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J Clin Invest. 2011;121(11):4289-4302. <https://doi.org/10.1172/JCI45144>.

Research Article

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Denitrosylation of HDAC2 by targeting Nrf2 restores glucocorticosteroid sensitivity in macrophages from COPD patients

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Chronic obstructive pulmonary disease (COPD), which is caused primarily by cigarette smoking, is a major health problem worldwide. The progressive decline in lung function that occurs in COPD is a result of persistent inflammation of the airways and destruction of the lung parenchyma. Despite the key role of inflammation in the pathogenesis of COPD, treatment with corticosteroids – normally highly effective antiinflammatory drugs – has little therapeutic benefit. This corticosteroid resistance is largely caused by inactivation of histone deacetylase 2 (HDAC2), which is critical for the transrepressive activity of the glucocorticoid receptor (GR) that mediates the antiinflammatory effect of corticosteroids. Here, we show that in alveolar macrophages from patients with COPD, S-nitrosylation of HDAC2 is increased and that this abolishes its GR-transrepression activity and promotes corticosteroid insensitivity. Cys-262 and Cys-274 of HDAC2 were found to be the targets of S-nitrosylation, and exogenous glutathione treatment of macrophages from individuals with COPD restored HDAC2 activity. Treatment with sulforaphane, a small-molecule activator of the transcription factor nuclear factor erythroid 2–related factor 2 (NRF2), was also able to denitrosylate HDAC2, restoring dexamethasone sensitivity in alveolar macrophages from patients with COPD. These effects of sulforaphane were glutathione dependent. We conclude that NRF2 is a novel drug target for reversing corticosteroid resistance in COPD and other corticosteroid-resistant inflammatory diseases.

Introduction

Chronic obstructive pulmonary disease (COPD) is an environmental disease characterized by a progressive decline in lung function occurring as a result of chronic obstructive bronchitis and/or emphysema (1, 2). Caused primarily by cigarette smoking, COPD is a major global health problem (3). The pathogenesis of COPD involves oxidative stress-initiated persistent inflammation in the airways and destruction of the lung parenchyma (4, 5). Patients with COPD frequently experience exacerbations caused by bacteria or viral infection that are characterized by enhanced pulmonary inflammation (6). These exacerbations impose a substantial burden on patients, affecting their quality of life, longevity, and healthcare costs, and are associated with a faster decline in lung function (7, 8). Current treatments such as glucocorticosteroids (GCs), which are highly effective antiinflammatory drugs for asthma, have little therapeutic benefit in COPD patients because of their diminished GC sensitivity (9, 10). Although high doses of inhaled GCs are used widely to manage COPD, they reduce exacerbations by only 20%–25% and do not alter disease progression or survival (8, 9, 11). High doses of systemic GCs are used to treat acute

exacerbations of COPD, but they reduce the length of hospitalization by only 9% (12). Therefore, treatments aimed at reducing GC resistance in COPD may be of substantial benefit.

Histone deacetylase (HDAC) plays a critical role in the regulation of inflammatory responses (13). Class I HDACs (HDAC1, HDAC2, HDAC3, and HDAC8) mediate the deacetylation of histones, thereby inducing chromatin condensation and transcriptional repression. HDACs also mediate the deacetylation of nonhistone proteins, specifically transcription-related factors, thereby altering protein-protein interactions and DNA binding and regulating the transcriptional program (13). The antiinflammatory response induced by GCs is mediated by the glucocorticoid receptor (GR), in part by repressing NF- κ B-dependent cytokine gene expression by means of transrepression (14). HDAC2 is a critical component of the GR-corepressor complex that mediates the transrepression of NF- κ B transcriptional activity by deacetylating histones in the proinflammatory gene promoters (15) and deacetylating the GR (14).

HDAC2 is substantially reduced in the alveolar macrophages and peripheral lung tissue of patients with COPD, and its level is inversely correlated with disease severity and airway inflammation (16). Loss of HDAC2 causes corticosteroid resistance in COPD, whereas genetic overexpression of HDAC2 or pharmacological HDAC activator restores corticosteroid responsiveness (14, 17). Although the specific mechanisms to account for the HDAC2 inactivity in COPD are unclear, oxidative stress- and nitrosative stress-induced posttranslational modifications, such as phosphorylation of serine/threonine residues (18) and/or nitration of tyrosine residues (19), are thought to be involved.

Authorship note: Deepti Malhotra and Rajesh K. Thimmulappa contributed equally to this work.

Conflict of interest: Shyam Biswal, Rajesh K. Thimmulappa, and the Johns Hopkins University hold intellectual property on the development of Nrf2-based therapeutics in COPD. Shyam Biswal and Rajesh K. Thimmulappa are cofounders of, have equity in, and serve as scientific consultants for Cureveda LLC.

Citation for this article: *J Clin Invest.* 2011;121(11):4289–4302. doi:10.1172/JCI45144.

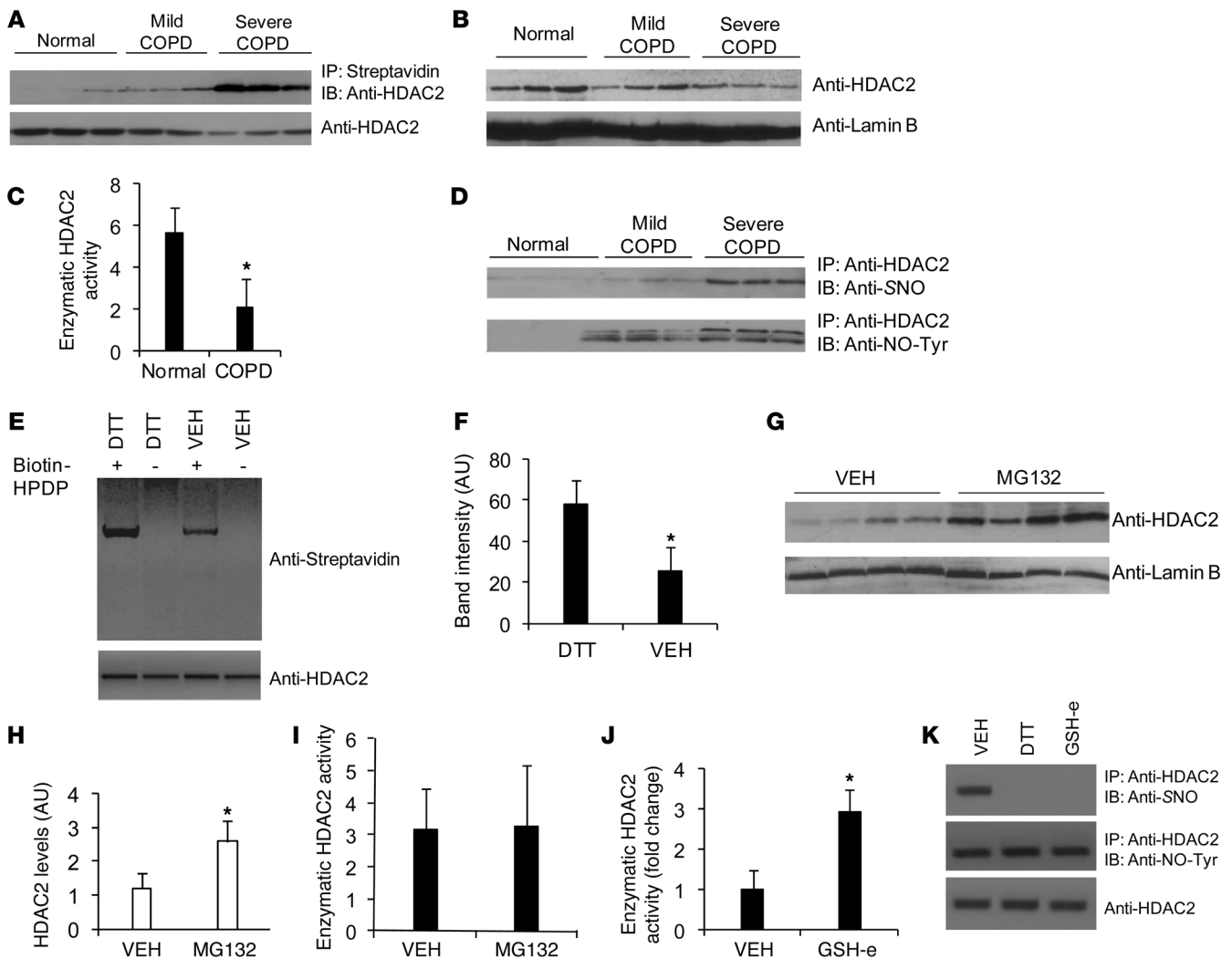


Figure 1

S-nitrosylation of HDAC2 protein and concomitant decline in HDAC2 activity in the lungs of patients with COPD. (A) Levels of S-nitrosylated HDAC2 in peripheral lung tissue samples from COPD and non-COPD subjects, as assessed by biotin-switch assay. (B and C) Immunoblot analysis of nuclear HDAC2 protein levels using anti-HDAC2 antibody (B) and enzymatic activity of immunoprecipitated HDAC2 (C) in peripheral lung tissue samples from COPD (n = 6) and non-COPD (n = 3) subjects. (D) Immunoblot analysis of tyrosine nitration (anti-NO-Tyr antibody) and cysteine S-nitrosylation (anti-SNO antibody) modification of immunoprecipitated HDAC2 from peripheral lung tissues of COPD (n = 6) and non-COPD (n = 3) subjects. (E and F) S-nitrosylated HDAC2 levels in alveolar macrophages from patients with COPD, as assessed by a modified biotin-switch assay. (E) Representative blot. (F) Mean band intensity for 6 patients. (G–I) Immunoblot analysis (G) and densitometric quantification (H) of total nuclear HDAC2 protein, and HDAC2 enzymatic activity (I) using immunoprecipitated HDAC2, in COPD alveolar macrophages after treatment with vehicle (VEH) or proteasome inhibitor MG132 (n = 4 per group). (C and I) Enzymatic HDAC2 activity was expressed as “ μ M of standard.” (J and K) HDAC2 enzymatic activity (J) and HDAC2 protein modification by immunoblot analysis (K) in COPD alveolar macrophages after treatment with GSH-e. Immunoprecipitated HDAC2 from vehicle-treated COPD macrophages was incubated with or without reducing agent DTT as a positive control. *P < 0.01, Student’s t test.

Recent evidence suggests that HDAC2 also undergoes reversible nitrosylation of some of its cysteine residues (i.e., S-nitrosylation), which can affect protein activity and function (20, 21).

