantified ADP-stimulated depolarization of $\Delta\psi_m$ in mitochondria isolated from normoxia, hyperoxia, and hyperoxia+H₂ rat lungs using R123. Figure 2 shows that in the presence of mitochondria and pyruvate + malate (complex I substrates), the addition of ADP (state 3) stimulated a transient and reversible efflux of R123 from mitochondria, consistent with transient and reversible partial depolarization of $\Delta\psi_m$ (19). Addition of the mitochondrial uncoupler FCCP depolarized

$\Delta\psi_m$ resulting in the maximal efflux of R123 from mitochondria (19, 21). Similar results were obtained with succinate (complex II substrate) as substrate. One measure of the kinetics of ADP-stimulated $\Delta\psi_m$ depolarization and repolarization is the full width at half maximum time (FWHM) for R123 return to baseline (state 4), see Figure 2. Table 7 shows that rat exposure to hyperoxia for 48 h increased FWHM time by ~50%. This suggests that $\Delta\psi_m$ recovery from ADP-induced depolarization in mitochondria from hyperoxia lungs was substantially slower than that in normoxia lungs, consistent with decreases in complex I and II activities in lungs of hyperoxia rats (22). Table 7 shows that the $\Delta\psi_m$ recovery time (FWHM) from ADP-stimulated depolarization, which increased with hyperoxia, partially reversed with hyperoxia+H₂, consistent with the ability of H₂ to protect mitochondria from functional degradation by hyperoxia-induced oxidative stress.

Imaging results

Lung uptake of ^{99m}Tc-HMPAO and ^{99m}Tc-duramycin was quantified from the biomarker images in groups of normoxia and hyperoxia rats with and without H₂. Figure 3 shows representative ^{99m}Tc-HMPAO images obtained at steady state from a normoxia rat (left), and from rats 48 h after exposure to either hyperoxia (middle), or hyperoxia+H₂ (right), where the lung ROI is outlined. The images show enhanced ^{99m}Tc-HMPAO uptake in the lungs of the hyperoxia rat, which is reduced in the hyperoxia+H₂ rat. Figure 4 shows lung uptake (the ratio of lung-to-background signal at steady state) of ^{99m}Tc-HMPAO over 60 h of exposure to hyperoxia (filled circles) or hyperoxia+H₂ (open circles). ^{99m}Tc-HMPAO uptake increased in a time-dependent manner, reaching a maximum increase of ~270% at 60 h. At each time point, inclusion of H₂ in the chamber gas mixture significantly reduced ^{99m}Tc-HMPAO uptake; at 60-h of exposure uptake was reduced to ~120% of that of normoxia rats. For a given treatment (hyperoxia, hyperoxia +H₂), one-way ANOVA followed by Tukey range test was used to evaluate differences between means of groups at the four exposure times. Unpaired *t* tests were used to evaluate differences between hyperoxia and hyperoxia+H₂ at each time point.

TABLE 4. Effect of H₂ on injury endpoints

Group	3-NT (n)	4-HNE (n)	Pleural effusion (g) (n)
Normoxia	1.0 ± 0.332 (6)	1.0 ± 0.34 (6)	NG
48-h: hyperoxia	3.21 ± 0.75* (6)	1.52 ± 0.47 (6)	NG
	(<i>P</i> = 0.023)		
48-h: hyperoxia + H ₂	3.07 ± 0.77* (6)	0.94 ± 0.28 (6)	NG
	(<i>P</i> = 0.041)		
Normoxia	1.0 ± 0.113 (6)	1.0 ± 0.15 (6)	NG
60-h: hyperoxia	8.87 ± 1.68* (6)	1.48 ± 0.30 (6)	9.3 ± 0.6 (17)
	(<i>P</i> = 0.002)		
60-h: hyperoxia + H ₂	4.25 ± 0.78* [†] (6)	1.62 ± 0.42 (6)	2.9 ± 0.6 [†] (15)
	*(<i>P</i> = 0.002)		(<i>P</i> < 0.001)
	[†] (<i>P</i> = 0.032)		

3-NT and 4-HNE band density normalized to β actin and resulting values normalized to normoxia. Unpaired Student *t* test or Mann–Whitney rank sum test.

*Different from normoxia.

[†]Different from 60-h hyperoxia.

n indicates number of rats; NG, negligible.

