The role of oxidative stress in COPD:
current concepts and perspectives*

O papel do estresse oxidativo na DPOC: conceitos atuais e perspectivas

Antonio George de Matos Cavalcante, Pedro Felipe Carvalhedo de Bruin

Abstract
Worldwide, COPD is a major cause of morbidity and mortality. The clinical and functional manifestations of COPD result from lung injury occurring through various mechanisms, including oxidative stress, inflammation, protease-antiprotease imbalance and apoptosis. Oxidative stress is central to the pathogenesis of COPD, since it can directly damage lung structures and exacerbate the other mechanisms involved. The cellular and molecular events involved in such lung injury are believed to occur long before the clinical and functional expression of COPD. Although the use of bronchodilators is currently the principal treatment for COPD, bronchodilators have little or no effect on disease progression. A better understanding of the pathogenesis of COPD, together with renewed efforts in basic and clinical research, will allow the diagnosis of COPD at a pre-clinical stage and provide more appropriate monitoring of disease activity, as well as leading to the development of novel therapeutic agents that will effectively prevent the progression of the disease.

Keywords: Pulmonary disease, chronic obstructive; Oxidative stress; Oxidants; Antioxidants; Inflammation.

Introduction
Worldwide, COPD is a health problem with severe economic and social repercussions; at the personal level, COPD constitutes a major cause of patient disability and of low quality of life for patients and their caregivers.\(^1\)\(^2\) According to the World Health Organization, 80 million people suffer from moderate or severe COPD.\(^3\) In Brazil, the prevalence of COPD in large urban centers such as the city of São Paulo ranges from 6% to over 15%, depending on the diagnostic criteria adopted.\(^4\) The fifth leading cause of death worldwide, COPD will have reached, according to recent estimates, the third position by 2030.\(^5\) The increase in the mortality rate for COPD contrasts with the marked reduction in the mortality rate for diseases such as cancer,
Free radicals and reactive species

Free radicals are atoms, groups of atoms or molecules that have unpaired electrons on the outer orbital, which explains their instability and high reactivity. However, the term free radical is not ideal to describe the group of reactive pathogenic species, because some of them do not have unpaired electrons on the outer orbital, although they participate in redox reactions. Therefore, the terms reactive oxygen species (ROS) and reactive nitrogen species (RNS) are considered to be more appropriate because they better describe these chemical agents.

The ROS are found in all biological systems and originate from the metabolism of molecular oxygen \( \text{O}_2 \). Under physiological conditions, \( \text{O}_2 \) undergoes reduction by accepting four electrons, which results in the formation of water. During this process, reactive intermediates such as the superoxide \( \text{O}_2^- \) radical, the hydrogen peroxide \( \text{H}_2\text{O}_2 \) radical and the hydroxyl \( \text{OH}^- \) radical are formed (Figure 1). Most of the RNS are formed from the synthesis of nitric oxide (NO) through the conversion of L-arginine into L-citrulline by nitric oxide synthases.

The production of reactive species is an integral part of metabolism and is present under normal conditions, notably in the physiological processes involved in the production of energy, regulation of cell growth, phagocytosis, intracellular signaling and synthesis of important substances, such as hormones and enzymes. In order to offset this production and its potential negative effects, the body has an antioxidant system. In situations in which there is an imbalance between the pro-oxidant system and the antioxidant system (and oxidants predominate), oxidative stress occurs.

Endogenous and exogenous sources of reactive species

Due to the fact that the respiratory tract is in direct contact with the external environment...
The role of oxidative stress in COPD: current concepts and perspectives

J Bras Pneumol. 2009;35(12):1227-1237

1229

...exposed to high concentrations of oxygen, it is a major target of injury caused by oxidants of endogenous or exogenous origin.\(^{(18,19)}\)

The reactive species of endogenous origin are generally produced through enzymatic and non-enzymatic reactions of electron transfer. The principal cellular sites and processes that generate oxidants are the mitochondria, the microsomes, the xanthine/xanthine oxidase system and, on a larger scale, NADPH oxidase.\(^{(19,20)}\) In the respiratory tract, the principal endogenous sources of oxidants are alveolar macrophages, epithelial cells, endothelial cells and recruited inflammatory cells such as neutrophils, eosinophils, monocytes and lymphocytes.\(^{(18)}\) The activation of these cells results in the formation of \(O_2^-\), which is rapidly converted into \(H_2O_2\) by the enzyme superoxide dismutase (SOD). Through a non-enzymatic secondary reaction, \(H_2O_2\) forms, in the presence of iron, \(OH^-\) (Fenton reaction).\(^{(19)}\) The reactive species produced by phagocytes are the principal cause of the tissue injury associated with chronic inflammatory lung diseases.\(^{(18)}\) The exogenous oxidants originate from air pollutants such as ozone, nitric dioxide, sulfur dioxide and, in particular, cigarette smoke. Cigarette smoke contains approximately five thousand toxic compounds, including potent oxidants (approximately \(10^{14}\) free radicals per inhalation) such as acrolein, \(H_2O_2\), \(OH^-\) and organic free radicals.\(^{(18)}\)

