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Forum Review

Oxidative and Nitrative Stress in Bronchial Asthma

HISATOSHI SUGIURA and MASAKAZU ICHINOSE

ABSTRACT

There has been a marked increase in the global prevalence, morbidity, and mortality of asthma, and its associated economic burden has also grown over the last 40 years. Approximately 300 million people worldwide currently have asthma, and its prevalence increases by 50% every decade. Airway inflammation is the most proximate cause of the recurrent episodes of airflow limitation in asthma. Recent research has revealed that numerous biologically active proinflammatory mediators are responsible for the pathogenesis of asthma. Among these mediators, there is increasing evidence that endogenous or exogenous reactive oxygen species (ROS) and reactive nitrogen species (RNS) are responsible for the airway inflammation of asthma. Many reports have shown that there is an excessive production of ROS and RNS in the airways of asthmatic individuals compared with healthy subjects. Excessively produced ROS and RNS have been reported to lead to airway inflammation, airway hyper-responsiveness, airway microvascular hyperpermeability, tissue injury, and remodeling in animal models and human studies. Although human lungs have a potent antioxidant system, excessive oxidative and nitrative stress leads to an imbalance of oxidants/antioxidants. This review describes the rapidly accruing data linking oxidative and nitrative events to the pathogenesis of bronchial asthma. *Antioxid. Redox Signal.* 10, 785–797.

INTRODUCTION

In various inflammatory lung diseases, reactive oxygen species (ROS) and reactive nitrogen species (RNS), including superoxide anion, hydroxyl radicals, hydrogen peroxide, hypochlorous acid, ozone, and peroxynitrite, have been reported to play a pivotal role in the airway inflammation and pathogenesis (58, 84, 111). Among the inflammatory lung diseases, especially in bronchial asthma, oxidative and nitrative stress has been shown to be related to the pathogenesis (4, 9, 85). Oxidant generation is part of the normal metabolism of many types of cells and is critical for cell homeostasis. Although the lung has a well-developed antioxidant system to protect itself against exposure to endogenous or exogenous noxious oxidants (59, 86), excessively produced ROS and RNS can still cause inflammation in the lungs.

Asthma is a chronic inflammatory disease of the airways in which various resident and migrated cell-derived molecules play a role (20, 26). Many experimental and clinical data suggest that an imbalance between oxidants and antioxidants causes the airway inflammation and airway hyper-responsiveness that are major features of asthma (6, 13, 15). In animal models, allergen- (105) and ozone-induced (106) airway inflammation and airway hyper-responsiveness are largely modified by inhibitors of the synthesis of reactive oxygen and related species or by scavengers of radical species, supporting this hypothesis. Superoxide anion (O_2^-) may also be exaggerated in asthmatic airways via the upregulation of xanthine oxidase (XO) in microvascular endothelial cells (44) and NADPH oxidase in the infiltrated eosinophils (96). These results suggest that ROS may be related to the pathophysiology of bronchial asthma.

In addition, nitric oxide (NO) production is increased in asthmatic airways, possibly via the inducible type of NO synthase (iNOS) (33, 47), and steroid treatment reduces the NO generation (91). NO rapidly reacts with superoxide anion which is released from inflammatory cells, including eosinophils, re-

Third Department of Internal Medicine, Wakayama Medical University School of Medicine, Wakayama City, Wakayama, Japan.

sulting in the formation of the highly proinflammatory molecule, peroxynitrite (10, 82). In addition, since RNS, including peroxynitrite, cause tissue injury in a variety of organs, nitrative stress may be partly responsible for the airway inflammation in asthmatic patients.

This review describes the pathophysiological mechanisms and the clinical relevance of ROS and RNS in bronchial asthma. The role of ROS and RNS on airway remodeling observed in asthmatic airways is described. Furthermore, this review will examine the relationship between oxidative/nitrative stress and the refractoriness to steroids in refractory asthma.

ROS AND BRONCHIAL ASTHMA

Endogenous oxidants and bronchial asthma

In asthmatic airways, infiltrated inflammatory cells into the airways including eosinophils, neutrophils, and mast cells produce many oxidants by various stimuli (53, 76, 96). In particular, prominent eosinophil infiltration is observed in airways of asthmatic patients. Eosinophils are thought to injure the airway tissues by secreting proteins from its granules, including eosinophil cationic protein, major basic protein, and oxidants (24). It has been reported that eosinophils are stimulated by platelet activating factor (PAF) and injure epithelial cells in the presence of halogen atoms such as chloride and bromide (9). In addition, eosinophils, like neutrophils, have NADPH oxidase (24). In a previous study, eosinophils from asthmatic patients produced more superoxide anion than those from healthy subjects, suggesting that eosinophils from asthmatic patients may be primed by unknown stimuli (94). Moreover, macrophages (21) and neutrophils (25) from asthmatic patients are also reported to produce more oxidants than those from healthy subjects. In many animal asthmatic models, greater than normal amounts of endogenous ROS and RNS were produced (12, 17, 63, 87, 120). These results suggest that the production of ROS and RNS is upregulated in the airways of asthma, causing airway inflammation and hyper-responsiveness in bronchial asthma.

Exogenous oxidants and bronchial asthma

The lungs receive exogenous oxidative stress because of their exposure to the atmosphere. In a guinea pig model, exogenously administered ozone caused injury to epithelial cells, induced the infiltration of inflammatory cells into airway walls, and caused airway hyper-responsiveness (39), which resembled the pathophysiology of asthmatic airways. In this model, various possibilities were raised to explain the mechanism by which exogenously administered ozone induced the airway inflammation and hyper-responsiveness. First, ozone injures epithelial cells. Epithelial cells have neutral endopeptidase (NEP) and angiotensin converting enzyme (ACE) which catalyzes substance P (SP) and bradykinin (BK). SP and BK induce airway microvascular hyperpermeability (116) and smooth muscle contraction (109). The breakdown of NEP and ACE may prolong the survival of tachykinins, leading to the neurogenic inflammation observed in the airways of asthma. This hypothesis is supported by the finding that the levels are upregulated in the airways of asthmatic patients compared with healthy subjects (18, 19). In a guinea pig model of ozone-induced airway hyper-responsiveness, it was reported that ozone stimulated the release of histamine, prostaglandins, leukotrien B_4 (LTB_4), and thromboxane B_2 (TxB_2) (55). These mediators can induce bronchoconstriction and induce the infiltration of inflammatory cells into the airways (16). Cigarette smoke contains huge amounts of oxygen radicals and nitrogen species (83). It is a well-known fact that cigarette smoke worsens the airway inflammation and hyper-responsiveness in healthy subjects and asthmatic patients (74). The inhalation of exogenous oxidants may stimulate the inflammatory cells and worsen the airway inflammation in the airways of bronchial asthma.