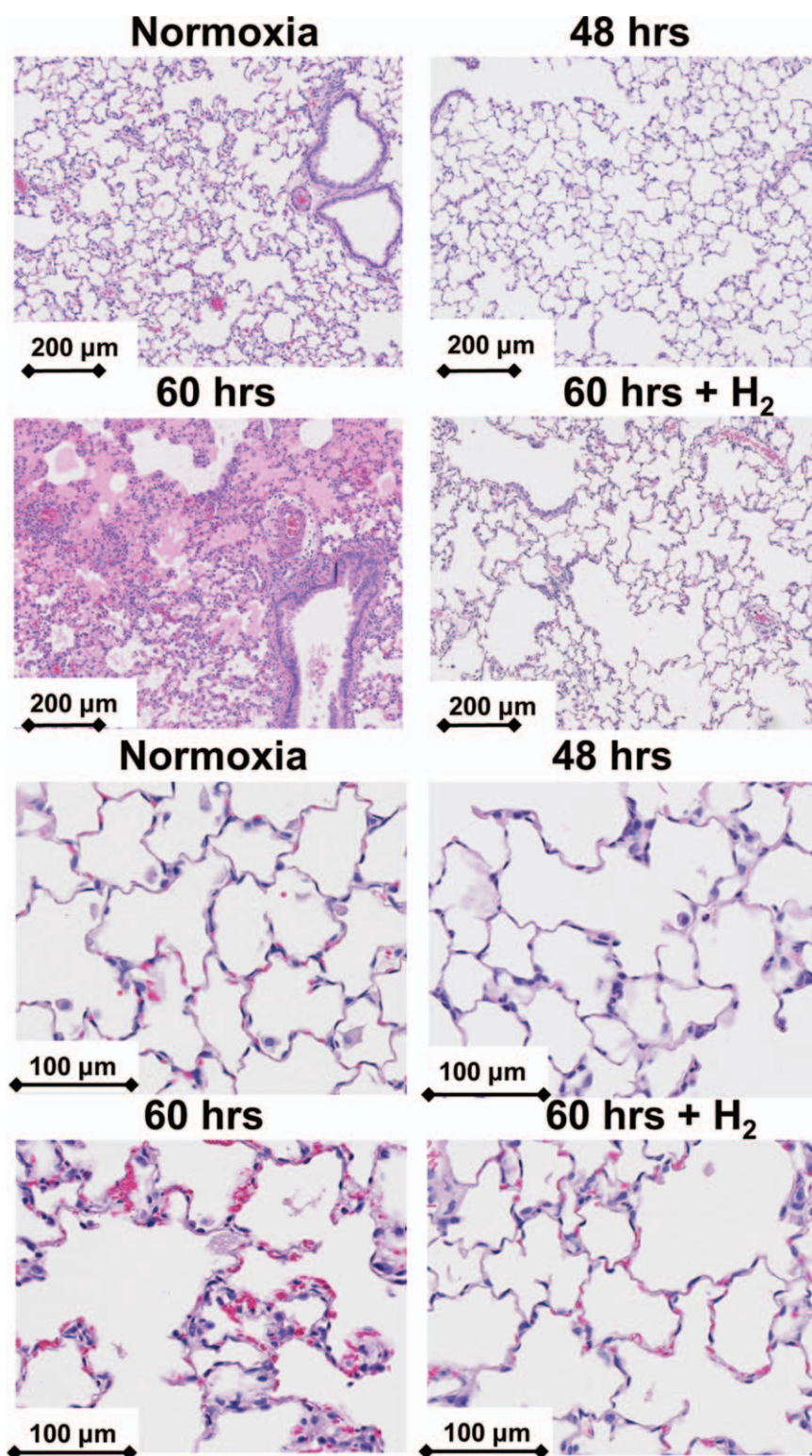


FIG. 1. H&E lung slices from a normoxia rat, and from rats exposed to hyperoxia for 48 and 60 h or to hyperoxia+H₂ for 60 h. Top panels are at lower power than lower panels to facilitate assessment of neutrophilic influx and edema. Higher power images were used to assess thickness of the alveolar septum. H&E indicates hematoxylin and eosin.