Nuclear factor erythroid 2-related factor 2 (Nrf2) is a redox-sensitive basic leucine zipper transcription factor that induces a multitude of antioxidant genes that protect cells from the oxidative stress and inflammation induced by cigarette smoke (CS) (22–29). Under normal conditions, Nrf2 is sequestered in the cytoplasm by Keap1 which is anchored to the actin cytoskeleton. In response to oxidative

stress, Nrf2 disassociates from Keap1-Nrf2 complex, translocates to the nucleus and transcribes its target genes by binding to its cis-responsive element called “antioxidant responsive element” in the promoter region (30). Disruption of Nrf2 in mice (Nrf2^{-/-}), in response to chronic CS, causes increased pulmonary oxidative stress and inflammation that results in early onset and severe emphysema (22). A marked decline in the expression of the NRF2 pathway is seen in the peripheral lung tissue and alveolar macrophages with increasing COPD severity (23, 28, 31, 32), and pharmacological acti-

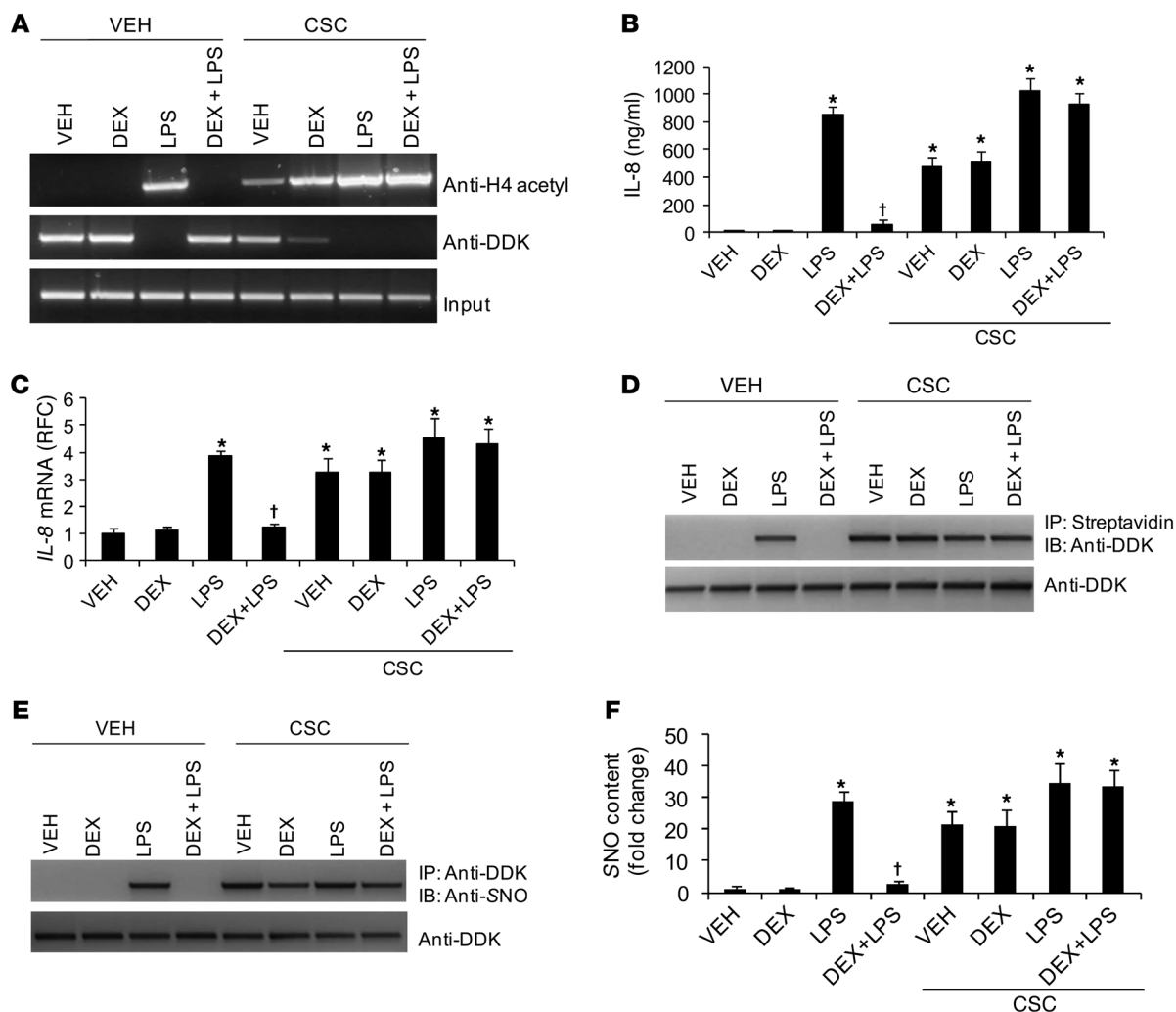


Figure 2

Exposure to CSC induces S-nitrosylation of HDAC2 and causes dexamethasone resistance in THP-1 cells overexpressing the Myc-DDK-tagged HDAC2 plasmid. THP-1 cells were exposed to 200 $\mu\text{g/ml}$ CSC for 24 hours, then to 10 $\mu\text{g/ml}$ LPS for 4 hours. Cells were exposed to 1 μM dexamethasone (DEX) 0.5 hours before LPS exposure. (A) Histone H4 acetylation and HDAC2 binding to IL-8 promoter, as assessed by CHIP assay using anti-pan-H4 acetyl antibody and anti-DDK antibody. (B and C) IL-8 mRNA and protein content, as determined by quantitative RT-PCR and ELISA, respectively. RFC, relative fold change. (D–F) S-nitrosylation of HDAC2, determined by biotin-switch assay (D), immunoblotting with anti-SNO antibody (E), and Saville assay (F). Each assay was conducted in triplicate and also repeated at least 3 times. * $P < 0.01$ versus vehicle, † $P < 0.01$ versus LPS only, Student's *t* test.

vation of Nrf2 inhibits CS-induced oxidative stress and emphysema in a mouse model of COPD (25). More recently, a defect in Nrf2 signaling has been shown to compromise bacterial phagocytosis and clearance in CS-exposed mice and macrophages of COPD patients (29). In the present study, we investigated the mechanism of nitrosative stress-induced steroid resistance in patients with COPD and asked whether activating NRF2 could restore HDAC2 function and reinstate GC responsiveness in their alveolar macrophages.

Results

S-nitrosylation of HDAC2 is increased in the peripheral lung tissues and alveolar macrophages from patients with COPD. The decrease in HDAC2 activity seen in COPD patients has been attributed to posttranslational modifications such as the phosphorylation of serine/threonine residues (18) and nitrotyrosine modifications

that promote the proteasomal degradation of HDAC2 protein (18, 33). Recent studies suggest that HDAC2 is susceptible to S-nitrosylation, which impairs its DNA-binding function (20, 34) and its deacetylase enzymatic activity (21).

We first asked whether HDAC2 is modified by S-nitrosylation in peripheral lung tissues isolated from healthy smokers without COPD and from smokers with COPD. Detailed characteristics of the patients used for isolation of peripheral lung tissues are provided in Supplemental Table 1 (supplemental material available online with this article; doi:10.1172/JCI45144DS1). We found that HDAC2 was S-nitrosylated in COPD peripheral lung tissue, and there was minimal to no S-nitrosylation in non-COPD lung tissue, as assessed by biotin-switch assay (ref. 35 and Figure 1A). We also observed a significantly lower level of total nuclear HDAC2 protein and HDAC2 enzymatic activity in the peripheral lung tissues of

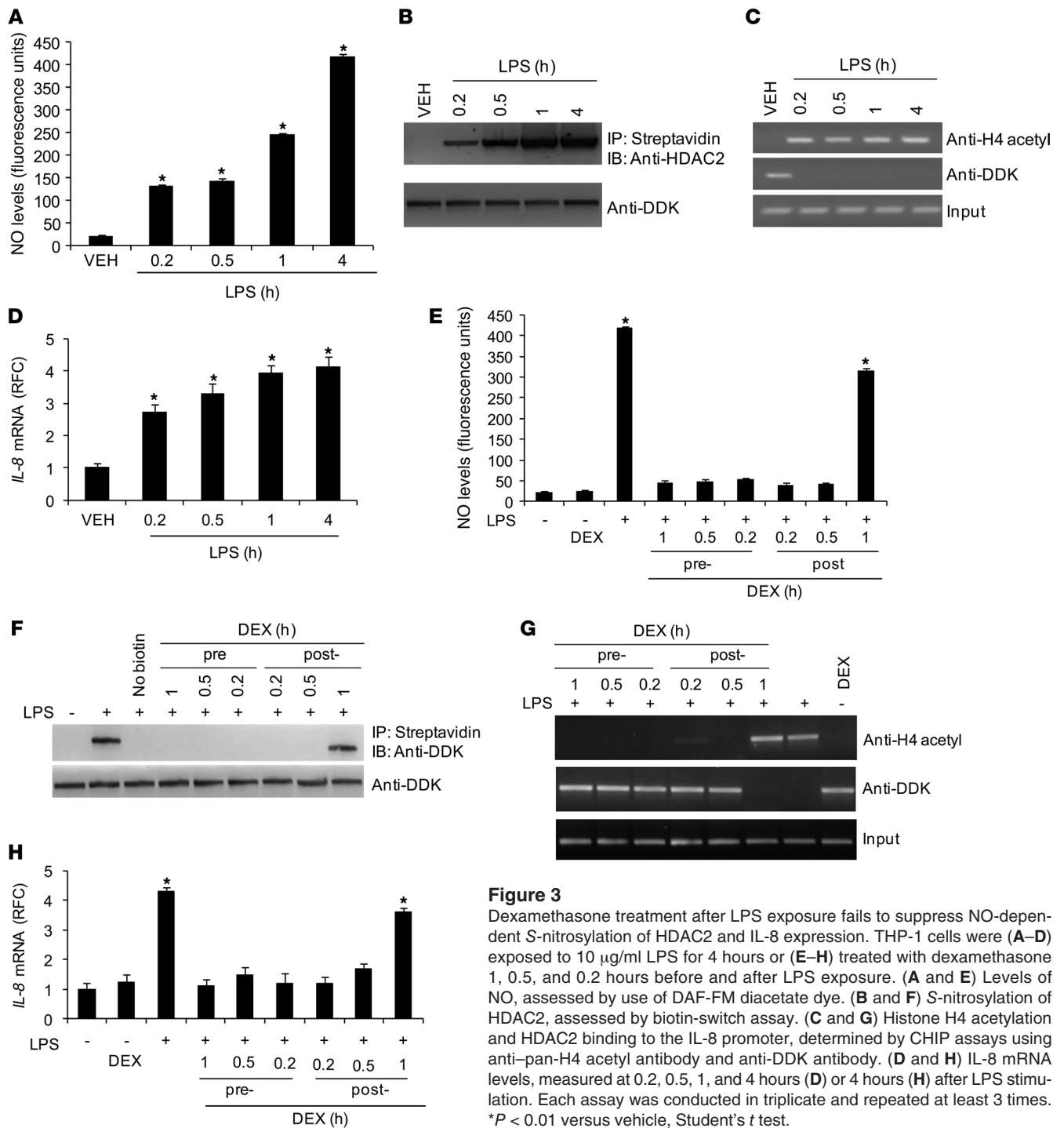


Figure 3

Dexamethasone treatment after LPS exposure fails to suppress NO-dependent S-nitrosylation of HDAC2 and IL-8 expression. THP-1 cells were (A–D) exposed to 10 μg/ml LPS for 4 hours or (E–H) treated with dexamethasone 1, 0.5, and 0.2 hours before and after LPS exposure. (A and E) Levels of NO, assessed by use of DAF-FM diacetate dye. (B and F) S-nitrosylation of HDAC2, assessed by biotin-switch assay. (C and G) Histone H4 acetylation and HDAC2 binding to the IL-8 promoter, determined by CHIP assays using anti-pan-H4 acetyl antibody and anti-DDK antibody. (D and H) IL-8 mRNA levels, measured at 0.2, 0.5, 1, and 4 hours (D) or 4 hours (H) after LPS stimulation. Each assay was conducted in triplicate and repeated at least 3 times. *P < 0.01 versus vehicle, Student's t test.