Effect of oxidants on resident cells in lungs

Epithelial cells. Injury and shedding of epithelial cells are observed in the airways of asthmatic patients (26). These pathophysiological changes of epithelial cells are mediated by various noxious agents. Epithelial cells are exposed to exogenous oxidants and endogenous oxidants derived from infiltrated inflammatory cells, and are therefore thought to have the most frequent opportunities to receive oxidative stress. In fact, when eosinophils were stimulated by PAF, they injured epithelial cells *in vitro* (118). Since this type of injury was suppressed by catalase, hydrogen peroxide was responsible for this eosinophil-mediated epithelial cell injury (118). Once epithelial cells are injured, NEP and ACE are inactivated as described above. Furthermore, epithelial cells secrete much prostaglandin E2 (PGE_2) which has bronchodilatory action (36). The loss of epithelial cells by oxidative stress can stimulate airway smooth muscle cell contraction through the above-mentioned mechanisms. This epithelial cell injury leads to the loss of the barrier function. As a result of this loss, it is easy for various antigens and stimuli to achieve access to the airway tissue and thereby worsen the airway inflammation in asthmatic patients.

Airway smooth muscle cells. When 10^{-4}–10^{-3} *M* hydrogen peroxide is administered to the trachea of guinea pig, airway smooth muscle contraction is observed (88). This contraction is augmented when the epithelial cells are removed, suggesting that hydrogen peroxide-mediated airway smooth muscle cell contraction is related to the inactivation of relaxant factors such as prostaglandins derived from epithelial cells (36, 88). Since in asthmatic airways, there is shedding of epithelial cells, the contractile effect of endogenous or exogenous hydrogen peroxide in airway smooth muscle cells might be enhanced in asthmatic individuals.

Secretary cells. Inhalation of ozone induces excessive mucus secretion from secretary glands and goblet cells in the trachea of sheep (80). This hypersecretion is inhibited by cyclooxigenase (COX) inhibitors, suggesting that ozone could stimulate COX activity and the products of COX could be related to this excessive secretion. Furthermore, superoxide anion stimulates the production of mucin-like glycoproteins by airway epithelial cells through COX pathways (2). These results suggest that oxidants enhance mucus secretion in epithelial cells. The excessive secretion observed in the airways of asthmatic patients may be due to this oxidant-mediated COX activation.

Endothelial cells. Superoxide anion generated by the xanthine-xanthine oxidase system injures endothelial cells and enhances microvascular permeability *in vivo* (60). The amount of superoxide anion production shows a good correlation with the albumin in bronchoalveolar lavage fluid (BALf) from antigen-challenged asthmatic patients, suggesting that oxidants may cause the extravasation of serum in asthmatic airways (92). Recently, we showed that endogenous NO, superoxide anion, and peroxynitrite could augment the microvascular permeability during the late allergic response in guinea pigs (105). Each inhibitor or scavenger inhibited the microvascular hyperpermeability during the late allergic response (Fig. 1). In the airways of asthmatic patients, especially during exacerbations of bronchial asthma, marked edema of the airways was observed (48, 68, 69). Because excessive production of oxidants occurs in the airways of asthmatic patients during exacerbations, oxidants may be involved in the formation of airway wall edema.

Inflammatory cells. Oxidants are reported to have various effects on inflammatory cells. When inflammatory cells are exposed to oxidants, chemotactic factors are released from them through the arachidonic cascade (79). Moreover, when mast cells are exposed to oxidants, the release of histamine and serotonin is significantly increased (78). These mediators are related to the pathogenesis of bronchial asthma, and oxidants may be related to the inflammation of airways through this mechanism.

Other cells. ROS can oxidize the lipid membrane of many types of cells and activate the arachidonic cascade. The oxidation of the lipid membrane by oxidants can produce prostaglandins and leukotrienes (107). These products can contract airway smooth muscle cells, augment the chemotaxis of inflammatory cells toward inflammatory sites, and enhance the extravasation of serum. Another report showed that oxidants can suppress the function of β-adrenergic receptors (52), which may enhance smooth muscle contraction. There is increasing evidence that ROS can activate the DNA binding capacity of nucleus factor kappa B (NF-kB) which mediates various proinflammatory cytokines, adhesion molecules, and chemokines (5, 7, 93). NF-kB can control the expression of various proinflammatory mediators. These mediators are thought to be important in the inflammation of airways in asthmatic patients. Therefore, the suppression or depletion of oxidants by specific inhibitors or scavengers may be a potent therapeutic target for the suppression of airway inflammation in asthmatic patients in the future.

Antioxidant system in lungs and bronchial asthma

Since the lungs are exposed to various types of oxidative stress, both endogenous and exogenous, the antioxidant system is well developed in lungs. Table 1 shows the antioxidant system in human lungs. There is increasing evidence that there are alterations of the antioxidant capacity in asthmatic individuals