We investigated the role of GSH in ^{99m}Tc-HMPAO lung uptake by imaging rats before and after treatment with DEM (12). DEM treatment resulted in significantly reduced uptake in both the hyperoxia (Fig. 4, filled circles vs. filled triangles) and hyperoxia+H₂ groups (open circles vs. open triangles),

suggesting the role of GSH in the uptake of ^{99m}Tc-HMPAO. The reduction in ^{99m}Tc-HMPAO uptake in hyperoxia (50%) and hyperoxia+H₂ (33%) rats was a greater fraction than that of normoxia rats (24%) (Fig. 4). For rats exposed to hyperoxia or hyperoxia+H₂ for 24 h, the enhanced ^{99m}Tc-HMPAO lung

TABLE 5. H&E inflammation scores

Group (n)	Neutrophils	Edema	Thickness diffusion barrier
Normoxia (4)	0 ± 0	0 ± 0	0 ± 0
60-h: hyperoxia (5)	1.40 ± 0.16* (P < 0.001)	0.33 ± 0.19	1.09 ± 0.09* (P < 0.001)
60-h: hyperoxia + H ₂ (4)	0.08 ± 0.08† (P < 0.001)	0 ± 0	0.25 ± 0.13† (P < 0.001)

Kruskal–Wallis one-way ANOVA on ranks followed by Dunn test.

*Different from normoxia.

†Different from hyperoxia.

H&E indicates hematoxylin and eosin; n, number of rats.

uptake was mostly DEM-sensitive. On the other hand, for rats exposed to hyperoxia or hyperoxia+H₂ for 48 and 60 h, only ~50% of the measured increase in ^{99m}Tc-HMPAO lung uptake was DEM-sensitive. For a given treatment (hyperoxia + DEM, hyperoxia + H₂ + DEM), one-way ANOVA followed by Tukey range test was used to evaluate differences between means of groups at the four exposure times. A paired *t* test was used to evaluate differences pre and post DEM for a given group. For a given exposure time, an unpaired *t* test was used to evaluate differences between hyperoxia and hyperoxia+H₂.

Figure 5 shows representative ^{99m}Tc-duramycin images at steady state obtained from a normoxia rat (left), and from rats 60 h after exposure to either hyperoxia (middle), or hyperoxia+H₂ (right). The enhanced ^{99m}Tc-duramycin uptake evident in the hyperoxia rat appears reduced in the hyperoxia+H₂ rat. Figure 6 shows the time course of ^{99m}Tc-duramycin uptake in lungs of rats exposed to either hyperoxia (filled circles) or hyperoxia+H₂ (open circles). The time-dependent increase in ^{99m}Tc-duramycin lung uptake reported previously with hyperoxia was reduced from ~150% at 60 h of exposure (11) to ~70% increase when H₂ was included in the chamber gas mixture. For a given treatment (hyperoxia, hyperoxia + H₂), one-way ANOVA followed by Tukey range test was used to evaluate differences between means of groups at the three exposure times. For a given exposure time, an unpaired *t* test was used to evaluate differences between hyperoxia and hyperoxia+H₂.

Lung GSH content

Table 8 shows the results of the glutathione assays indicating that rat exposure to hyperoxia increased lung tissue GSH content after 48 h (36%) of exposure as compared with lungs

TABLE 6. BAL protein and cell counts

Group (n)	Protein (mg/mL)	Cell count (× 10 ⁴) in collected BAL fluid
Normoxia (6)	0.73 ± 0.03	91 ± 22
48-h: hyperoxia (5)	1.82 ± 0.36* (P = 0.009)	76 ± 5
48-h: hyperoxia + H ₂ (6)	1.19 ± 0.15* (P = 0.041)	48 ± 5*† (P = 0.041), # (P = 0.005)

Unpaired Student *t* test or Mann–Whitney rank sum test.

*Different from normoxia.

†Different from hyperoxia.

BAL indicates bronchoalveolar lavage; n, number of rats.

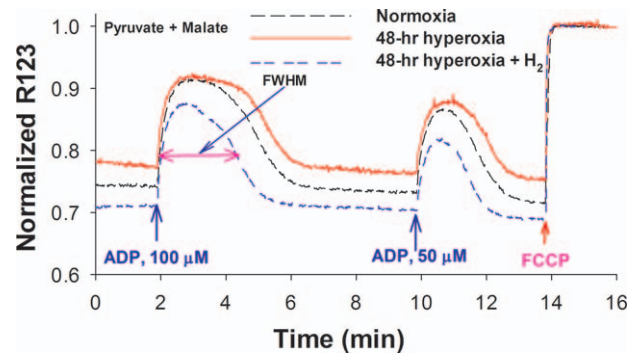


FIG. 2. Averaged R123 emission signal in mitochondria isolated from lungs of normoxia, 48-h hyperoxia, and 48-h hyperoxia+H₂ rats. FWHM indicates full width, half maximum.

of normoxia rats. Rat exposure to hyperoxia+H₂ for 48 h reduced that increase by 42%. Figure 7 suggests a strong relationship between GSH tissue content measured from lung tissue assays and *in vivo* ^{99m}Tc-HMPAO lung uptake determined from imaging (12).