Antioxidants

According to their structure, antioxidants can be classified as enzymatic or non-enzymatic. The principal components of the enzymatic antioxidant system are SOD, catalase and glutathione peroxidase (GPx), which are active at the beginning of the reaction through which reactive species are formed, and this avoids the accumulation of \(O_2^-\) radicals and \(H_2O_2\) radicals. Non-enzymatic antioxidants include compounds produced in vivo, such as reduced glutathione (GSH), ubiquinone, uric acid and the proteins that transport transition metals (transferrin and ceruloplasmin), and compounds obtained directly from the diet, such as beta-carotene, vitamin C and vitamin E.\(^{(21,22)}\)

The principal antioxidants in respiratory tract lining fluid include mucin, GSH, uric acid, proteins (especially albumin) and ascorbic acid.\(^{(22)}\) Information regarding the antioxidant defense system in the respiratory epithelium of smokers and COPD patients remains scarce. Chronic smokers present elevated levels of GSH in the bronchoalveolar lavage fluid. However, this increase in GSH levels might not be enough
products. Due to this characteristic, melatonin is sometimes referred to as a terminal or suicidal antioxidant.

**Oxidative stress and etiopathogenic mechanisms of COPD**

Cigarette smoke is the principal environmental factor for the development of COPD. However, the rate of decline in pulmonary function in smokers varies, and only approximately 25% will develop a clinical expression of the disease, suggesting that the pathogenesis of COPD depends on the interaction between environmental and genetic factors.

Emphysema due to alpha-1 antitrypsin deficiency is the only form of expression of COPD that is associated with alterations in a single gene and that does not require interaction with environmental factors. All the other cases of the disease seem to result from molecular alterations that are due to a complex interaction between multiple genes and environmental factors. The genes associated with the alterations observed in COPD include those related to the protease-antiprotease system, antioxidants, inflammation and apoptosis.

Oxidative stress plays an important role in the pathogenesis of COPD through direct injury to the respiratory tract, as well as through exacerbation of the other mechanisms involved (Figure 2).

![Figure 2](image-url)
**Oxidative stress and lipid peroxidation**

Lipid peroxidation basically consists of the incorporation of molecular oxygen into a polyunsaturated fatty acid, resulting in oxidative degradation of the latter. Cell membrane phospholipids are particularly susceptible to peroxidation. This leads to alterations in the structure and permeability of the membrane, resulting in loss of ion-exchange selectivity, release of the contents of organelles, such as the hydrolytic enzymes of the lysosomes, and formation of cytotoxic products, such as malondialdehyde (MDA).

In eukaryotic cells, cell membrane phospholipids can be hydrolyzed by the phospholipase enzyme, producing nonesterified arachidonic acid, which can undergo peroxidation through two pathways: the enzymatic pathway, involving cyclooxygenases and lipoxygenases, and the non-enzymatic pathway, through the participation of ROS, RNS, transition metals and other free radicals (Figure 3). The end products of the lipid peroxidation mediated by reactive species include 4-hydroxynonenal (4-HNE), MDA and isoprostanes. One isoprostane that has been extensively studied as a marker of pulmonary and systemic oxidative stress is 8-iso-prostaglandin F2α (8-isoprostane).

In addition to their importance as markers of oxidative stress, isoprostanes, particularly 8-isoprostane, have various biological effects and are considered to be mediators of oxidative damage. Among the various biological activities of 8-isoprostane is the contraction of the smooth muscles of the bronchi, which is why 8-isoprostane has been reported as being one of the mediators of the reversible component of the obstruction observed in most patients with COPD.

**Modification of proteins and DNA**

In eukaryotic cells, a protein seldom performs its functions in the form in which it was originally transcribed. After leaving the ribosomes, proteins often undergo modifications, known as post-translational modifications, considered essential to their activity. In addition to these physiological modifications, proteins are subject to a range of modifications produced by reactive species under pathological conditions. These oxidative modifications can inactivate the enzymatic functions and cause structural degeneration of the proteins or activate transcription factors and proteolytic systems.