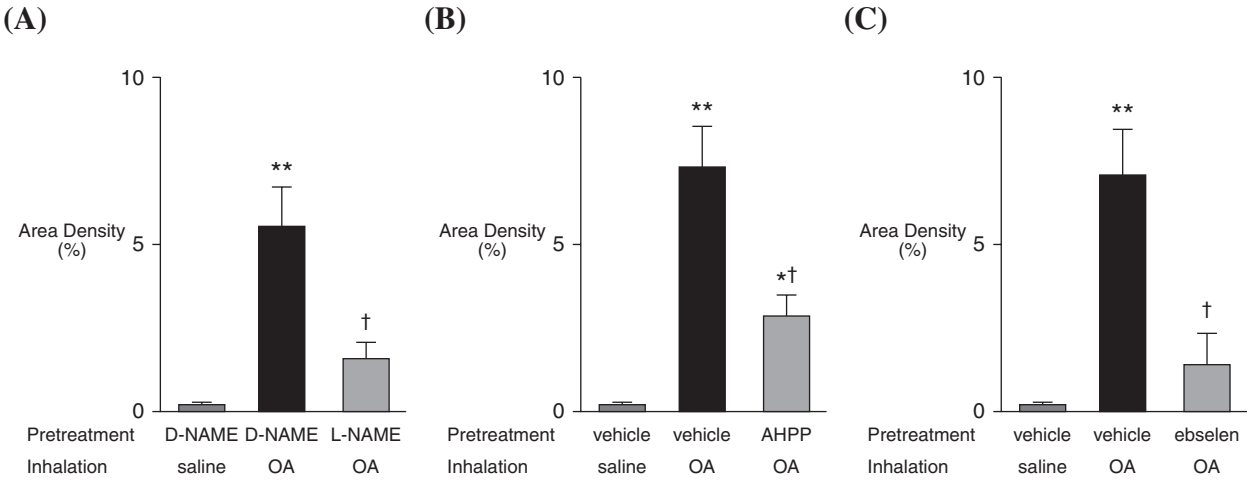

FIG. 1. Effects of nitric oxide synthase (NOS) inhibitor, xanthine oxidase (XO) inhibitor, and peroxynitrite scavenger on airway microvascular permeability during late allergic response (LAR). *Vertical axes* showed percentages of leaky microvasculature in trachea of guinea pigs. The NOS inhibitor, N^{δ}-nitro-L-arginine methyl ester (L-NAME), significantly suppressed the microvascular permeability during LAR [(**A**) *open bar*: vehicle-treated saline-exposed animals; *closed bar*: inactive enantiomar, N^{δ}-nitro-D-arginine methyl ester (D-NAME)-treated antigen-challenged animals; *hatched bar*: L-NAME-treated antigen challenged animals]. The XO inhibitor, {4-amino-6-hydroxypyrazolo(3,4-d)pyrimidine}(AHPP), significantly suppressed the microvascular permeability during LAR [(**B**), *open bar*: vehicle-treated saline-exposed animals; *closed bar*: vehicle-treated antigen-challenged animals; *hatched bar*: AHPP-treated antigen challenged animals]. The peroxynitrite scavenger, ebselen, significantly suppressed the microvascular permeability during LAR [(**C**) *open bar*: vehicle-treated saline-exposed animals; *closed bar*: vehicle-treated antigen-challenged animals; *hatched bar*: ebselen-treated antigen challenged animals). $*p < 0.05$, $**p < 0.01$ compared with vehicle-treated saline-exposed group. $+p < 0.05$ compared with each inhibitor or scavenger-treated antigen-challenged group. Excerpted with permission Sugiura H, Ichinose M, Oyake T *et al*. *Am J Respir Crit Care Med* 1999; 160: 663–671. Copyright 1999 American Thoracic Society.

Table 1. Antioxidants in Human Lungs

Antioxidants	*Localization*
Cu, Zn-superoxide dismutase	Cytosol
Mn-superoxide dismutase	Mitochondria
Extracellular-superoxide dismutase	Epithelial lining fluid
Catalase	Cytosol, Alveolar space
Glutathione	Cytosol, Epithelial lining fluid
Glutathione peroxidase	Cytosol
Heme oxygenase-1, -2	Cytosol
Ascorbic acid	Extracellular
α-Tocophenol	Cell membrane
β-Carotene	Cell membrane

as compared with healthy subjects. Additionally, there are discrepancies in the expression of antioxidants in bronchial asthma. For instance, the expression of some antioxidants such as GSH and heme oxygenase was reported to be increased in bronchial asthmatic patients compared with healthy subjects, whereas other antioxidants such as SOD and glutathione peroxidase were decreased (84). The reasons for such discrepancies have not been elucidated. The relationship between antioxidant and bronchial asthma is reviewed in the following section.

Glutathione (GSH). GSH has an SH residue and reacts with oxygen radicals. GSH is also a low molecular weight, water-soluble radical scavenger, and a high concentration of GSH ($\sim$500 μM) exists in the epithelial lining fluid of the airways (14). The ratio of GSSG, the oxidized form of GSH, to 2GSH (GSSG/2GSH) can serve as a good indicator of the cellular redox state (77, 84). This ratio in GSH may be determined by the rates of hydrogen peroxide reduction by glutathione peroxidase and GSSG reduction by glutathione peroxidase (84). Thus, antioxidant enzymes play a critical role in the maintenance of the cellular reductive potential. In the airways of asthmatic patients, the levels of GSH are increased in BALf, suggesting that GSH production may be upregulated to protect the lungs from excessive oxidative stress in asthmatic patients (99). Because excessive oxidative stress enhances the airway inflammation, GSH could be a therapeutic target for bronchial asthma. A previous report showed that inhalation of GSH using an ultranebulizer induced bronchoconstriction in mild asthmatic patients; the low pH (3.0) of the GSH solution caused bronchoconstriction in mild asthmatics (62). The effect of GSH on asthmatic patients is not well known using other routes of GSH administration.

Superoxide dismutase (SOD). SOD is present in essentially every cell in the body and has been shown to play an important role in protecting cells and tissues against superoxide anion (66, 67). This antioxidant enzyme decomposes superoxide anion into hydrogen peroxide and oxygen as shown in the following equation:

$$2O_2^- + 2H^+ \rightarrow H_2O_2 + O_2$$

Three types of SODs have been reported (84). All the forms of SODs act by a common mechanism of dismutation of superoxide anion to the less potent hydrogen peroxide. One of the three forms of SODs is Cu,ZnSOD (66, 84). Its molecular weight is 17–28 kDa and it is mainly located in the cytosol. In lungs, it is localized in the bronchial and alveolar epithelium, macrophages, fibroblasts, and pneumocytes. Another form of SOD is MnSOD (84). The molecular weight of this form of SOD is 88 kDa and it is mainly located in mitochondria. It is localized in bronchial epithelium, macrophages, neutrophils, endothelial cells, vascular smooth muscle cells, and pneumocytes. The other form of SOD is an extra-cellular SOD (EC-SOD) (38). Its molecular weight is 135 kDa and it is abundantly present in blood vessels and the airways. It is a secretory, tetrameric glycoprotein and requires Cu and Zn for its activity. The expression of EC-SOD is induced by interferon-γ and depressed by tumor necrosis factor (TNF-α), transforming growth factor-β (TGF-β), and interleukin-1α (IL-1α) in fibroblasts (61). EC-SOD has also been found to be expressed by bronchial epithelial cells, type II pneumocytes, endothelial cells, and alveolar mecrophages (102). Our previous study showed that superoxide anion can cause airway hyper-responsiveness in an animal model (46). Intratracheal administration of xanthine-xanthine oxidase induces airway hyper-responsiveness in cat (46). This airway hyper-responsiveness was suppressed by pretreatment with Cu,ZnSOD, suggesting that the generation of superoxide anion is associated with the formation of airway hyper-responsiveness, which is a major feature of bronchial asthma (8). We also previously showed that exposure to ozone-induced airway hyper-responsiveness to methacholine and SOD reversed the increased airway hyper-responsiveness in cat (106), suggesting that superoxide anion is related to the ozone-induced airway hyper-responsiveness. A previous study showed that the activity of SOD was decreased in the epithelial cells from asthmatic patients compared with healthy subjects (100). Furthermore, the activity of SOD in the BALf from asthmatic patients was decreased compared with healthy subjects (100). The decreased SOD activity may prolong the survival of superoxide anion in the lung tissues. Because superoxide can induce injury of the airway epithelial cells and airway microvascular hyperpermeability, the decreased SOD activity may be associated with the airway inflammation and formation of hyper-responsiveness in asthmatic patients.