patients with COPD than in those without COPD (Figure 1, B and C). In subcellular fractionation experiments, HDAC2 protein was detected only in the nuclear fractions; none was detectable in the cytosolic fractions (Supplemental Figure 1A). In agreement with a previous report (33), immunoblot analysis using an anti-nitrotyrosine antibody showed a higher level of nitrotyrosine modification of HDAC2 in the peripheral lung tissues of patients with COPD than in those without COPD (Figure 1D). Reprobing the same blot with anti-S-nitrosylation (anti-SNO) antibody demonstrated

an increase in S-nitrosylated HDAC2 (Figure 1D); the specificity of the anti-SNO antibody is documented in Supplemental Figure 1B. These results suggest that an increase in S-nitrosylation and nitrotyrosine modifications of HDAC2 occurs as COPD progresses.

Next, we took a different approach to analyze S-nitrosylation of HDAC2 specifically in the alveolar macrophages of COPD patients (detailed patient characteristics are given in Supplemental Table 2). To assess the relative levels of S-nitrosylated HDAC2 protein in the alveolar macrophage samples from COPD patients, we used a modi-

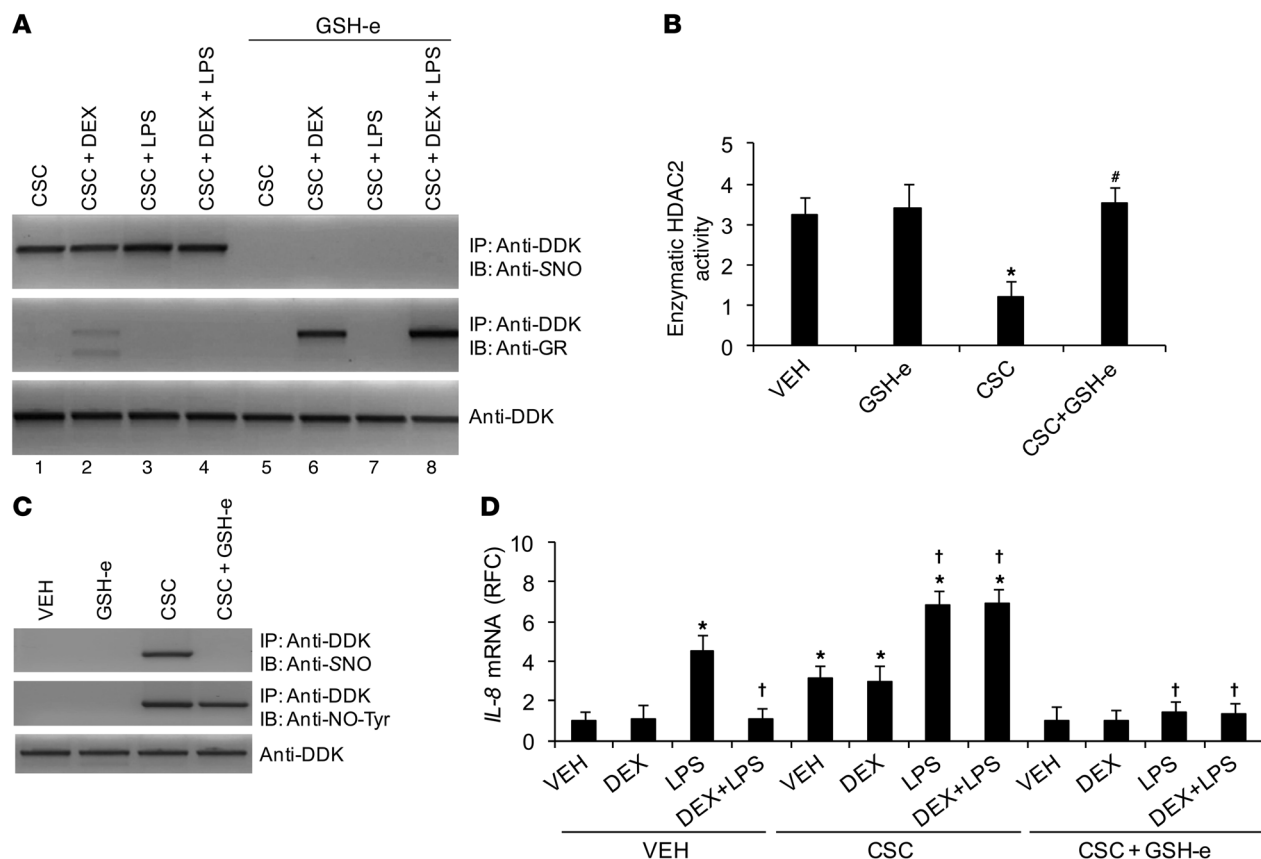


Figure 4

Treatment with exogenous glutathione reverses HDAC2 S-nitrosylation of and restores HDAC2 activity and dexamethasone sensitivity in CSC-exposed THP-1 cells. THP-1 cells were exposed to 200 $\mu\text{g/ml}$ CSC for 24 hours, then with 0.5 mM GSH-e for 2 hours. Cells were then incubated with or without dexamethasone for 1 hour, and then 10 $\mu\text{g/ml}$ LPS for an additional 4 hours. (A) Immunoblot analysis of S-nitrosylation and GR binding in coimmunoprecipitated HDAC2, using anti-SNO antibody and anti-GR antibody. (B) HDAC2 activity assay. Enzymatic HDAC2 activity was expressed as “ μM of standard.” (C) Immunoblot analysis of nitrotyrosine modification and S-nitrosylation of HDAC2, detected using anti-nitrotyrosine and anti-SNO antibodies, respectively. (D) IL-8 expression. Each assay was conducted in triplicate and repeated at least 3 times. * $P < 0.01$ versus vehicle, # $P < 0.01$ versus CSC only, † $P < 0.01$ versus LPS only, Student’s *t* test.

fied biotin-switch assay (see Supplemental Methods) that employed an infrared-labeled streptavidin secondary antibody in place of the streptavidin-biotin pulldown assay. We first incubated the immunoprecipitated HDAC2 with or without dithiothreitol (DTT), making the assumption that DTT effectively removes S-nitrosylations and other thiol modifications, then performed the modified biotin-switch assay. The percentage of S-nitrosylation was calculated by dividing the fluorescence band intensity of the DTT-treated sample by that of the sample without DTT treatment. Approximately 30%–50% of the total HDAC2 was S-nitrosylated in the alveolar macrophages of COPD patients ($n = 6$; Figure 1, E and F).

S-nitrosylation regulates HDAC2 activity in COPD alveolar macrophages. Given the level of nitrosylation that we observed, we next examined the possibility that S-nitrosylation regulates HDAC2 activity in the alveolar macrophages of COPD patients. Because nitrotyrosine modification has previously been shown to promote the proteasomal degradation of HDAC2 (33), we first asked whether inhibiting proteasome activity restores HDAC2 activity in alveolar macrophages isolated from patients with COPD. When the COPD macrophages were cultured in the presence of the proteasomal inhibitor MG132 (10 μM), we found an

increase in the total levels of HDAC2 protein (Figure 1, G and H); however, there was no change in its enzymatic activity (Figure 1I). Thus, the HDAC2 protein remained dysfunctional in the alveolar macrophages isolated from COPD patients despite inhibition of its proteasomal degradation, which suggests a role for protein modifications in disrupting HDAC2 function by means other than protein instability.

GSH promotes denitrosylation of proteins by means of a transnitrosylation reaction (36). We next investigated whether GSH could mediate the denitrosylation of HDAC2 and restore its enzymatic activity. For this purpose, we used a cell-free in vitro approach in which we exposed either recombinant HDAC2 (rHDAC2) or immunoprecipitated HDAC2 (DDK-HDAC2) from human THP-1 cells overexpressing Myc-DDK-tagged HDAC2 (DDK) plasmid to NO donor S-nitrosoglutathione (GSNO; 500 μM) for 1 hour. GSNO exposure caused S-nitrosylation of the immunoprecipitated HDAC2 (Supplemental Figure 1C; immunoblot analysis using anti-SNO) and rHDAC2 (Supplemental Figure 1D; Saville assay) and concomitantly decreased the enzymatic activity of HDAC2 (Supplemental Figure 1, E and F); this decrease was reversed by GSH post-treatment. The effect of pH (4.5–9.0) and the kinetics of the GSH-medi-