DISCUSSION AND CONCLUSIONS

The present study detects and tracks the anti-oxidant and anti-apoptotic properties of H₂ therapy *in vivo* and to demonstrate protection after as early as 24 h of hyperoxia exposure. The results demonstrate the ability of the two molecular biomarkers ^{99m}Tc-HMPAO and ^{99m}Tc-duramycin to quantify lung injury and the response to H₂ treatment *in vivo* in rats exposed to hyperoxia as a model of human ALI/ARDS. Smaller increases in the lung uptake of both ^{99m}Tc-HMPAO and ^{99m}Tc-duramycin over the 60-h exposure period were observed in rats exposed to hyperoxia+H₂ as compared with rats exposed to hyperoxia alone. These results are consistent with the anti-oxidant, anti-apoptotic, and anti-inflammatory properties of H₂ (5–9). They are also in agreement with our observations of decreased injury severity in H₂ treated rats based on lung histology and lavage constituents, pleural effusion, and less mitochondrial dysfunction as identified by kinetic responses of isolated mitochondria.

^{99m}Tc-HMPAO was originally developed as a brain perfusion agent but its uptake and retention in several tissues serve as a marker of tissue redox state (23). ^{99m}Tc-HMPAO reduction and thus its cellular retention has been shown to be strongly dependent on the oxidoreductive state of the tissue including intracellular GSH content and other factors involving mitochondrial redox

TABLE 7. Δψ_m recovery time from ADP-stimulated depolarization

Group	FWHM (min) pyruvate + malate (n)	FWHM (min) succinate (n)
Normoxia	1.98 ± 0.18 (7)	1.75 ± 0.16 (6)
48-h: hyperoxia	3.30 ± 0.29* (6) (P = 0.002)	2.79 ± 0.34* (7) (P = 0.036)
48-h: hyperoxia + H ₂	2.45 ± 0.26 (6)	1.78 ± 0.20 (6)

Mitochondrial membrane potential Δψ_m.

Unpaired Student *t* test or Mann–Whitney Rank Sum test: *different from normoxia, n, number of rats.

FWHM indicates full width at half maximum for 100 mM ADP-stimulated depolarization of Δψ_m.

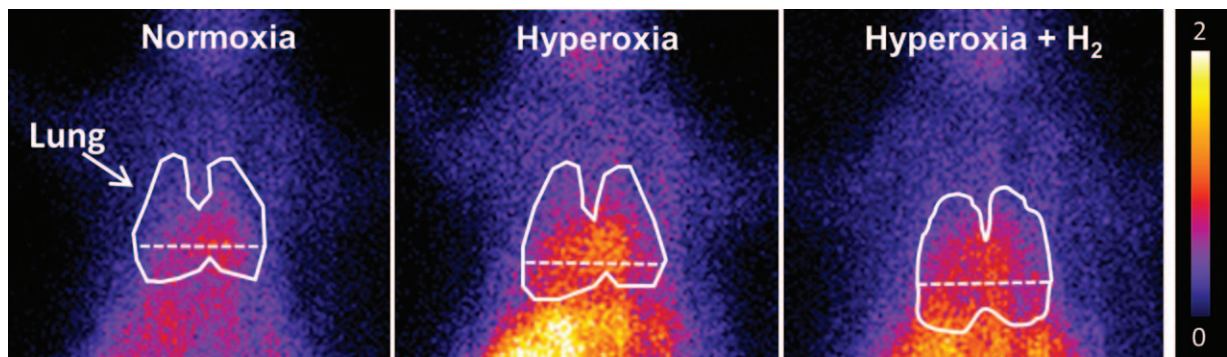


FIG. 3. Representative planar images of ^{99m}Tc-HMPAO distribution in a normoxia (left), 48-h hyperoxia (center), and 48-h hyperoxia + H₂ (right) rat 20 min following injection. Lung ROI is determined from the ^{99m}Tc-MAA image with the dashed horizontal lower boundary to avoid liver contribution.

state (12). Recently, we demonstrated a strong correlation between ^{99m}Tc-HMPAO lung uptake and lung tissue GSH content (12). The results of the current study (Fig. 4) show that ^{99m}Tc-HMPAO lung uptake increased steadily over the 60-h hyperoxia exposure period, and that most of the increase was DEM-inhabitable or GSH-dependent, consistent with lung tissue response to hyperoxia-induced oxidative stress.