Catalase. Catalase is a homotetrameric protein and has a high molecular weight (240 kDa). This antioxidant enzyme decomposes hydrogen peroxide into water and oxygen as shown in the following equation (32):

$$2H_2O_2 \rightarrow 2H_2O + O_2$$

Catalase is ubiquitous in most animal cells. Catalase is located in peroxisomes and in the cytosol and is specially localized in type II pneumocytes and alveolar macrophages (49). A high concentration of catalase exists in the epithelial lining fluid and it is thought to play a protective role against oxidative stress in the lungs (31). When sensitized sheep were exposed to antigen, airway hyper-responsiveness to carbacol was observed. Pretreatment with catalase suppressed the increased airway hyperresponsiveness, suggesting that hydrogen peroxide plays a role in the airway hyper-responsiveness in asthma and catalase may protect against oxidant-induced airway hyper-responsiveness (54).

Glutathione peroxidase. Glutathione peroxidases are a family of selenium-dependent and -independent antioxidant enzymes. These antioxidant enzymes are divided into two forms, cellular and extracellular. Glutathione peroxidase is a 85 kDa protein with a tetrameric structure. It requires four atoms of selenium bound as seleno-cycteine moieties which confer catalytic activity. Glutathione peroxidase reduces hydrogen peroxide to water in the presence of GSH. Glutathione peroxidase has four isoforms. Three are selenium-dependent glutathione peroxidases and the other one is selenium independent. These glutathione peroxidases have been identified in a variety of cells (73) and are ubiquitously present in the cytosol. In asthmatic patients, the levels of glutathione peroxidase in blood are decreased compared to healthy subjects (30). There is increasing evidence that reactive nitrogen species including peroxynitrite are associated with the pathophysiology of bronchial asthma (41, 89). Because selenium-related antioxidants are powerful scavengers of peroxynitrite, glutathione peroxidase may reduce the inflammation of airways in asthmatic patients (98).

Heme oxygenase. Heme oxygenase is a member of the heat-shock protein family that catalyses the degradation of the heme molecule into biliverdin in a reaction that generates carbon monoxide and iron (113). This antioxidant enzyme has cytoprotective effects against oxidative stress. It has been reported that heme oxygenase knockout mice were markedly sensitive to oxidative stress (81). In an asthmatic model, heme oxygenase-1 induced by repeated administration of hemin suppressed the inflammation of the airways (114). The carbon monoxide concentration in the exhaled air from asthmatic patients is significantly elevated compared with healthy subjects (119), suggesting that heme oxygenase may have a protective effect against the oxidative stress in bronchial asthma.

Ascorbic acid. Ascorbic acid is a low molecular weight and water-soluble radical scavenger. Administration of ascorbic acid to asthmatic patients is reported to improve their airway hyper-responsiveness to methacholine and partially block exercise-induced bronchoconstriction (71).

Sources of ROS in lungs

Recruited inflammatory cells and lung resident cells including epithelial cells can produce oxidants. The univalent reaction of oxygen to superoxide anion is the most important step in the production of oxidants. Three major sources of superoxide anion have been identified as follows.

NADPH oxidase system. The generation of superoxide anion is mediated by NADPH as an electron donor in the one-electron reduction of oxygen to produce superoxide anion. NADPH oxidase is a multicomponent enzyme complex, part of which is located in the plasma membrane. Cell fractionation experiments have shown that the dormant oxidase is located in the plasma membrane and that it requires a cytosolic component for activation. The plasma membrane components include a 99 kDa glycosylated subunit and a 22 kDa nonglycosylated subunit. Together, the two subunits are tightly associated and contain a heme group, likely bound to the 22 kDa subunit. These two subunits and heme act as a unit to form the terminal component of the NADPH oxidase, since it directly reduces oxygen to superoxide anion. Another membrane component is a 67 kDa protein, likely a flavoprotein, requiring flavin adenine dinucleotide to function, and it probably acts to convert intracellular NADPH to NADP+. In addition to the membrane components, there are at least two, and probably more, cytoplasmic subunit components. A 47 kDa protein is phosphorylated following stimulation. The second is a 65 kDa protein which migrates from the cytosol to the plasma and phagolysosomal membranes following NADPH activation. Because eosinophils and neutrophils from asthmatic patients can produce more superoxide anion compared to those of healthy subjects (25, 94), NADPH oxidase in asthmatic subjects may be activated.

Xanthine oxidase. Xanthine oxidoreductase (XOR), first identified a century ago in milk, is a highly conserved member of the molybdoenzyme family. XOR has two interconvertible forms, xanthine dehydrogenase (XDH) and xanthine oxidase (XO). Both forms catalyze the conversion of hypoxanthine to xanthine and xanthine to uric acid (UA), the terminal two reactions of the purine degradation pathway. Basal expression of the XOR gene is mediated by several transcription factors including C/EBP, ETS-1, AP-1, AP-2, and TF-IID (115). Although the basal expression of XOR is low, a variety of factors including hypoxia, lipopolysaccharide (LPS), IFN-γ, IL-1, IL-6, TNF-α, and steroids upregulate the transcription (27). In an asthmatic model, the XOR activity was upregulated in the lung during the late allergic response phase (105). Moreover, an XOR inhibitor, {4-amino-6-hydroxypyrazolo(3,4-d)pyrimidine}(AHPP), suppressed allergen-induced microvascular hyperpermeability during LAR, suggesting that XOR may be associated with the extravasation induced by allergen challenge.