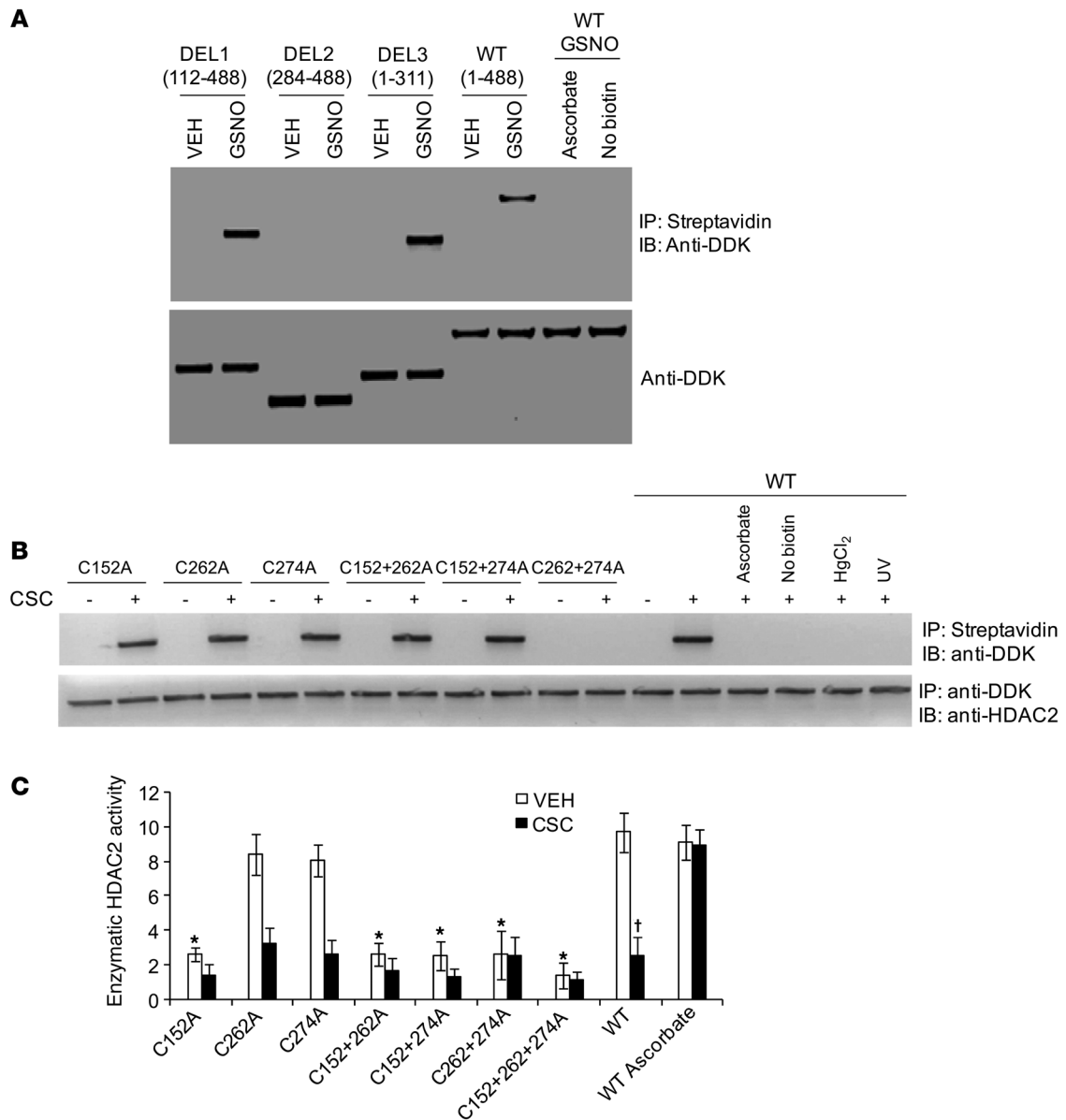


Figure 5

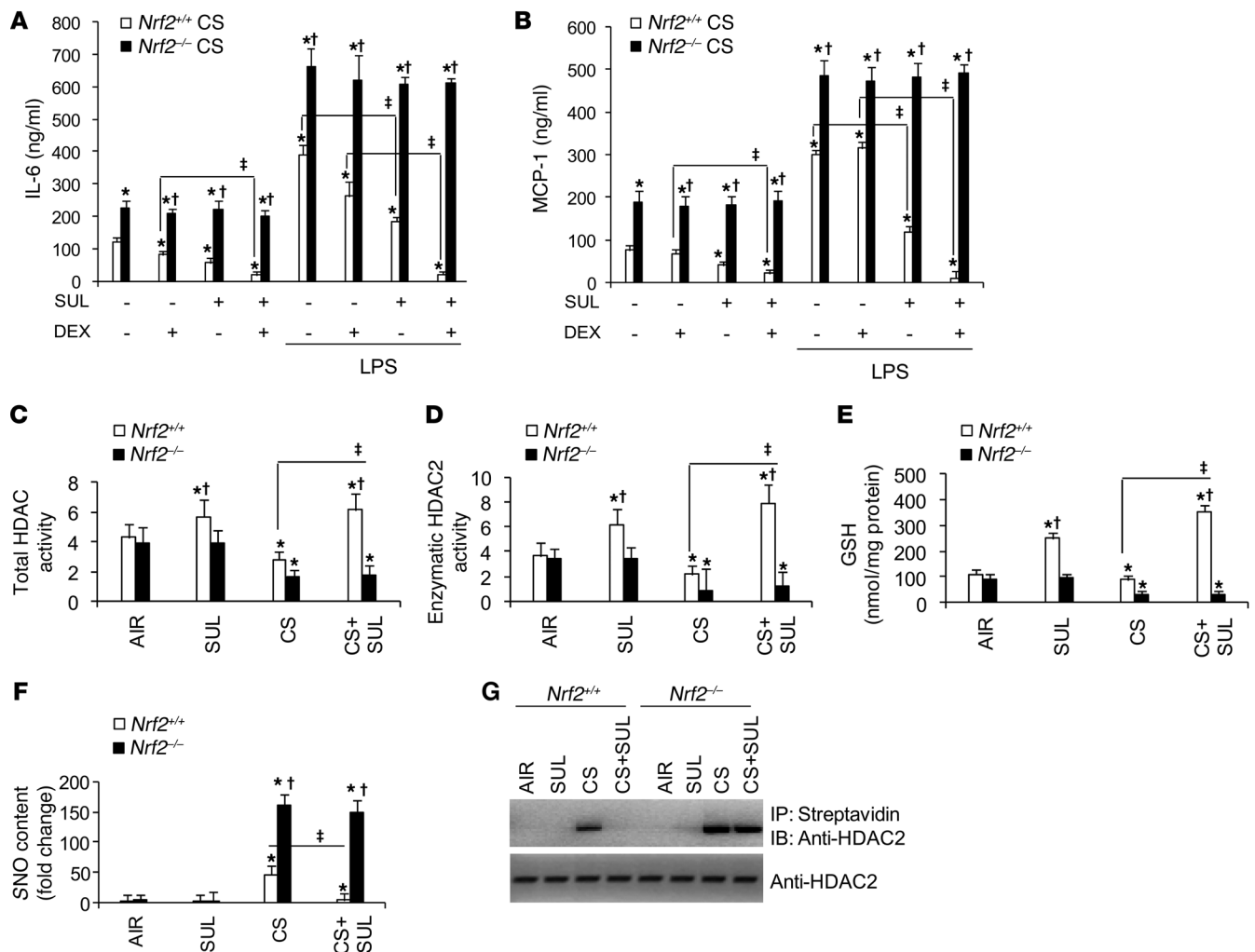
Cys-262 and Cys-274 of HDAC2 protein undergo S-nitrosylation after exposure to CSC in THP-1 cells. THP-1 cells overexpressing WT, DEL1, DEL2, and DEL3 constructs were exposed to GSNO. **(A)** S-nitrosylation of immunoprecipitated WT or truncated mutants of HDAC2, as detected by biotin-switch assay. **(B and C)** THP-1 cells were transfected with WT form or 1 of the site-directed mutants of HDAC2, then exposed to CSC for 24 hours, and S-nitrosylation was assessed by biotin-switch assay **(B)** and enzymatic activity **(C)**. Ascorbate, UV, or HgCl₂ was used as a reducing agent to reverse S-nitrosylation and to demonstrate the specificity of biotin-switch assay. Enzymatic HDAC2 activity was expressed as “ μ M of standard.” Each assay was conducted in triplicate and repeated at least 3 times. * $P < 0.01$ versus vehicle WT; † $P < 0.01$, CSC versus WT, Student’s *t* test.

ated denitrosylation reaction are shown in Supplemental Figure 1, G and H, and described in Supplemental Methods. These results suggest that GSH may restore HDAC2 activity via denitrosylation.

Given this effect of GSH, we then asked whether treatment with GSH-monoethylester (GSH-e), a cell-permeable derivative of GSH could restore HDAC2 activity in alveolar macrophages from patients with COPD. For this purpose, HDAC2 was immunoprecipitated from alveolar macrophages 1 hour after incubation with or without GSH-e (0.5 mM). Compared with vehicle treatment, GSH-e produced a significant increase in HDAC2 enzymatic activity and a concomitant

decrease in S-nitrosylation of HDAC2 (Figure 1, J and K). However, the levels of nitrotyrosine modification were unaffected by GSH-e exposure (Figure 1K), which suggests that S-nitrosylation is responsible for inhibiting HDAC2 enzymatic activity. We observed no change in total HDAC2 protein after GSH-e treatment (Figure 1K).

S-nitrosylation of HDAC2 promotes GC resistance in HDAC2-overexpressing macrophages. Impaired HDAC2 activity causes GC resistance in the alveolar macrophages of patients with COPD (14). In agreement with previous studies (37), the synthetic GC dexamethasone failed to suppress LPS-induced acetylation of H4 on

**Figure 6**

Sulforaphane, by activating Nrf2, suppresses S-nitrosylation and restores HDAC2 activity in the alveolar macrophages and lungs of mice exposed to CS. (A and B) After CS exposure, mice were treated daily with sulforaphane for 3 days (0.5 mg/mouse). Alveolar macrophages and lungs were isolated 24 hours after the last dose of sulforaphane. Alveolar macrophages were then incubated with dexamethasone for 1 hour, followed by LPS exposure for an additional 4 hours. Secretion of IL-6 (A) and MCP-1 (B) was measured in the cell-free culture medium by ELISA. (C and D) Enzymatic HDAC2 activity was expressed as "μM of standard." Enzymatic activity of total HDAC (C) and HDAC2 (D); GSH levels (E) and S-nitrosylated HDAC2 levels, as determined by Saville assay (F) and biotin-switch assay (G), were analyzed in lung lysates ($n = 6$ mice). Immunoblot data are representative of 3 independent experiments. * $P < 0.01$ versus vehicle, ANOVA followed by Bonferroni post-test. † $P < 0.01$ versus respective *Nrf2*^{+/+}, † $P < 0.01$ as shown by brackets, Student's *t* test. Unless otherwise indicated, a total of 6 samples was used.

the IL-8 promoter or IL-8 expression in the presence of the HDAC inhibitor trichostatin A (TSA) in THP-1 cells overexpressing Myc-DDK-tagged HDAC2 (Supplemental Figure 2, A-D), indicative of GC resistance. Throughout this study, we used THP-1 cells overexpressing Myc-DDK-tagged HDAC2 unless otherwise indicated; these cells had considerably higher transfection efficiency than did alveolar macrophages from either mice or humans.