Markers of oxidative stress and DNA damage are significantly higher in patients with COPD, especially in those whose causative factor is smoking. Patients with COPD present a high incidence of lung neoplasia, and DNA modifications induced by the reactive species might be the link between these two conditions.

**Oxidative stress and inflammation**

Smokers without COPD present a mild inflammatory response that probably represents a defense reaction of the mucosa against the chronic inhalation of irritants. In individuals who develop COPD, there is a marked exacerbation of

![Figure 3](image-url) - Arachidonic acid can be metabolized via the enzymatic pathway, through cyclooxygenases and lipoxygenases, or via the non-enzymatic pathway, through redox processes.
the inflammatory response, which increases with the progression of the disease.\textsuperscript{31,32} The molecular mechanism of this exacerbation remains unknown; however, genetic factors, latent viral infections and prolonged oxidative stress have been reported as being potentially responsible for the exacerbation.\textsuperscript{10,33} Chronic inflammation in COPD is associated with an increase in the production of various mediators and proinflammatory proteins, including cytokines, chemokines, inflammatory enzymes, receptors and adhesion molecules, which are regulated by gene transcription factors.\textsuperscript{10,33} Among the mediators, those that are chemotactic for inflammatory cells, in particular leukotriene B4 and IL-8, as well as proinflammatory cytokines, such as TNF-\(\alpha\), IL-1\(\beta\) and IL-6, are noteworthy.\textsuperscript{33} Growth factors, including TGF-\(\beta\), which induces fibrosis in the small airways, are also considered important.\textsuperscript{33} The most important cellular elements in the inflammation in COPD are epithelial cells, neutrophils, alveolar macrophages, CD8 lymphocytes and, during periods of exacerbation, eosinophils.\textsuperscript{10,33}

Cell response to stimuli depends on a complex signaling process. The stimuli of the extracellular medium are transmitted to the intracellular medium through an organized sequence of reactions, part of which are dependent on redox reactions, generally referred to as redox-sensitive signaling.\textsuperscript{19,34} Under physiological conditions, the control of redox-sensitive signaling involves a temporary deviation from the redox state toward an increase in the concentration of oxidants. These small oxidative episodes generate low cellular concentrations of ROS when stimulated by substances such as cytokines (IL-1, IL-6, IL-3 and TNF-\(\alpha\)), angiotensin II and growth factors.\textsuperscript{19} The signals for the elements responsible for the expression of certain genes are normally transmitted to the nucleus by a class of proteins known as transcription factors. This process of signaling transduction results in biological functions such as muscle contraction, gene expression, cell growth and nervous transmission. Therefore, the initiation and correct functioning of various transduction pathways depend on ROS as signaling molecules, which act as a second messenger.\textsuperscript{19} Under pathological conditions, however, abnormally high concentrations of ROS in the cells might lead to permanent changes in signaling transduction and gene expression, as observed in chronic inflammatory diseases, including COPD.

Gene expression might be influenced by the enzymes histone acetyltransferases (HATs) and histone deacetylases (HDACs). The acetylation of lysine residues at the N-terminus of these proteins, catalyzed by HATs, removes positive charges and therefore reduces the DNA affinity of these proteins, making chromatin less compact and more accessible to transcription factors and RNA polymerase. Conversely, deacetylation, catalyzed by HDACs, makes chromatin more compact and less accessible (Figure 4). Consequently, in most cases, HATs intensify transcription, whereas HDACs repress it. Intracellular oxidative stress promotes the activation of the encoding genes of various proinflammatory proteins through two mechanisms: first, by activating the enzyme 1 kappa B kinase, which degrades the inhibitor protein complex known as inhibitor of kappa B, promoting the release of the nuclear factor NF-kappa B; and second, by inactivating the enzyme histone deacetylase 2 (HDAC2), allowing a greater degree of acetylation of the protein by the HAT enzyme, resulting in chromatin decompaction and allowing transcription factors greater access to genes.\textsuperscript{19,31,35}

The suppression of proinflammatory genes by glucocorticoids is due, in part, to the recruitment of the enzyme HDAC2, which promotes the compaction of chromatin, thus preventing the transcription of proinflammatory proteins. As mentioned previously, the inflammation in COPD is relatively insensitive to treatment with corticosteroids. One of the mechanisms proposed to explain this relative resistance is the reduction in the levels of the enzyme HDAC2 through oxidative degradation induced by reactive species such as peroxynitrite (ONOO\(^-\)), acrolein and 4-HNE.\textsuperscript{9,35} The alveolar macrophages of patients with COPD present reduced concentrations of HDAC2 when compared with the macrophages of individuals with normal lung function, and this reduction is correlated with insensitivity to corticosteroids. The restoration of the expression of HDAC2 reverses this resistance.\textsuperscript{36}