Mitochondrial respiration chain. The third major pathway for the generation of superoxide anion is the mitochondrial respiration chain. Mitochondrial superoxide anion can be generated from several sites in the respiration chain. The matrix side of the organelle associated with complex I, complex III, and the Q pool can generate superoxide anion in mitochondria. Superoxide may have a direct interaction with some

targets such as aconitase that may contribute to cell signaling through the release of iron from the enzyme. In bronchial asthma, the role of mitochondrial superoxide anion has not been well clarified. Because eosinophils from asthmatic patients can generate more superoxide anion than those from healthy subjects, the generation of superoxide anion from mitochondrion may be upregulated.

RNS AND BRONCHIAL ASTHMA

NO in the respiratory system

NO has a variety of physiological effects in mammalian cells (43, 72). In the respiratory system, endogenous NO plays a key role in the physiological regulation of the airway function. NO and related compounds are produced by a wide variety of residential and inflammatory cells in the respiratory system. NO is generated via a five-electron oxidation of a terminal guanidinium nitrogen on the amino acid L-arginine. The reaction is both oxygen- and NADPH-dependent and yields the coproduct L-citrulline. This reaction is catalyzed by three isoforms of NO synthase (NOS). Neural NOS (NOS-I or nNOS) and endothelial NOS (NOS-III or eNOS) are both the constitutive type of NOS. The inducible type of NOS (NOS-II or iNOS) is upregulated by various cytokines, such as TNF-α, IFN-γ, and IL-1β, and can generate more NO compared with the constitutive type of NOS. The NO-generating cell types in lungs are listed in Table 2. In inflammatory sites, superoxide anion can be generated at the same time. It has been reported that NO reacts with superoxide anion very rapidly ($k = 6.7 \times 10^9$ $M^{-1}S^{-1}$) and forms peroxynitrite (10, 82). RNS are also formed via the H2O2/peroxidase-dependent nitrite oxidation pathway (28). These RNS cause airway inflammation (105), namely the activation of matrix metalloproteinase (MMP) (75), and an enhancement of the production of the proinflammatory cytokine TNF-α (65). Therefore, RNS may be involved in the pathophysiology of the inflammatory process of bronchial asthma.

Table 2. Localization of Nitric Oxide Synthases (NOS) in Human Lungs

Isoforms	*Localization*
NOS I	Neurons (ganglion, trachea, and bronchus)
	Airway epithelial cells
	Neutrophils
NOS II	Macrophages
	Airway epithelial cells
	Type II pheumocytes
	Endothelial cells
	Fibroblasts
	Vascular smooth muscle cells
	Neutrophils
	Eosinophils
	Mast cells
NOS III	Endothelial cells
	Airway epithelial cells
	Platelets

Role of NOS in bronchial asthma

NO derived from cNOS plays a physiological role in the respiratory system. NO derived from NOS I is thought to partly regulate the airway smooth muscle tone. In the pulmonary vasculature, the role of NO from NOS III has been controversial. Conversely, NO derived from NOS II is thought to play a critical role in the airway inflammation. The role of each NOS is reviewed in this section.

NOS I. The inhibitory nonadrenergic noncholinergic (iNANC) nerve is the only neural bronchodilator system in human airways, where its bronchodilatory function has been demonstrated *in vitro* by electrical field stimulation (EFS) (108), as well as *in vivo* by reflex stimulation (42). The neurotransmitter of this nervous system has been suggested to be vasoactive intestinal peptide (VIP) or other related peptides in several species, since these peptides have a potent bronchodilatory action. NO has also been recognized as a transmitter of iNANC nerves distributed in various organs (110), including airways (110), by functional studies using inhibitors for NOS. Histochemically, colocalization of nicotinamide adenine dinucleotide phosphate (NADPH)-diaphorase activity, a marker for the nervous system, was used to demonstrate the existence of NOS I in guinea pig airways. In guinea pig airways, both NO and VIP have been reported to functionally mediate iNANC relaxation (57). In human airways, NO is thought to mainly mediate iNANC responses (11). This bronchodilatory function of iNANC may be impaired in asthmatic airways. According to our previous report, the bronchodilatory function of iNANC by EFS in the tracheas from antigen-challenged guinea pigs was impaired, compared to control animals (70). Furthermore, the impaired bronchodilatory function of iNANC was restored by pretreatment with SOD, suggesting that excessively produced superoxide anion inactivates the bronchodilatory action of NO derived from NOS I (70).

NOS III. Some studies showed that NO derived from NOS III regulated the pulmonary vascular tone in various species (34). These findings are based on studies using NOS inhibitors. However, other studies showed that even the highest doses of NOS inhibitor did not show any vasoconstriction in pulmonary vasculatures. In human, Stamler *et al*. reported that L-NMMA caused pulmonary vasoconstriction in healthy human volunteers (101). However, the effect of NOS inhibitors was more dominant in the systemic circulation than in the pulmonary circulation (34). Data obtained from *in vitro* human preparations are also inconclusive (23). Taken together, the role of NO derived from NOS III has not been fully elucidated yet.

NOS II. In various inflammatory lung diseases including asthma, chronic obstructive pulmonary diseases (COPD), idiopathic pulmonary fibrosis (IPF), and cystic fibrosis, iNOS is reported to be upregulated in the airways and lungs. iNOS gene is stimulated by various proinflammatory cytokines. In asthmatic individuals, increased levels of exhaled NO have been found (47). In asthmatic airways, the expression of iNOS was enhanced in pathological examinations (33). Increased expression of iNOS was seen in infiltrated inflammatory cells and macrophages, and the increased expression was corticosteroid

sensitive (91). Because steroids can suppress both iNOS expression and the exhaled NO levels, the increasing NO levels in expired air from asthmatic patients is thought to be derived from iNOS. This result is supported by the fact that inhalation of a relatively specific inhibitor of iNOS, SC-51, reduced the expired NO levels in asthmatic individuals (35). We previously showed that iNOS immunopositive cell counts in induced sputum had a significantly positive correlation with the NO levels in exhaled air in asthmatic patients (Fig. 2) (41). These results suggest that the enhanced iNOS expression in the airways of asthmatic patients is responsible for the increased NO levels in expired air. According to previous studies, exhaled NO may reflect the clinical control of asthma, particularly during exacerbations (64).

Nitrative stress and airway inflammation in bronchial asthma

Our previous report showed that nitrative stress could induce airway inflammation during the late allergic phase in an antigen-challenged guinea pig model (105). During the late phase, the NO levels in antigen-challenged animals significantly increased compared to control animals. A nonspecific NOS inhibitor, L-NAME, and the peroxynitrite scavenger, ebselen, inhibited the antigen-induced microvascular hyperpermeability, suggesting that nitrative stress may contribute to the airway inflammation in bronchial asthma. Moreover, exogenously administered peroxynitrite stimulated the release of toxic granules from eosinophils (95). In addition, because eosinophil cationic protein and major basic protein from eosinophils can cause tissue injury (22) and muscarinic 2 (M2) receptor dysfunction (56), RNS may be responsible for the airway inflammation in asthma through eosinophil activation.