Next, we asked whether S-nitrosylation of HDAC2 induces GC insensitivity. For this purpose, we first determined whether S-nitrosylation of HDAC2 by exposure to GSNO prior to LPS exposure induces dexamethasone insensitivity in THP-1 cells. GSNO treatment indeed induced S-nitrosylation of HDAC2 in these cells, as measured by the biotin-switch and Saville (38) assays, and also

reduced HDAC2 activity (Supplemental Figure 2, E-G). In addition, we found that dexamethasone failed to suppress LPS-induced IL-8 expression in THP-1 cells exposed to GSNO (Supplemental Figure 2, H and I), indicative of GC resistance.

CS inhalation diminishes GC sensitivity in mouse models (39), and treatment of bronchial epithelial cells and macrophages with CS condensate (CSC) in vitro has been shown to replicate dexamethasone insensitivity (40). We therefore asked whether CSC induces dexamethasone insensitivity as a result of the S-nitrosylation of HDAC2. First, we treated THP-1 cells with CSC or vehicle for 24 hours and then with dexamethasone 0.5 hours before LPS stimulation for 4 hours. In vehicle-treated THP-1 cells, ChIP analysis using anti-pan-acetylated histone H4 and anti-DDK

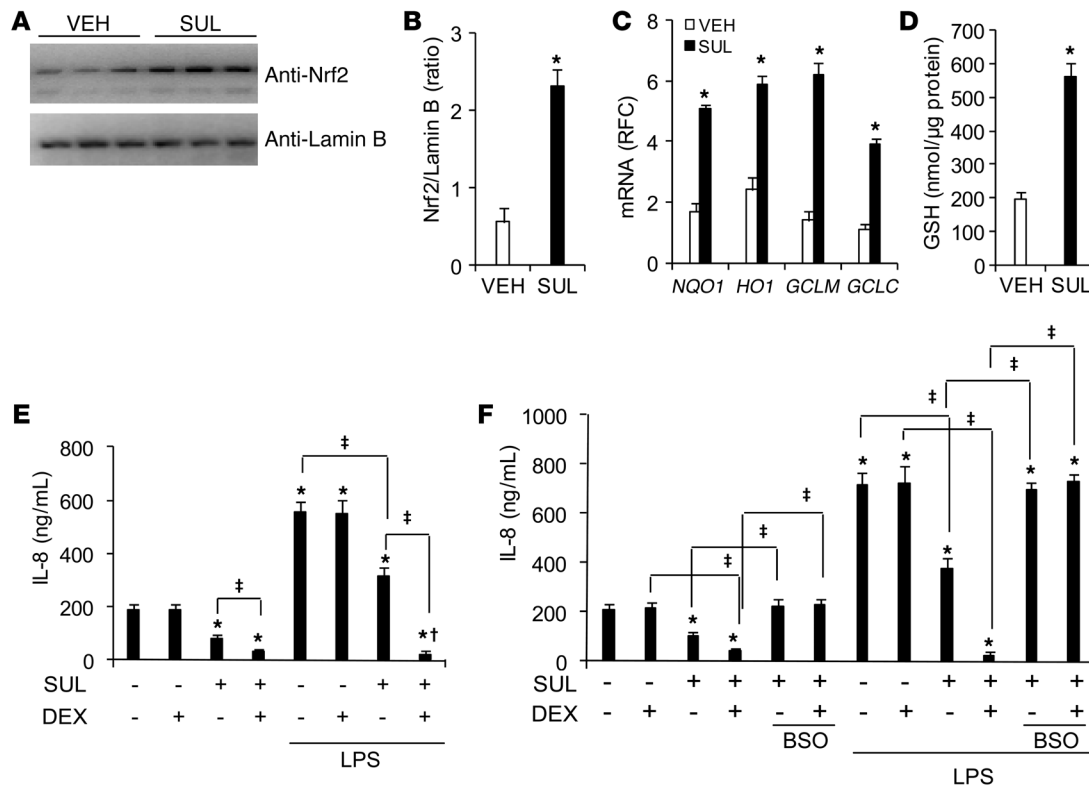


Figure 7

Sulforaphane increases Nrf2-dependent antioxidant defenses and improves corticosteroid responsiveness in alveolar macrophages. Nuclear extracts of alveolar macrophages were treated with 5 μM sulforaphane (SUL) for 16 hours or with vehicle. (A) Immunoblot analysis of the Nrf2 protein (n = 3 patients) and (B) densitometry analysis of immunoblots normalized to lamin B (n = 9 patients). (C) mRNA analysis of Nrf2-regulated antioxidant genes (n = 9 patients). (D) GSH levels (n = 9 patients). (E) Basal and LPS-induced secretory levels of IL-8 after incubation with or without dexamethasone (DEX) (n = 22 patients). (F) Basal and LPS-induced secretory levels of IL-8 after incubation with or without dexamethasone in the presence or absence of 1 mM BSO for 16 hours. *P < 0.01 versus vehicle, ANOVA followed by Bonferroni post-test. †P < 0.01 versus dexamethasone (with and without LPS); ‡P < 0.01 as shown by brackets, Student's t test. All assays were repeated 3 times.

antibodies revealed elevated levels of H4 acetylation and derecruitment of HDAC2 from the IL-8 promoter, respectively, which was correlated with increased IL-8 protein and mRNA expression after LPS treatment (Figure 2, A–C). Dexamethasone treatment prior to LPS stimulation repressed IL-8 transcription and was correlated with HDAC2 occupancy and reduced acetylation of H4 on the IL-8 promoter (Figure 2, A–C). In contrast, in CSC-treated THP-1 cells, dexamethasone failed to repress LPS-induced IL-8 expression, and this result was accompanied by an increase in H4 acetylation and no occupancy of HDAC2 on the IL-8 gene promoter (Figure 2, A–C). Concurrently, we assessed S-nitrosylation of HDAC2 after immunoprecipitation with an anti-DDK antibody. Biotin-switch assay and immunoblotting (using anti-SNO antibody) showed S-nitrosylation of immunoprecipitated HDAC2 after CSC treatment that persisted even in the presence of dexamethasone (data shown for 4 hours after dexamethasone treatment; Figure 2, D and E). Dexamethasone suppressed LPS-induced S-nitrosylation in vehicle- but not CSC-treated THP-1 cells (Figure 2, D and E). We also measured S-nitrosylation of immunoprecipitated HDAC2 by Saville assay. As shown in Figure 2F, S-nitrosylated content of immunoprecipitated HDAC2 from CSC-treated THP-1 cells was significantly higher than that with vehicle treatment (about 15-fold). Note that, because of

limitations in the sensitivity of the Saville assay, the fold increase is likely an overestimation. However, all 3 methods of S-nitrosylation analysis showed that HDAC2 was S-nitrosylated in the CSC-exposed THP-1 cells (Figure 2, D–F). High levels of S-nitrosylated HDAC2 could result from increase iNOS activity after CSC exposure. Taken together, these results suggest that exposure to GSNO or CSC induces S-nitrosylation of HDAC2 that may promote dexamethasone insensitivity.

LPS stimulation promotes S-nitrosylation of HDAC2. Our results indicated that LPS stimulation alone could cause S-nitrosylation of HDAC2 in THP-1 cells (Figure 2, D–F). Previous studies have shown that LPS stimulation induces NO generation and S-nitrosylation of HDAC2 (34) in macrophages. We found a time-dependent increase in NO generation and a concomitant increase in S-nitrosylation of HDAC2, as assessed by biotin-switch assay, in THP-1 cells after LPS stimulation alone (Figure 3, A and B). Nott et al. previously demonstrated that S-nitrosylation impairs the DNA-binding function of HDAC2 (20). In agreement with that study, our ChIP analysis showed release of HDAC2 from the IL-8 promoter after S-nitrosylation, concomitant with increased H4 acetylation on the IL-8 promoter and with increased IL-8 mRNA levels, in THP-1 cells after LPS treatment (Figure 3, C and D). However, dexamethasone treatment 60, 30, or 10 minutes prior to or

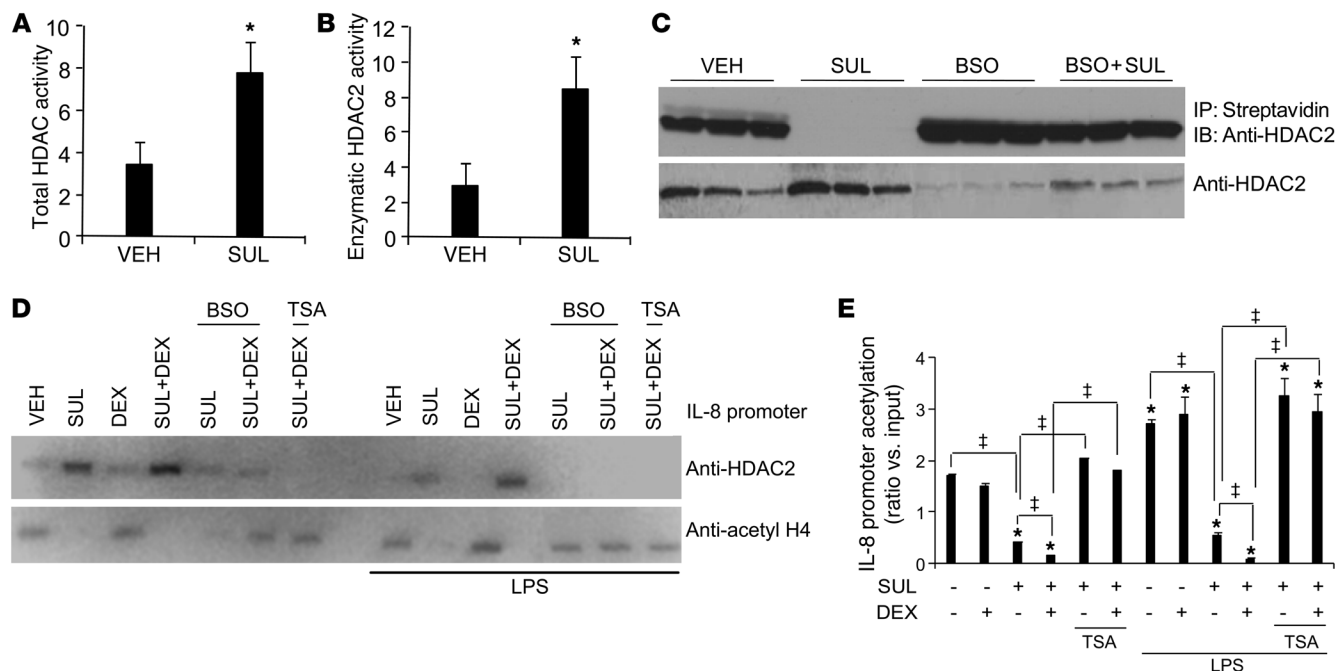


Figure 8

Sulforaphane improves corticosteroid sensitivity by increasing HDAC2 activity in a GSH-dependent manner. (A) Total HDAC activity and (B) HDAC2 enzymatic activity in alveolar macrophages treated with or without 5 μ M sulforaphane for 16 hours. Enzymatic HDAC2 activity was expressed as “ μ M of standard.” (C) HDAC2 S-nitrosylation, assessed by biotin-switch assay, in COPD alveolar macrophages after sulforaphane treatment in the presence of 1 mM BSO for 16 hours. (D) ChIP analysis of HDAC2 binding and histone acetylation in the IL-8 promoter of alveolar macrophages after sulforaphane cotreatment with 10 mM TSA in ethanol for 2 hours or with 1 mM BSO for 16 hours in the presence or absence of dexamethasone. (E) Basal and LPS-induced histone acetylation in the promoter of the IL-8 gene in alveolar macrophages after coexposure to sulforaphane and 10 mM TSA in ethanol for 2 hours in the presence or absence of dexamethasone. * $P < 0.01$ versus vehicle, ANOVA followed by Bonferroni post-test. † $P < 0.01$ as denoted by arrows, Student’s *t* test. $n = 22$ patient samples unless otherwise indicated.