**Oxidative stress and protease-antiprotease imbalance**

There is strong evidence that an imbalance between proteases and endogenous
antiproteases plays an important role in the pathogenesis of COPD. Among the factors that contribute to this imbalance are oxidative stress, genetic polymorphism and an abnormal inflammatory response to the respiratory tract injury caused by smoking.\(^{[33,37,38]}\)

Three classes of proteases are considered relevant to the etiopathogenesis of COPD: serine proteases, which can degrade elastin and certain forms of collagen; cysteine proteases, which degrade matrix components; and matrix metalloproteinases, which act on collagen, gelatin and laminin. Each of these classes of enzymes can be inhibited by one or more antiproteases.

Oxidants can potentiate the effects of proteases on COPD through the activation of these enzymes. Reactive species increase the activity of matrix metalloproteinases by activating metalloproteinase precursors. The oxidation of methionine residues at active sites of alpha-1 antitrypsin results in a dramatic reduction in their in vitro inhibitory ability; therefore, this pathway has been reported as being one of the possible causes of the imbalance in favor of proteases.\(^{[33,37,38]}\)

**Oxidative stress and apoptosis**

Recent studies have highlighted the importance of apoptosis in the pathogenesis of COPD.\(^{[38,39]}\) It is believed that an increase in the apoptosis of the epithelial and endothelial cells of the lungs, not offset by an increase in the proliferation of these cells, results in tissue destruction and in the development of emphysema.

There is evidence that VEGF is necessary for the maintenance of the cellular structure of the lungs.\(^{[40]}\) In fact, VEGF represents a subfamily of growth factors derived from the platelets that bind to three sets of receptors: VEGFR-1, VEGFR-2 and VEGFR-3. The binding of VEGF to VEGFR-2 receptors stimulates endothelial cells and type II pneumocytes, promoting their development and increasing their survival. The interruption of the VEGF signaling to VEGFR-2 receptors results in arrested lung development,
which manifests clinically as bronchopulmonary dysplasia in children and as emphysema in adults.\(^{(43)}\)

Human emphysema might be associated with a reduced expression of the encoding gene of VEGF. A rat model of emphysema induced by VEGF blockade demonstrated that apoptosis predominates in lung areas under oxidative stress and that the experimental blockade of apoptosis markedly reduced the expression of oxidative stress markers. The administration of compounds with antioxidant activity can prevent the development of alveolar cell apoptosis, suggesting an interaction, through positive feedback, between oxidative stress and apoptosis.\(^{(41)}\) It has recently been reported that oxidative stress is associated with a reduction in the levels of VEGF in the sputum of patients with COPD. It has been suggested that oxidative stress can lead to epithelial cell damage, thus reducing the levels of VEGF and, consequently, favoring the development of emphysema.\(^{(32)}\)

Another mechanism that has been reported as inducing apoptosis through oxidative stress is the activation of certain mitochondrial enzymes, including caspase-3.\(^{(199)}\)

**Evaluation of the oxidative stress in COPD**

Oxidative stress can be measured through direct quantification of the production of oxidants or, indirectly, through quantification of the products resulting from lipid peroxidation, such as 8-isoprostane, 4-HNE and MDA, in the alveolar space, in the exhaled air, in the sputum and in the blood.\(^{(47)}\)

The collection of exhaled breath condensate (EBC) is a noninvasive method for obtaining samples of material from the lower respiratory tract.\(^{(42)}\) This method has been used to determine the concentration of various oxidative stress markers, such as H\(_2\)O\(_2\), NO derivatives (nitrite, nitrate and S-nitrosothiols) and 8-isoprostane, in patients with COPD.\(^{(11,42,43)}\)

Various studies showed an increase in oxidative stress markers in the lungs of patients with COPD when compared with normal individuals and with individuals with the same smoking history without COPD.\(^{(30,32)}\) Smokers and patients with COPD present higher levels of H\(_2\)O\(_2\) in the EBC (a direct measure of the oxidative load of the air space) than do former smokers with COPD and nonsmokers.\(^{(47)}\) Patients with COPD related to the inhalation of smoke from biomass burning present MDA levels similar to those observed in patients with COPD associated with smoking and significantly higher than those in normal controls.\(^{(44)}\) During acute exacerbations of COPD, the concentrations of H\(_2\)O\(_2\) are higher than they are during the stable phase of the disease.\(^{(37,45)}\)