Nitrative stress and airway hyper-responsiveness in bronchial asthma

To clarify the role of iNOS in the airway hyper-responsiveness in asthmatic airways, we investigated further by using an asthmatic mouse model. We showed that iNOS was upregulated after antigen challenge in sensitized mice (Fig. 3) (50). Furthermore, we showed that both pharmacological blockade of iNOS (50) and depletion of iNOS gene (51) also inhibited the antigen-induced airway hyper-responsiveness in mice. In iNOS knockout mice, nitrotyrosine formation, which is a footprint of RNS, was completely diminished. Furthermore, Sadeghi–Hashjin *et al*. showed that exogenously administered peroxynitrite induced airway hyper-responsiveness *in vivo* and *in vitro* (95). Taken together, nitrative stress appears to cause airway hyper-responsiveness in bronchial asthma. In humans, we reported that the exhaled NO level significantly correlated with the baseline FEV1 values in steroid naïve asthmatic patients (40). Treatment with inhaled corticosteroids was associated with a reduction in the NO levels in exhaled air and an improvement in FEV1 and airway hyper-responsiveness, suggesting that exhaled NO can serve as a marker of airway inflammation and is associated with the airway caliber and hyper-responsiveness induced by the airway inflammation.

Nitrative stress and airway remodeling in bronchial asthma

Excessive production of NO during inflammatory and immune processes leads to the formation of RNS including peroxynitrite and nitrogen dioxide (NO_2). These RNS are formed from NO and superoxide anion or via the H_2O_2/peroxidase-dependent nitrite oxidation pathway. In inflammatory condi-

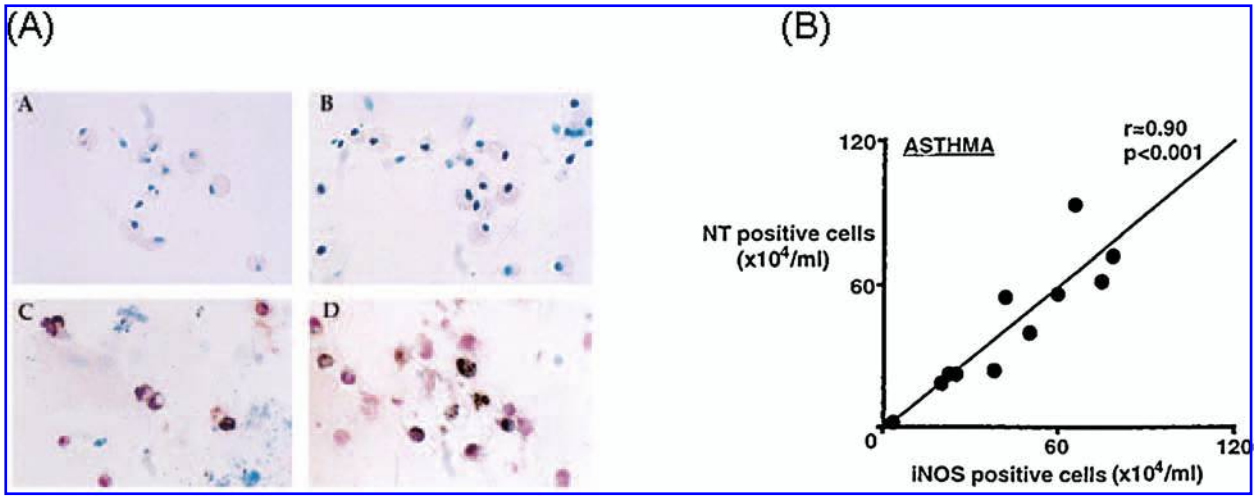

FIG. 2. Immunocytostaining of the inducible type of nitric oxide synthase (iNOS) and nitrotyrosine. (**A**) Representative photographs of immunocytostaining of iNOS (*left panels*) and nitrotyrosine (*right panels*) from healthy (*upper panels*) and asthmatic subjects (*lower panels*) are shown. Relation of iNOS-positive cell counts to nitrotyrosine (NT)-positive cell counts in induced sputum from asthmatic subjects (**B**). R is correlation coefficient; the line and *p* value correspond to the fitted regression equation. Excerpted with permission Ichinose M, Sugiura H, Yamagata S *et al*. *Am J Respir Crit Care Med* 2000; 162: 701–706. Copyright 2000 American Thoracic Society.