On the other hand, exposure to hyperoxia+H₂ decreased ^{99m}Tc-HMPAO lung uptake in comparison to lung uptake in rats exposed to hyperoxia alone, and most of the decrease was in the GSH-dependent component. Since antioxidants such as GSH increase in response to oxidative stress, the effect of H₂ on the DEM-sensitive portion of ^{99m}Tc-HMPAO lung uptake and on the GSH content of lung homogenate suggests that H₂ treatment reduced hyperoxia-induced oxidative stress. This is

reflective of H₂'s anti-oxidant properties and consistent with its ability to mitigate the hyperoxia-induced increase in 3-NT expression in our studies (Table 4). Sun et al. (9) showed that rat exposure to hyperoxia for 60 h increased lung tissue superoxide dismutase (SOD) activity compared with that of normoxia rats, and that the increased SOD activity was smaller in lungs of hyperoxia-exposed rat that received multiple intraperitoneal injections of H₂-rich saline during the exposure period. In that study, the anti-oxidant properties of H₂ were reflected by its ability to mitigate hyperoxia-induced increase in lung tissue lipid and DNA oxidation (Table 9). Kawamura et al. (5) suggested that the H₂ protective effect is via the induction of the nuclear factor erythroid two-related factor antioxidant response element (Nrf2-ARE) signaling pathway. They showed that the expressions of Nrf2-ARE dependent enzymes, including heme oxygenase (HO-1), increased more in lungs of rats exposed to hyperoxia+H₂ for 60 h than in lungs of rats exposed to hyperoxia alone (5). HO-1 is important for removing free heme, a source of iron which plays a key role in hydroxyl radical formation via the Fenton reaction (5). Although the exact mechanism by which H₂ exerts its anti-oxidant properties is still not fully understood, the results of current and previous studies suggest that the mechanism could be either by directly scavenging hydroxyl radical via an exothermic reaction (8) and/or indirectly by its effect on the expression of HO-1 (5).

The increase in GSH content of lung homogenate (+36% for 48-h hyperoxia and +21% for 48-h hyperoxia+H₂ compared with normoxia) is lower than the ~100% to 170% increase in HMPAO lung uptake measured from the *in vivo* images and the ~50% to 280% increase in the DEM-sensitive portion of the HMPAO lung uptake. One explanation for this difference could be the fact that the GSH content reported in this study is the average GSH content of all lung cells and alveolar fluid. Although the results of this study do not provide information regarding the specific types of lung cells contributing to the lung uptake and retention of HMPAO, previous studies have suggested that its retention is predominantly attributable to endothelial cells (24, 25), which account for ~50% of lung cells and are in direct contact with blood (4). Other studies have also demonstrated that different cell types have different GSH content, and oxidant stress has different effects on the GSH content of these cells (26, 27). For instance, Deneke et al. (26) demonstrated that exposure of endothelial cells to hyperoxia