30 minutes after LPS stimulation suppressed NO generation and prevented S-nitrosylation of HDAC2 (Figure 3, E and F). Previous studies have shown that treatment with dexamethasone prior to LPS exposure inhibits NO generation in macrophages (41). We also found that dexamethasone inhibited HDAC2 release and acetylation of H4 on the IL-8 promoter (Figure 3G). Intriguingly, dexamethasone treatment 1 hour or more after LPS exposure failed to reduce the levels of S-nitrosylated HDAC2 or to recruit HDAC2 on the IL-8 promoter (Figure 3, F and G), which suggests that most of the functional HDAC2 protein in the nucleus is S-nitrosylated by 1 hour after LPS exposure. In addition, dexamethasone failed to suppress H4 acetylation on the IL-8 promoter or expression of IL-8 (Figure 3, G and H). Similar results were observed in PMA-differentiated THP-1 macrophages without the overexpression of HDAC2 (data not shown). Taken together, these results suggest that the dexamethasone-mediated repression of IL-8 is abolished when HDAC2 is S-nitrosylated.

Denitrosylation of HDAC2 by GSH treatment restores sensitivity to GC. Next, we asked whether GSH-e-mediated denitrosylation of HDAC2 could restore the dexamethasone sensitivity of THP-1 cells. Incubation of THP-1 cells with GSH-e for 2 hours after CSC or GSNO exposure caused denitrosylation of HDAC2, as assessed by immunoblotting analysis using anti-SNO antibody, and concurrently restored HDAC2 enzymatic activity (Figure 4, A and B, and Supplemental Figure 3A). Immunoblot analysis confirmed that GSH-e reversed S-nitrosylation, but not nitrotyrosine modifi-

cation, of immunoprecipitated HDAC2 (Figure 4C). Furthermore, GSH-e restored the repressive effect of dexamethasone on LPS-induced IL-8 expression in THP-1 cells exposed to CSC or GSNO (Figure 4D and Supplemental Figure 3B).

The interaction of HDAC2 with the GR is critical for the transrepression of NF- κ B (14). To determine whether S-nitrosylation of HDAC2 affects its interaction with the GR corepressor complex, we performed immunoblot analysis using immunoprecipitated DDK-HDAC2 with an anti-GR antibody. We found that S-nitrosylated HDAC2 protein failed to interact with the GR corepressor complex in cells exposed to CSC (Figure 4A, lanes 2 and 4). Furthermore, GSH-e pretreatment restored the HDAC2-GR interaction in cells exposed to CSC (Figure 4A, lanes 6 and 8), reinstating HDAC2-mediated recruitment of the IL-8 promoter after dexamethasone treatment. These results suggest that S-nitrosylation of the HDAC2 protein impairs its interaction with the GR repressor complex and ablates of the transrepressive effect of GR on IL-8 expression.

Cys-262 and Cys-274 are targets of S-nitrosylation in the HDAC2 protein. We investigated which cysteine residues in HDAC2 are susceptible to S-nitrosylation. HDAC2 protein contains 488 amino acids, including 10 cysteine residues (Supplemental Figure 4A). THP-1 cells overexpressing either the WT Myc-DDK-tagged HDAC2 construct or one of a series of HDAC2 deletion mutants containing amino acid deletions 112–488, 286–488, and 1–311 (referred to herein as DEL1, DEL2, and DEL3, respectively; Supplemental Figure 4A) were exposed to GSNO. To assess

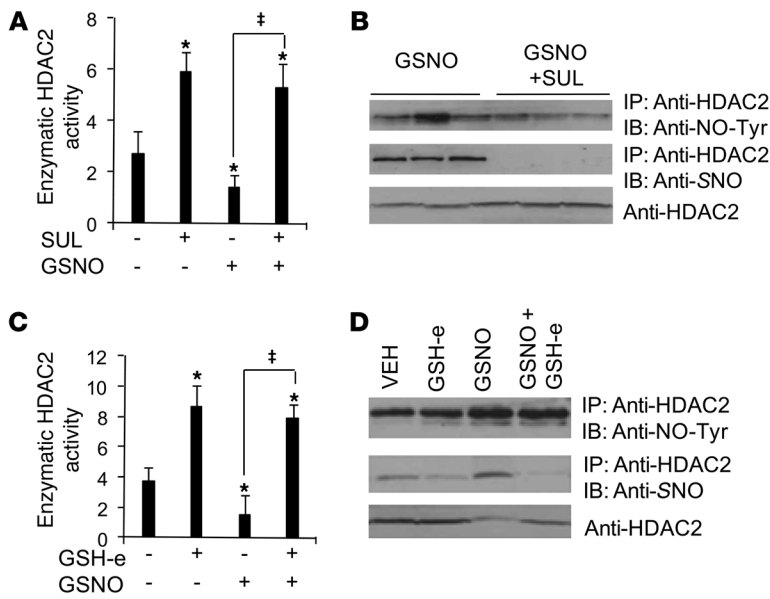


Figure 9

Sulforaphane or exogenous GSH increases HDAC2 activity in COPD alveolar macrophages exposed to GSNO. **(A)** Enzymatic activity of HDAC2 in GSNO-exposed (0.5 mM, 2 hours) COPD alveolar macrophages after sulforaphane treatment ($n = 6$ per group). **(B)** Immunoblot analysis of nitrotyrosine modification and S-nitrosylation of HDAC2 in GSNO-exposed alveolar macrophages after treatment with sulforaphane. **(C)** Enzymatic activity of HDAC2 in GSNO-exposed alveolar macrophages after GSH-e treatment (0.5 mM, 2 hours) ($n = 6$ per group). **(D)** Immunoblot analysis of nitrotyrosine modification and S-nitrosylation of HDAC2 in GSNO-exposed alveolar macrophages after GSH-e treatment. **(A and C)** Enzymatic HDAC2 activity was expressed as “μM of standard.” * $P < 0.01$ versus vehicle, ANOVA followed by Bonferroni post-test. † $P < 0.01$ as shown by brackets, Student's t test.

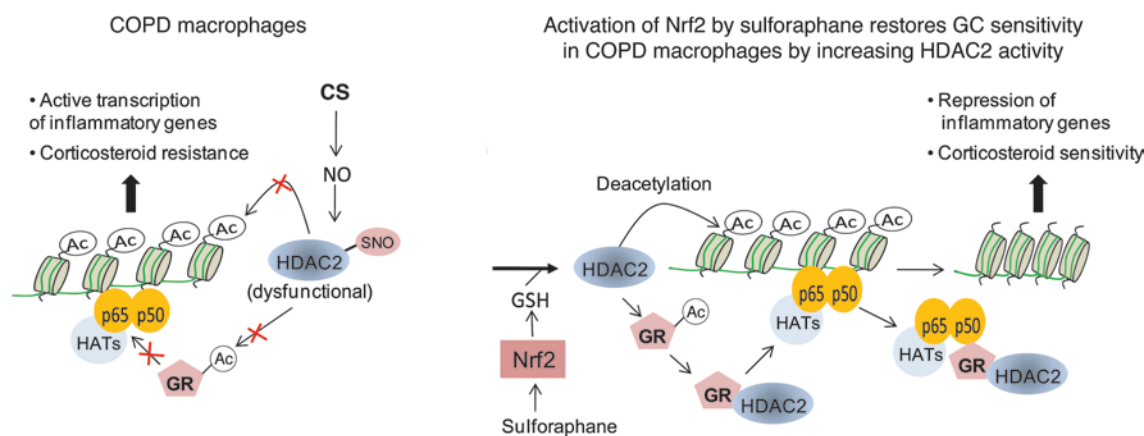
S-nitrosylation, WT DDK-HDAC2 or truncated mutant proteins were immunoprecipitated using anti-DDK antibody and analyzed by biotin-switch assay. We detected S-nitrosylation in the WT construct and the DEL1 and DEL3 mutants, but not in the DEL2 mutant (Figure 5A), which suggests that Cys-13, Cys-101, Cys-111, Cys-152, Cys-262, Cys-274, and Cys-285 are potential sites for S-nitrosylation. Consensus motif analysis using GPS-SNO software (version 1.0) to identify S-nitrosylation sites in HDAC2 protein predicted Cys-262 and Cys-152 to be S-nitrosylated. Nott et al. previously reported that S-nitrosylation of HDAC2 occurs at 2 cysteine residues, Cys-262 and Cys-274 (20). Therefore, we first chose to generate single (C262A, C274A, or C152A), double (C262+274A, C262+152A, or C152+274A), or triple (C262+274+152A) cysteine-to-alanine site-directed mutants. The WT form and the site-directed mutants of HDAC2 were transfected into THP-1 cells, which were exposed to GSNO for 2 hours or to CSC for 24 hours. S-nitrosylation was assessed by biotin-switch assay. Exposure to GSNO resulted in S-nitrosylation of Cys-152, Cys-262, and Cys-274 (Supplemental Figure 4B). Exposure to CSC caused S-nitrosylation of all mutants except C262+274A (Figure 5B), which suggests that S-nitrosylation of HDAC2 occurs at Cys-262 and Cys-274. Exposure to ascorbate, HgCl₂, and ultraviolet radiation (UV), which reverse S-nitrosylation, served as controls for the biotin-switch assay.

Next, we analyzed the deacetylase activity of immunoprecipitated WT and cysteine mutants of HDAC2. We found that, independent of CSC or GSNO exposure, mutation C152A, which is located in the catalytic domain of HDAC2, abolished the activity of the enzyme (Figure 5C and Supplemental Figure 4C). The enzymatic activities of single mutants C262A and C274A were comparable to that of WT and could be inhibited by exposure to CSC or GSNO (Figure 5C and Supplemental Figure 4C). Unexpectedly, the basal enzymatic activity of C262+274A was significantly reduced (Figure 5C), preventing us from determining whether overexpression of this double mutant can render THP-1 cells sensitive to dexamethasone after CSC exposure. Taken together, these results suggest that Cys-262 and Cys-274 are potential sites of S-nitrosylation after CSC exposure.