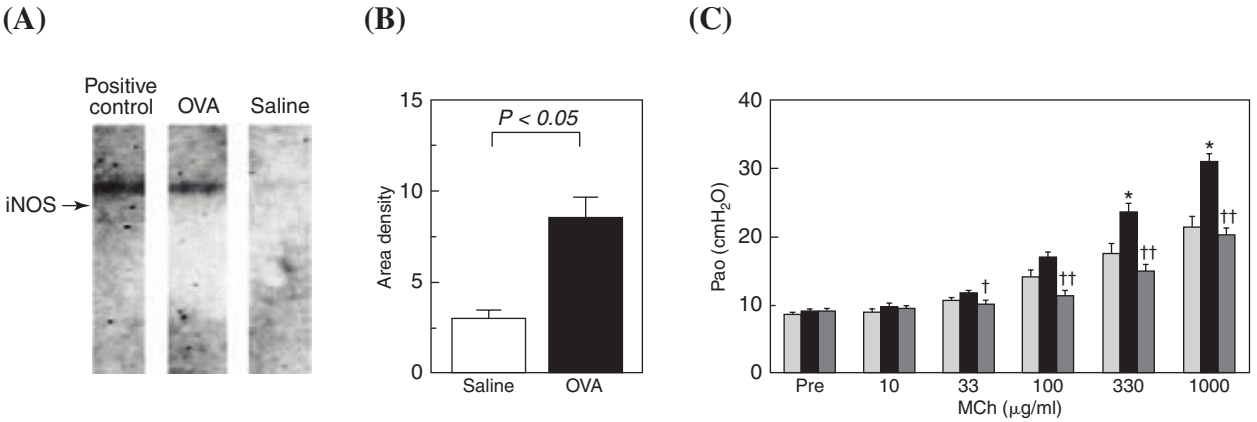

FIG. 3. Inducible type of nitric oxide synthase (iNOS) expression during late phase allergic reaction in mice and effect of the specific iNOS inhibitor, 1,400 W, on airway hyper-responsiveness. (**A**) Immunoblot analysis of the expression of iNOS in airway tissue isolated from sensitized mice. Positive control: sample of mice macrophage lysates stimulated with interferon-γ (IFN-γ) and lipopolysaccharide (LPS); OVA: 24 h after ovalbumin (OVA) challenge; saline: 24 h after saline exposure. (**B**) Quantification of the intensity of the bands by densitometry. Lanes are the same as in (**A**). (**C**) Effect of 1,400 W on airway hyper-responsiveness after OVA challenge in sensitized mice. Airway responsiveness was assessed by means of airway opening pressure (Pao) measurement after intravenous methacholine (MCh) administration. $*p < 0.01$ compared with the saline-pretreated saline challenged mice. $+p < 0.05$ and $++p < 0.01$ compared with the saline-pretreated OVA-challenged mice. Each value indicates mean + SEM. *Open bars*: saline-pretreated saline-challenged; *filled bars*: saline-pretreated OVA-challenged; *hatched bars*: 1,400 W-pretreated OVA-challenged. Excerpted with permission, Koarai A, Ichinose M, Sugiura H *et al*. *Pulm Pharmacol Ther* 2000; 13: 267–275. Copyright 2000 Elsevier Ltd.

tions where superoxide anion is generated, NO is rapidly consumed by reacting with superoxide to produce highly reactive peroxynitrite. Peroxynitrite is an extremely powerful oxidant and is presumed to be largely responsible for many of the adverse effects of the excessive generation of NO. Excessive production of RNS causes tissue injury, lipid peroxidation, and nitration of tyrosine residues. Consistent with the role of this pathway in disease, excessive production of 3-nitrotyrosine has been observed in various inflammatory lung diseases, including bronchial asthma (33, 91, 103), COPD (37, 103), and IPF (90). Inflammatory processes are frequently accompanied by alterations in the tissue structure. Such alterations may result from tissue damage due to active proteases or toxic moieties released by inflammatory cells. In addition, mediators released at inflammatory sites are capable of directly altering the cell function, leading to tissue repair and remodeling. The production of RNS causes tissue injury, but whether RNS can affect tissue repair and remodeling remains unknown. Recently, we reported the effect of peroxynitrite on tissue remodeling by using a collagen gel contraction assay model mediated by human lung fibroblasts *in vitro* (104). As shown in Fig. 4, exogenously administered peroxynitrite augmented fibroblast-mediated collagen gel contraction in a dose-dependent manner. Peroxynitrite also stimulated the production of TGF-β_1, fibronectin, and vascular endothelial growth factor (VEGF), which are thought to play critical roles in lung tissue remodeling (104). Furthermore, treatment with peroxynitrite augmented the chemotaxis of fibroblasts toward fibronectin through augmenting the expression of integrins, which are receptors for fibronectin (104). The augmented collagen gel contraction, mediator production, and chemotaxis were reversed by treatment with neutralizing anti-TGF-β antibody (104). These results suggest that peroxynitrite or other RNS may cause tissue remodeling through TGF-β_1 activation. In fact, TGF-β_1 is a key mediator in a variety of physiological and pathological processes, including fibroblast repair responses. TGF-β

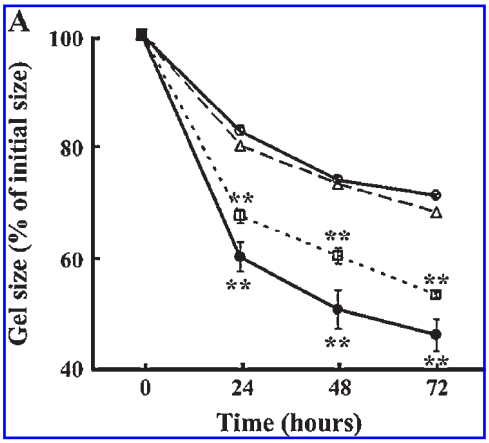

FIG. 4. Effect of authentic peroxynitrite on collagen gel contraction by human fetal lung fibroblasts (HFL-1). Fibroblasts were cast into three-dimensional collagen gels and floated in medium containing various concentrations of peroxynitrite. Gel size was measured daily. When the gel size becomes smaller, the fibroblast-mediated tissue remodeling is augmented. *Vertical axis*: gel size (% of initial size); *horizontal axis*: time. $**p < 0.01$; compared with the values of control. *Open circles*, control; *triangles*, 0.1 μM peroxynitrite; *squares*, 1 μM peroxynitrite; *filled circles*, 10 μM peroxynitrite. Excerpted with permission, Sugiura H, Liu X, Kobayashi T *et al*. *Am J Respir Cell Mol Biol* 2006; 34: 592–599. Copyright 2006 American Thoracic Society.

TABLE 3. OXIDATIVE AND NITRATIVE STRESS IN LUNG TISSUES

Target tissue and cells	*Effects of ROS and RNS*
Epithelial cells	Injury
	Proinflammatory mediators production
Mucus glands	Mucus hypersecretion
Airway micro vessels	Plasma leakage
	Edema
	Vasodilatation
	Neovascularization
Sensory nerves	Activation
Inhibitory nonadrenergic noncholinergic nerves	Inactivation
Fibroblasts	Activation
	Augmentation of migration
Airway smooth muscle cells	Contraction
Inflammatory cells	Mediator production and secretion
	MMP activation

ROS, reactive oxygen species; RNS, reactive nitrogen species; MMP, matrix metalloproteinase.

regulates the fibroblast migration, proliferation, differentiation, and production of matrix and soluble factors. In addition, TGF-β stimulates the fibroblast-mediated contraction of the extracellular matrix. Through these actions, TGF-β is believed to be a major regulator of tissue remodeling. Among the mediators induced by TGF-β are fibronectin (117) and VEGF (112). Fibronectin can form a provisional extracellular matrix following injury and is a potent chemoattractant for fibroblasts. VEGF is a multifunctional cytokine that stimulates endothelial cell mitogenesis and migration and modulates the endothelial permeability. The production of VEGF, therefore, could play a role in the neovascularization that characterizes tissue repair following injury. In fact, the production of these mediators was augmented in asthmatic airways and excessive extracellular matrix deposition was observed in the basement membrane in the airways of asthmatic patients (29). Therefore, nitrative stress may contribute to the formation of the airway remodeling observed in asthmatics, especially in refractory asthmatic patients.