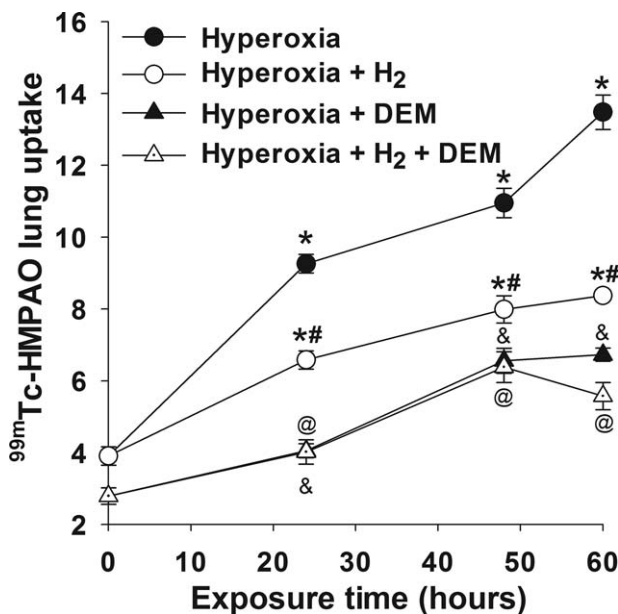


FIG. 4. Lung uptake of ^{99m}Tc-HMPAO in rats exposed to hyperoxia (filled circles) or hyperoxia + H₂ (open circles) for 24, 48, or 60 h. *Different from normoxia (time = 0), #different from hyperoxia alone, &different from hyperoxia pre DEM, @different from hyperoxia+H₂ pre DEM, all with *P* < 0.001. (n) = number of rats: normoxia (7), normoxia + DEM (7), 24-h hyperoxia (5), 24-h hyperoxia + DEM (5), 24-h hyperoxia+H₂ (7), 24-h hyperoxia + H₂ + DEM (7), 48-h hyperoxia (5), 48-h hyperoxia + DEM (5), 48-h hyperoxia + H₂ (8), 48-h hyperoxia + H₂ + DEM (5), 60-h hyperoxia (6), 60-h hyperoxia + DEM (5), 60-h hyperoxia+H₂ (4), 60-h hyperoxia + H₂ + DEM (4).

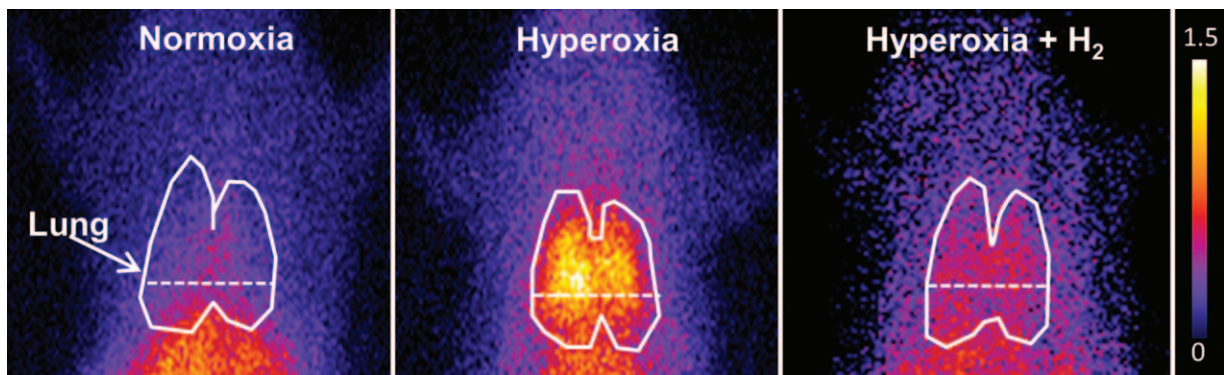


FIG. 5. Representative planar images of ^{99m}Tc -duramycin distribution in a normoxia (left), 60-h hyperoxia (center), and 60-h hyperoxia+ H_2 (right) rat 20 min following injection. Lung ROI is determined from the ^{99m}Tc -MAA image with the dashed horizontal lower boundary to avoid liver contribution. ROI indicates region of interest.

(85% O_2 for 48 h) increased GSH content by 85%. On the other hand, neutrophil GSH content is not sensitive to oxidant injury (27). Thus, depending on the GSH content of the various lung cells and how the GSH content of these cells change in response to exposure to hyperoxia, the GSH content in lung homogenate measured in this study may overestimate or underestimate the effect of hyperoxia or hyperoxia+ H_2 on GSH content of pulmonary capillary endothelial cells.

^{99m}Tc -duramycin serves as a molecular probe that binds to phosphatidylethanolamine, which has little presence on the surface of normal viable cells, but becomes exposed onto the cell surface and/or accessible to the extracellular milieu with apoptosis and necrosis, respectively (11, 28). Previously, we reported an increase in the lung uptake of ^{99m}Tc -duramycin

in rats exposed to hyperoxia or radiation, and demonstrated a strong correlation between ^{99m}Tc -duramycin lung uptake and cleaved caspase 3 positive cells, predominantly endothelial cells (11, 14). Figure 6 shows that ^{99m}Tc -duramycin lung uptake was significantly lower in lungs of rats exposed to hyperoxia+ H_2 as compared with that in lungs of rats exposed to hyperoxia alone (11), reflective of the anti-apoptotic properties of H_2 (5, 8, 9). This result is consistent with those reported by others (Table 9). For instance, Sun et al. (9) reported that H_2 treatment mitigated hyperoxia-induced increases in TUNEL positive lung cells. Kawamura et al. (5) demonstrated the ability of H_2 to protect against hyperoxia-induced increases in the number of caspase 3 positive lung cells. Additional results show that H_2 inhibited hyperoxia-induced increases in the expression of the anti-apoptotic protein Bcl-2 and decreases in the expression of the pro-apoptotic protein Bax (5). Dixon et al. (8) suggested that H_2 's anti-apoptotic effect is via its ability to inhibit the activation of caspase-3.