Increasing intracellular GSH by sulforaphane treatment activates Nrf2 and restores GC sensitivity in alveolar macrophages from CS-exposed mice. Nrf2 transcriptionally regulates basal and inducible expression of *Gclm* and *Gclc* genes, which regulate biosynthesis of GSH (42). We hypothesized that the activation of Nrf2 by the small-molecule activator sulforaphane (42) would increase GSH-dependent denitrosylation of HDAC2 and restore the dexamethasone sensitivity of alveolar macrophages. Our results indicated that alveolar macrophages isolated from CS-exposed *Nrf2*^{-/-} and *Nrf2*^{+/+} mice were insensitive to dexamethasone; this GC failed to repress basal and LPS-induced IL-6 or MCP-1 cytokine expression (Figure 6, A and B). However, incubation with sulforaphane increased the GSH levels (Supplemental Figure 5A) and improved the dexamethasone sensitivity of alveolar macrophages isolated from CS-exposed *Nrf2*^{+/+} mice, but not *Nrf2*^{-/-} mice (Figure 6, A and B).

We also analyzed HDAC2 activity in the lungs of mice after 2 weeks of CS exposure. We observed a significant decrease in total HDAC activity and immunoprecipitated HDAC2 enzymatic activity in the lungs of CS-exposed *Nrf2*^{+/+} and *Nrf2*^{-/-} mice (Figure 6, C and D). However, sulforaphane treatment after CS exposure increased the enzymatic activity in *Nrf2*^{+/+} mice, but not *Nrf2*^{-/-} mice (Figure 6D). Sulforaphane treatment also increased the levels of Nrf2-regulated target genes (*Nqo1*, *Ho1*, and GSH-biosynthesizing enzymes *Gclc* and *Gclm*; Supplemental Figure 5, A–D) and GSH (Figure 6E). In addition, it reduced the levels of S-nitrosylated HDAC2 protein in the lungs of CS-exposed *Nrf2*^{+/+} mice, but not *Nrf2*^{-/-} mice, as determined by Saville and biotin-switch assays (Figure 6, F and G). Taken together, these results indicate that activation of Nrf2 by sulforaphane restores the enzymatic activity of HDAC2 via GSH-dependent denitrosylation.

Sulforaphane increases HDAC2 activity via denitrosylation and improves GC sensitivity in alveolar macrophages from COPD patients. Previous studies have reported a lower level of NRF2 signaling in the lungs and alveolar macrophages from patients with COPD than in those without COPD (23, 31, 32). Therefore, we asked whether sulforaphane activates NRF2 and increases its target antioxidant gene expression in alveolar macrophages from COPD patients. Treatment with sulforaphane resulted in significantly elevated levels

**Figure 10**

Schematic summarizing the study. S-nitrosylation impairs HDAC2-GR binding and HDAC2-DNA binding function. Activation of Nrf2 by sulforaphane increases GSH, which induces denitrosylation of HDAC2 and restores HDAC2 function and thereby GC sensitivity.

of NRF2 nuclear protein, NRF2-regulated target genes (*NQO1*, *HO1*, *GCLC*, and *GCLM*), and GSH in COPD alveolar macrophages (Figure 7, A–D). Next, we analyzed the ability of dexamethasone to suppress LPS-induced cytokine expression after sulforaphane treatment. Consistent with the results of previous studies (14), dexamethasone alone failed to suppress LPS-induced IL-8 secretion (Figure 7E). In contrast, sulforaphane treatment significantly restored dexamethasone's inhibitory effect on basal and LPS-induced IL-8 secretion (a 5-fold reduction in secretion; $P < 0.01$; $n = 22$ patients; Figure 7E). In addition, sulforaphane alone significantly reduced IL-8 levels basally and after LPS treatment.

We then asked whether sulforaphane restores dexamethasone sensitivity by increasing GSH biosynthesis in the alveolar macrophages of patients with COPD. In the presence of L-buthionine sulfoximine (BSO), a specific inhibitor of GSH synthesis, sulforaphane failed to reduce histone acetylation in the IL-8 gene promoter or to inhibit IL-8 expression in these cells and failed to restore dexamethasone's inhibitory effect on LPS-induced IL-8 expression, with a significant BSO-mediated reduction in GSH levels (Supplemental Figure 6, A–C, and Figure 7F).

Next, we addressed whether sulforaphane restores GC sensitivity by increasing HDAC2 activity. First, we determined whether sulforaphane restores dexamethasone sensitivity of alveolar macrophages from patients with COPD when the HDAC inhibitor TSA is present. TSA abolished sulforaphane's ability to restore dexamethasone sensitivity in these alveolar macrophages, as indicated by high levels of IL-8 expression (Supplemental Figure 7, A and B). Second, we asked whether sulforaphane modulates HDAC2 activity and found it to significantly increase both total and immunoprecipitated enzymatic HDAC2 activity ($P < 0.01$; Figure 8, A and B). Sulforaphane treatment was associated with a moderate increase in the level of HDAC2 protein in the alveolar macrophages, but did not affect the level of HDAC2 mRNA (Supplemental Figure 8, A–C). Third, we asked whether sulforaphane treatment causes denitrosylation of HDAC2. Biotin-switch assays showed a marked decrease in the levels of S-nitrosylated HDAC2 in alveolar macrophages from COPD patients after sulforaphane treatment; however, sulforaphane's ability to reduce the levels of S-nitrosylated HDAC2 protein was abolished in the macrophages

in the presence of BSO (Figure 8C). Fourth, we assessed the effect of dexamethasone treatment on HDAC2 recruitment and H4 acetylation on the IL-8 promoter in sulforaphane-exposed alveolar macrophages. Sulforaphane treatment increased the recruitment of HDAC2 and suppressed histone acetylation on the IL-8 promoter, and this effect was further enhanced in the presence of dexamethasone (Figure 8, D and E). Cotreatment with TSA abolished sulforaphane's ability to repress basal and LPS-induced histone acetylation in the IL-8 promoter region, with and without dexamethasone (Figure 8, D and E). Furthermore, in the presence of BSO, sulforaphane failed to increase HDAC2 binding to the IL-8 promoter, again indicating HDAC2's reliance on Nrf2-dependent GSH synthesis (Figure 8D). Taken together, these results indicate that sulforaphane restores GC sensitivity by increasing HDAC2 function in a GSH-dependent manner in alveolar macrophages from patients with COPD.

We also assessed the ability of sulforaphane to reduce S-nitrosylation after GSNO exposure in alveolar macrophages from patients with COPD. GSNO exposure for 2 hours decreased basal HDAC2 enzymatic activity, which was restored by sulforaphane treatment (Figure 9A). Immunoblot analysis using anti-SNO antibody showed significant reduction in the levels of S-nitrosylation, but not nitrotyrosine modification, of HDAC2 in GSNO-exposed COPD macrophages after sulforaphane treatment (Figure 9B). Like sulforaphane, GSH-e significantly increased HDAC2 activity after GSNO treatment and reduced the S-nitrosylation but not nitrotyrosine modification of HDAC2 (Figure 9, C and D). Taken together, these results indicate that sulforaphane, by mediating denitrosylation of HDAC2 in a GSH-dependent manner, restores HDAC2 function and GR-driven transrepression of inflammation in alveolar macrophages of patients with COPD.

Discussion

A growing body of evidence suggests that in patients with COPD, the decrease in HDAC2 activity in the alveolar macrophages and lung epithelial cells that occurs concomitantly with COPD progression is responsible for the amplified inflammation and GC resistance shown in these patients. We have shown here that pharmacological activation of Nrf2 by sulforaphane can lead to



restoration of GC responsiveness in alveolar macrophages from patients with COPD and further demonstrated that the basis for this improvement is increased HDAC2 activity (Figure 10). This finding may have considerable significance for the development of new therapies in COPD and related lung disorders.

Previous studies have shown that *S*-nitrosylation impairs the DNA-binding function (21) and enzymatic activity (20) of HDAC2. Brain-derived neurotrophic factor stimulation has previously been shown to rapidly induce *S*-nitrosylation that promotes the release of HDAC2 from the promoters of target genes, leading to histone acetylation in these promoters and, consequently, gene transcription (20). In macrophages, several proinflammatory genes, including IL-8, are regulated by HDAC2 (43). Consistent with a previous study (34), we found that *S*-nitrosylation caused the release of HDAC2 from the IL-8 promoter, resulting in histone H4 acetylation and transcription of IL-8 in THP-1 cells after LPS stimulation. Dexamethasone inhibits NO production in a GR-dependent manner through multiple mechanisms, including the destabilization of iNOS mRNA (41). In the present study, dexamethasone treatment prior to LPS exposure inhibited NO-dependent *S*-nitrosylation of HDAC2 and concomitantly suppressed HDAC2 release and H4 acetylation in the IL-8 promoter, leading to inhibition of IL-8 gene expression in THP-1 cells. However, in the same experiment, dexamethasone treatment 1 hour after LPS exposure failed to inhibit IL-8 expression and was unable to reduce NO-dependent *S*-nitrosylation of HDAC2 and recruitment of HDAC2 to the IL-8 promoter. Time-kinetics analysis showed that maximum levels of HDAC2 *S*-nitrosylation were achieved by 1 hour and sustained until the LPS stimulation was terminated at 4 hours. These results suggest that dexamethasone's inhibitory effect on LPS-induced IL-8 levels is abrogated by *S*-nitrosylation of HDAC2.

Our analysis of dexamethasone sensitivity in alveolar macrophages exposed to GSNO or to stressors such as CSC and CS indicated that nitrosative stress induced *S*-nitrosylation of HDAC2, resulting in a loss of HDAC2 occupancy on the IL-8 promoter; at the same time, dexamethasone failed to recruit HDAC2 to the IL-8 promoter or repress IL-8 gene transcription in these cells after LPS stimulation. Physiological levels of GSNO were in the nanomolar range; however, for demonstrating proof of principle, we used a supraphysiological 0.5-mM concentration of GSNO in our studies. Coimmunoprecipitation analysis indicated that *S*-nitrosylated HDAC2 failed to interact with the GR. Our mutational analysis identified Cys-274 and Cys-262 on HDAC2 as potential residues for *S*-nitrosylation after CSC exposure. In contrast to a previous report (20), we found that the C262+274A cysteine-to-alanine double mutation compromised the basal deacetylase activity of HDAC2. These results suggest that Cys-274 and Cys-262 may be critical for HDAC2 function; further studies are required to elucidate the role of cysteine *S*-nitrosylation in affecting HDAC2 enzymatic activity. Taken together, these results indicate that *S*-nitrosylation impairs the interaction of HDAC2 with the GR and DNA, thereby promoting dexamethasone resistance in macrophages.