NITRATIVE STRESS AND REFRACTORY ASTHMA

Asthma is a disorder characterized by chronic inflammation of the airways, airflow obstruction, and airway hyperreactivity. Most asthmatic patients are well controlled by low doses of anti-inflammatory agents with or without bronchodilators. However, 5–10% of asthmatic patients have more troublesome disease, reflected by a higher medication requirement to maintain good disease control or persistent symptoms and disease exacerbation, airflow obstruction, or low quality of life in spite of using high doses of steroids (3). To describe this subgroup of asthmatic patients with troublesome disease, the term "refractory asthma" has been used (3). It has been reported that individuals with refractory asthma are 15 times more likely to use emergency medical care than well-controlled asthmatic patients and are 20 times more likely to require hospital admission (97). Furthermore, these individuals with refractory asthma also have greater absenteeism from work on account of their

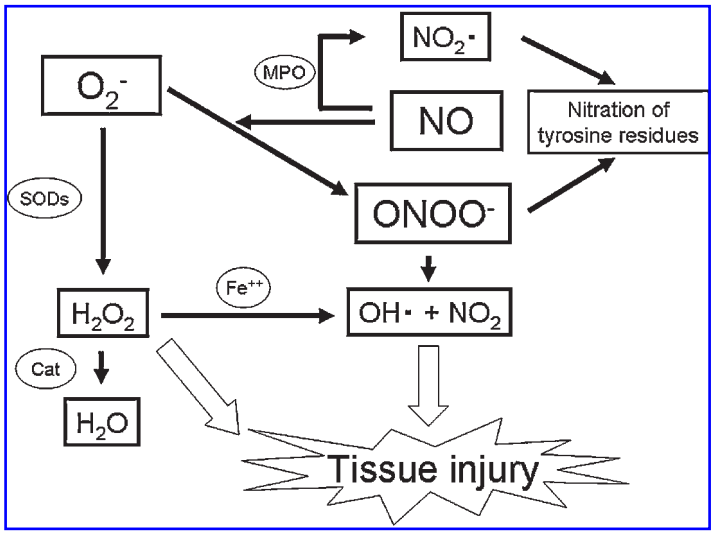

FIG. 5. Crosstalk between reactive oxygen species and reactive nitrogen species. Cat, catalase; Fe^{++}, ferrous ion; H_2O_2, hydrogen peroxide; MPO, myeloperoxidase; NO, nitric oxide; $NO_2^{\bullet}$, nitrogen dioxide radical, NO_2, nitrogen dioxide; $OH^{\bullet}$, hydroxyl radical; O_2^-, superoxide anion; $ONOO^-$, peroxynitrite, SODs, superoxide dismutases.

disease. However, there has been little information on the pathophysiological mechanisms responsible for refractory asthma. Understanding the differences in the airway inflammation between refractory and well-controlled asthma could therefore be important for determining the mechanisms responsible for refractory asthma. Recently, we investigated the differences in oxidative and nitrative stress among healthy subjects, well-controlled asthmatic subjects, and refractory asthmatic subjects. Oxidative stress and nitrative stress were enhanced in the refractory asthmatic group (unpublished data). Steroids have a number of anti-inflammatory actions, including the suppression of iNOS expression. In this study, steroids could not suppress iNOS expression or 3-nitrotyrosine formation in the sputum from patients with refractory asthma even at high doses. Recently, Ito and co-workers reported that peroxynitrite reduced the histone deacetylase 2 (HDAC 2) activity in epithelial cells through the nitration of tyrosine residues in HDAC 2 (45). A reduction of HDAC 2 activity could contribute to the worsening of inflammation through the excessive production of proinflammatory cytokines including IL-1β and IL-8 (1). They also showed that the HDAC 2 activity was decreased in asthmatic patients and patients with COPD (1). Inhibition of HDAC 2 was reported to interfere with glucocorticoid receptor-activated transcription (1). Taken together, it may be possible that an inactivation of HDAC 2 by excessive RNS occurs in refractory asthma. Moreover, since RNS may be associated with tissue remodeling as mentioned before, oxidative and nitrative stress may contribute to the refractoriness to steroid therapy in refractory asthmatic patients.

SUMMARY

The composite role of ROS and RNS in the lung pathology of asthma is shown in Table 3. Asthma is associated with increased levels of ROS and RNS due to the activation of infiltrated inflammatory cells and resident cells stimulated by proinflammatory mediators. Numerous reports have shown that oxidative and nitrative stress can cause airway inflammation and hyper-responsiveness which are the most important features of asthma. Because of excessive oxidative and nitrative stress, an imbalance of oxidants and antioxidants occurs in the airways of asthma. Interactions between ROS and RNS are summarized in Fig. 5. ROS and RNS may stimulate some transcription factor activities and change the transcription of proinflammatory cytokines. ROS and RNS appear to be related to the airway remodeling and refractoriness to steroids. Blockers or scavengers of ROS and RNS may become therapeutic targets in the future.

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ABBREVIATIONS

ACE, angiotensin converting enzyme; BALf, bronchoalveolar lavage fluid; BK, bradykinin; COPD, chronic obstructive pulmonary disease; COX, cyclooxygenase; EFS, electrical field stimulation; GSH, glutathione; HDAC, histone diacetylase; HFL, human fetal lung fibroblast; IFN, interferon; IL, interleukin; iNANC, inhibitory nonadrenergic noncholinergic; IPF, idiopathic pulmonary fibrosis; LAR, late allergic response; LPS, lipopolysaccharide; LT, leukotrien; MCh, methacholine, MMP, matrix metalloproteinase; NEP, neutral endopeptidase; NF-kB, nucleus factor kappa B; NO, nitric oxide; NOS, nitric oxide synthase; NT, nitrotyrosine; OVA, ovalbumin; PAF, platelet activating factor; Pao, airway opening pressure, PG, prostaglandin; RNS, reactive nitrogen species; ROS, reactive oxygen species; SOD, superoxide dismutase; SP, substance P; TGF, transforming growth factor; TNF, tumor necrosis factor; Tx, thromboxane; UA, uric acid; VEGF, vasoactive endothelial growth factor; VIP, vasoactive intestinal peptide; XDH, xanthine dehydrogenase; XO, xanthine oxidase; XOR, xanthine oxide reductase.

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Address reprint requests to:
Masakazu Ichinose, M.D., Ph.D.
Third Department of Internal Medicine
Wakayama Medical University School of Medicine
811-1 Kimiidera
Wakayama City
Wakayama 641-0012, Japan

E-mail: masakazu@wakayama-med.ac.jp

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