The anti-inflammation properties of H_2 are reflected in the histological (Fig. 1) and BAL (Table 6) results, which show less cellular infiltration in lungs of rats exposed to hyperoxia+ H_2 compared with those exposed to hyperoxia. These results are consistent with other studies (Table 9) that demonstrated the ability of H_2 to mitigate hyperoxia-induced increases in BAL protein, histology, and levels of pro-inflammatory cytokines in lung tissue (5, 9).

Isolated mitochondria studies using R123 (Fig. 2, Table 7) suggest the ability of H_2 to provide mitochondrial electron transport chain with partial protection from hyperoxia-induced

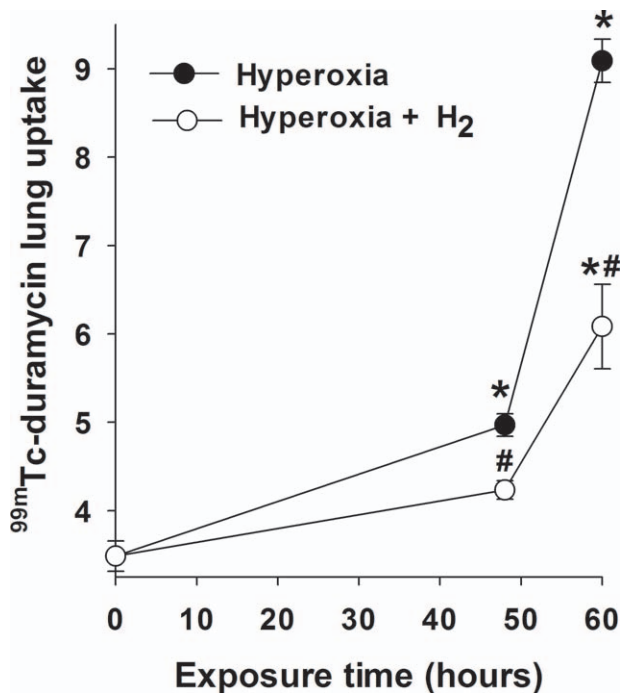


FIG. 6. Lung uptake of ^{99m}Tc -duramycin in rats exposed to hyperoxia (filled circles) or hyperoxia+ H_2 (open circles) for 48 or 60 h. *Different from normoxia (time 0) with $P < 0.001$, #different from hyperoxia alone with $P = 0.001$ for 48 h and $P < 0.001$ for 60 h. (n) = number of rats: normoxia (9), 48-h hyperoxia (7), 48-h hyperoxia+ H_2 (6), 60-h hyperoxia (7), 60-h hyperoxia+ H_2 (5).

TABLE 8. Glutathione (GSH) content of lung homogenate

Group (n)	GSH (fraction of normoxia)
Normoxia (7)	1.00 ± 0.08
48-h: hyperoxia (7)	1.36 ± 0.02* ($P < 0.001$)*
48-h: hyperoxia + H_2 (6)	1.21 ± 0.03*† ($P < 0.001$)* ($P < 0.001$)†

GSH concentration for normoxia lungs was 9.02 ± 0.38 (n = 7) $\mu\text{mol/g}$ dry wt.

Unpaired Student *t* test: *different from normoxia, †different from hyperoxia.

n indicates number of rats.

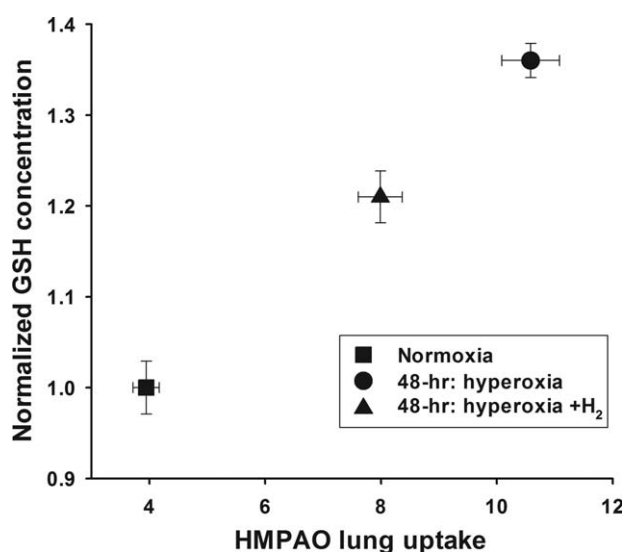


FIG. 7. Relationship between ^{99m}Tc-HMPAO lung uptake (Fig. 4 and lung tissue GSH content (as fraction of normoxia, Table 8). GSH indicates glutathione.