Several studies have shown that GSH mediates the denitrosylation of proteins by means of transnitrosylation reactions (36, 44, 45). Therefore, basal intracellular levels of *S*-nitrosylated proteins can be directly regulated, at least in part, by intracellular GSH levels. However, there are numerous proteins that are resistant to GSH-mediated denitrosylation (45). We found that incubation of *S*-nitrosylated HDAC2 with GSH reduced its level of *S*-nitro-

sylation and restored its deacetylase activity in a cell-free system. Similarly, incubation of CSC- or GSNO-exposed cells with GSH-e reduced *S*-nitrosylation of HDAC2, restored HDAC2-GR interaction, and rescued these cells from dexamethasone insensitivity. These results suggest that an increase in intracellular GSH levels may promote HDAC2 denitrosylation and restore both HDAC2 function and dexamethasone sensitivity.

As has been reported previously (16, 46), alveolar macrophages from patients with COPD showed dexamethasone insensitivity in our present study. Loss of HDAC2 activity in COPD has primarily been attributed to degradation of the HDAC2 protein by the ubiquitin-proteasome system as a result of its posttranslational modifications, such as phosphorylation of serine/threonine residues (18) and nitration of tyrosine residues on HDAC2 (47). Our findings suggest that *S*-nitrosylation is a critical posttranslational modification responsible for HDAC2 inactivation in COPD alveolar macrophages. *S*-nitrosylation is thought to be more favorable under physiological conditions, whereas excess nitrosative stress may predispose proteins to either modification (48). Unlike nitrotyrosine modification, *S*-nitrosylation is highly susceptible to denitrosylation by cytosolic reducing agents (36, 45). Because of the low GSH (23) and high NOS activity (49) associated with COPD severity, steady levels of *S*-nitrosylation of HDAC2 are likely to be maintained. Consistent with this notion, we detected elevated levels of HDAC2 *S*-nitrosylation in the lysates of alveolar macrophages and peripheral lung tissue. Furthermore, incubating immunoprecipitated HDAC2 from COPD patient alveolar macrophages with GSH increased HDAC2 enzymatic activity by reversing *S*-nitrosylation, but not nitrotyrosine modification, in HDAC2.

Nrf2 regulates cellular levels of GSH by transcriptionally regulating the rate-limiting enzyme glutamate-cysteine ligase (50). Cells deficient in Nrf2 show decreased levels of GSH and are sensitive to oxidative and nitrosative stressors (30, 51). Sulforaphane, an active ingredient in broccoli, is a potent activator of Nrf2 (52) and is extensively studied in humans (53, 54). Sulforaphane modifies the Cys-151 residue in Keap1 protein that impairs Nrf2 ubiquitination by cullin 3-based E3-ligase and stabilizes Nrf2 (55). We hypothesized that activation of Nrf2 by small-molecule sulforaphane might promote GSH-dependent denitrosylation of HDAC2 and restore the dexamethasone sensitivity of macrophages. Consistent with our hypothesis, sulforaphane treatment increased GSH levels, reduced *S*-nitrosylated HDAC2 levels, and concomitantly enhanced dexamethasone repression of IL-6 and MCP-1 expression in alveolar macrophages isolated from CS-exposed *Nrf2*^{+/+} mice, but not *Nrf2*^{-/-} mice.

Previously, we and others had reported that COPD patients exhibit a loss of NRF2 signaling in their lungs and alveolar macrophages compared with patients without COPD, as a result of NRF2 protein instability (25, 30, 31). We herein observed that sulforaphane treatment stabilized the NRF2 protein and increased NRF2-regulated antioxidants, including GSH, in these alveolar macrophages of COPD patients; furthermore, sulforaphane treatment reduced HDAC2 *S*-nitrosylation and restored HDAC2 enzymatic activity in these cells. The results of our ChIP assays also confirmed the recruitment of HDAC2, concurrent with low histone acetylation in the promoter of the IL-8 gene and repression of IL-8 expression in sulforaphane-treated alveolar macrophages. These effects were ablated by TSA or BSO, confirming that sulforaphane increased HDAC2 activity by elevating GSH levels. A similar increase in HDAC2 activity in the alveolar macrophages after exposure to exogenous GSH-e further supported this conclusion.



A recent study has proposed a role for the S-nitrosylation of Keap1 Cys-151 in stabilizing Nrf2 (56). Sulforaphane also modifies the Cys-151 residue of Keap1 by alkylation and thereby stabilizes Nrf2 (55). Although sulforaphane may promote the denitrosylation of Keap1, it is unlikely to hinder its role in activating Nrf2 signaling. Thus, our results strongly suggest that defective Nrf2 signaling contributes to HDAC2 inactivity and underscore the ability of Nrf2 activators to restore HDAC2 activity and GC sensitivity in alveolar macrophages.

Nrf2 activators such as sulforaphane can counteract oxidative and nitrosative stress and mediate GSH-dependent denitrosylation, thereby restoring HDAC2 activity. Alternatively, GSH-mediated denitrosylation of proteins may result in elevated levels of GSNO, an endogenous bronchodilator (57) that is metabolized by GSNO reductase (36). Therefore, it would be interesting to determine how Nrf2 affects the levels of GSNO and GSNO reductase in the airways of COPD patients. In addition to elevating GSH levels, Nrf2 transcriptionally regulates proteins such as carbonyl reductase, thioredoxin reductase, and glutathione peroxidase (58), which may also directly or indirectly contribute to the denitrosylation of proteins (36, 51). Further studies are required to determine whether impaired Nrf2 signaling promotes aberrant S-nitrosylation of proteins in human diseases. Because altering S-nitrosylation/denitrosylation may modulate a variety of NO-mediated physiological signaling mechanisms that regulate vasodilation and airway relaxation (including GPCR signaling), it is important to determine the role of this type of protein modification in the overall pathobiology of COPD. The results of the present study point to the significance of this process for COPD and suggest that the small-molecule Nrf2 activator sulforaphane may be useful as an adjuvant therapy to augment the antiinflammatory effects of GC in COPD and other inflammatory diseases (59).

Methods

Further information can be found in Supplemental Methods.

Patient characteristics. Patients with COPD were recruited from clinical populations at the Johns Hopkins Hospital and Johns Hopkins Bayview Medical Center. Frozen peripheral lung tissue samples were obtained from the NHLBI Lung Tissue Research Consortium. Clinical information and patient characteristics are summarized in Supplemental Tables 1 and 2.

Mouse studies. *Nrf2*^{+/+} and *Nrf2*^{-/-} mice (C57BL/6 strain, 8–10 weeks old) were used. *Nrf2*^{-/-} mice were procured from the laboratories of T. Kensler (Johns Hopkins University, Baltimore, Maryland, USA) and M. Yamamoto (Tohoku University Graduate School of Medicine, Sendai, Japan). Exposure to CS (1 month) was carried out as described previously (28). Alveolar macrophages from mice were isolated from BAL fluid (60).

Treatments. Macrophages (human and mouse) were adherence purified before analysis, and the macrophage purity was greater than 95%, as determined by the morphologic appearance of Diff-Quick staining preparations. The viability of the macrophages, as assessed by trypan blue exclusion, exceeded 90%. To induce corticosteroid resistance, PMs were exposed to CSC (200 µg/ml; Murty Pharmaceuticals) for 16 hours. Exposure to GSNO (0.5 mM) was limited to 4 hours. Cultured macrophages were treated with sulforaphane (5 µM for 16 hours; LKT Laboratories Inc.), GSH-e (1 mM for 4 hours; Sigma-Aldrich), or the appropriate vehicle (DMSO or PBS) in RPMI 1640 culture

medium with 10% FBS and 1% penicillin-streptomycin (Invitrogen) for 16 hours. To assess corticosteroid responsiveness, macrophages were incubated with dexamethasone (1 µM; Sigma-Aldrich) for 1 hour, followed by incubation with LPS (10 µg/ml; Sigma-Aldrich) for an additional 4 hours. Culture medium (serum-free) was used for cytokine analysis (human IL-8, mouse IL-6, or MCP-1) using ELISA kits (R&D Systems), and cell lysates were used for gene expression, enzymatic activity, GSH, NO, and immunoblot analyses.

HDAC enzymatic activity, GSH, and NO analysis. HDAC activity was measured using a fluorescent derivative of ε-acetyl-lysine according to the manufacturer's recommendations (Enzo Life Sciences). Enzymatic activity was expressed relative to a standard curve generated from fluorogenic substrate. The immunopurified HDAC2 was used to assess HDAC2 enzymatic activity. GSH levels were determined using the monochlorobimane fluorometric method. NO levels were monitored with DAF-FM diacetate dye (Invitrogen), which emits fluorescence after reaction with an active intermediate of NO formed during spontaneous oxidation of NO to nitrite.

S-nitrosylation and other assays. S-nitrosylation of proteins was analyzed by means of the biotin-switch (35), Saville (38), and anti-SNO antibody immunoblot assays. Immunoprecipitation, immunoblot, ChIP, and gene expression analyses were carried out as described previously (28, 51).

Statistics. Patient characteristics are presented as median values per group, interquartile (IQR) range, and first and fourth quartile values. Statistical significance was assessed using 2-tailed Student's *t* test for comparisons between 2 groups or by multivariate ANOVA analysis for multigroup comparisons. A *P* value less than 0.05 was considered significant. Data are presented as mean ± SD unless otherwise indicated.

Study approval. All study protocols related to human studies were approved by the Institutional Review Board of the Johns Hopkins University. Written, informed consent was obtained from all participants at the time of sample collection. All animal experiments were performed under a protocol approved by Johns Hopkins University Animal Care and Use Committee.

Acknowledgments

We thank Christopher Harvey for helping with the procurement of patient alveolar macrophages during initial optimization studies and Deborah McClellan for editorial assistance. We thank Thomas Kensler and Masayuki Yamamoto for providing *Nrf2*^{-/-} mice. This work was supported by NIH grant HL081205 (to S. Biswal), National Heart, Lung, and Blood Institute Specialized Centers of Clinically Oriented Research grant P50HL084945, the Flight Attendant Medical Research Institute (to S. Biswal and R.K. Thimmulappa), National Cancer Institute lung spore grant P50 CA058184 (to S. Biswal), and National Institute on Environmental Health Sciences grants P50ES015903, ES03819, U01HL105569, P50HL107169, and P01ES018176. The authors acknowledge the support of the Grace Anne Dorney fund for tobacco-related disease research.

Received for publication September 16, 2010, and accepted in revised form September 14, 2011.

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