oxidative stress. We previously demonstrated significant decreases in complex I and II activities in lung of rats exposed to hyperoxia for 48 h (22). Mitochondrial DNA (mtDNA) is highly sensitive to reactive oxygen species (ROS) (29). A hyperoxia-induced increase in the rate of ROS formation could damage mtDNA and as a result compromise complex I activity since 7 of 45 subunits of complex I are encoded by mtDNA (29, 30). This increase in ROS formation could also cause direct alteration to complex I activity by oxidizing the key phospholipid cardiolipin, which is sensitive to ROS (31, 32). Oxidation of cardiolipin could lead to an increase in the loss of electrons at complex I and in the rate of mitochondrial superoxide formation at complex I (31, 32). Furthermore, cardiolipin oxidation can affect complex II since it is required for its optimal activity and stability (33). Our results (Fig. 2, Table 7) using

R123 suggest that H₂ partially protected complex I and II activities from oxidative stress.

In the present study, the effect of H₂ on hyperoxia-induced body weight loss and increase in lung wet/dry weight ratio after 60 h of exposure (Tables 2 and 3) are not consistent with those reported by other studies (Table 9). For instance, both Sun et al. and Kawamura et al. reported lower lung wet/dry weight ratios in rats treated with hyperoxia+H₂ as compared with rats treated with hyperoxia (5, 9). In addition, Kawamura et al. (5) reported that H₂ reduced rat body weight loss after 60 h of exposure to hyperoxia. The difference between these results and results of the current study could be due to differences in rat strains (Sprague–Dawley vs. Lewis rats in Kawamura et al. (5)) or in H₂ administration (intraperitoneal injection of H₂-rich saline in Sun et al. (9)). Xie et al. (10) showed that the protective effects of H₂ against sepsis-induced lung injury are dose dependent over 1% to 4% range. Thus, additional protection might be observed in Sprague–Dawley rats with higher concentrations of H₂ than the 2% used in the present study.

Several gaseous therapies have been evaluated for hyperoxia-induced ALI/ARDS, including nitric oxide (NO), carbon monoxide (CO), and H₂ (8, 34, 35). Like NO and CO, H₂ is highly permeable across various cellular barriers and hence capable of accessing key cellular compartments such as mitochondrion which appear to play a key role in the pathogenesis of human ALI/ARDS. However, H₂ is advantageous since it does not affect the physiological or immune response of key ROS (superoxide and hydrogen peroxide). Moreover, H₂ is not toxic at high concentrations and is safe at concentrations < 4.1% when mixed with O₂ (8).

In conclusion, the results suggest the potential translational utility of imaging with two SPECT biomarkers, one of which is already in clinical use, for *in vivo* assessment of key cellular pathways involved in the pathogenesis of ALI/ARDS and for monitoring responses to potential therapies such as inhaled H₂ gas.

TABLE 9. Summary of effects of rat exposure to hyperoxia + H₂ for 60 h compared with exposure to hyperoxia alone for 60 h on various antioxidant enzymes and indices of lung injury

	Kawamura et al. 2013	Sun et al. 2011	Current study
Rat strain	Adult Lewis (male)	Adult SD (male)	Adult SD (male)
H ₂ delivery	2% H ₂ gas (inhaled)	Saline-rich H ₂ (i.p.)	2% H ₂ gas (inhaled)
Body weight loss	Lower	NA	NS
Lung wet weight	NA	NA	NS
Lung wet/dry	-8%	-7%	+5%
Pleural effusion	-40%	-30%	-70%
SOD	NA	-40%	NA
3-NT	NA	NA	-51%
4-HNE	NA	NA	NS
BAL protein	-46%	NA	NA
H&E score	Lower	Lower	Lower
Apoptosis	-31%	-33%	-53%
Pro-inflammatory cytokines	Lower	Lower	NA
MDA	NA	-40%	NA
8-OHdG	NA	-49%	NA
HO-1 expression	+136%	NA	NA
NQO1 expression	+93%	NA	NA
GSTA2 expression	+158%	NA	NA
Prdx1 expression	+105%	NA	NA

8-OHdG indicates 8-hydroxy-2'-deoxyguanosine; GSTA2, glutathione S-transferase A2; MDA, malondialdehyde; NA, not available; NS, not significant; Prdx1, peroxiredoxin 1; SOD, superoxide dismutase.

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