It is believed that high concentrations of H\(_2\)O\(_2\) in the EBC originate, in part, from a greater production of superoxide anions by the alveolar macrophage.\(^{(37)}\) The alveolar macrophages of smokers present greater iron content than do those of nonsmokers, resulting in an increase of free iron in the air space, which might stimulate the generation of ROS through the Fenton reaction.\(^{(15)}\) An additional source of O\(_2^\cdot\) and H\(_2\)O\(_2\) is the xanthine/xanthine oxidase reaction, which presents increased activity in the cells of the bronchoalveolar lavage fluid and in the plasma of smokers and of patients with COPD when compared with healthy nonsmokers.\(^{(15)}\)

The concentration of NO in the gaseous phase of exhaled air has been used as a direct marker of inflammation and, indirectly, of oxidative stress. Patients with COPD present lower levels of NO than do patients with asthma.\(^{(46)}\) The rapid reaction between NO and O\(_2^\cdot\), forming ONOO\(^-\), or between NO and thiols, forming nitrosothiols, can change the levels of NO in exhaled air and explain, at least in part, the difference in concentrations between asthma patients and COPD patients. The levels of NO in exhaled air are high in smokers with or without COPD, which limits the validity of this marker in the diagnosis of COPD.

Products of lipid peroxidation, such as thiobarbituric acid reactive substances, are increased in the sputum of patients with COPD and have a negative correlation with FEV\(_1\).\(^{(11)}\) Through a non-enzymatic reaction, arachidonic acid, undergoing peroxidation mediated by ROS, produces isoprostanes (Figure 3). Patients with COPD present elevated levels of 8-isoprostane in the EBC when compared with normal controls or with smokers without COPD.\(^{(47)}\) The levels of 8-isoprostane have a positive correlation with the percentage of neutrophils in induced sputum, which constitutes additional evidence that oxidative stress has a positive modulatory effect on the inflammation in COPD.\(^{(41)}\)
Systemic markers of oxidative stress and elevated plasma levels of inflammatory mediators have been reported in smokers and in patients with COPD. The peripheral neutrophils of patients with COPD release more ROS than do those of normal nonsmokers. Lipid peroxidation products are also increased in the plasma of smokers with COPD, particularly during periods of exacerbation. Oxidative stress and chronic inflammation are some of the factors involved in the mechanism that generates the systemic manifestations (e.g., weight loss and skeletal muscle dysfunction) observed in some patients with COPD. Patients with COPD are also at increased risk of cardiovascular disease. One of the probable mechanisms for this increase is the endothelial damage caused by systemic inflammation and systemic oxidative stress in these patients.

**Treatment and novel diagnostic methods**

The principal therapeutic agents available for the maintenance treatment of COPD are long-acting bronchodilators, including β2-agonists (formoterol and salmeterol) and anticholinergics (tiotropium), which have no significant impact on the progression of COPD or on COPD-related mortality.

Some factors explain the difficulty in developing more effective drugs for the treatment of COPD. First, animal models of COPD are considered inappropriate for drug trials. Models of emphysema are currently used instead of models of small airway disease; the latter, however, are more appropriate to evaluate potential drugs that can have an early effect on the progression of the disease. Second, studies investigating the effects of drugs on patient-centered outcomes, such as the reduction in loss of pulmonary function and in mortality, are expensive and take longer to be carried out. In addition, various patients with COPD present with comorbidities such as diabetes mellitus and coronary disease, which are commonly among the exclusion criteria for participation in clinical trials of new drugs. Finally, oxidative markers that monitor short-term efficacy, such as those in the blood, sputum and exhaled breath, are still in the validation phase.

More recently, there have been promising reports of novel diagnostic techniques and methods, as well as of potential therapeutic targets that can actually change the clinical course and the prognosis of the disease. Among the novel diagnostic methods, the collection of EBC is noteworthy. It is a simple and noninvasive method that allows us to obtain material from lung tissue in order to detect markers of inflammation and of oxidative stress. In the near future, the determination of the level of oxidative stress in the lungs will probably be used routinely as an indicator of the pathological changes that precede the clinical and functional expression of COPD.

Drugs that act directly or indirectly on the pathogenic mechanisms of COPD, including antioxidants to proinflammatory mediators, drugs that inhibit antiproteases and agents that modify the inflammatory response, as well as drugs that can change the resistance of COPD-related inflammation to steroids, are alternatives that can potentially influence the evolution and the prognosis of the disease. The therapeutic agents that constitute this last group—modifiers of the effect of corticosteroids on the inflammation in COPD—are considered to be the most promising. As previously mentioned, it is believed that the resistance of COPD-related inflammation to corticosteroids is due to a reduction in the expression and activity of HDAC2 caused by oxidative stress. It is known that drugs such as xanthines and certain macrolides can increase the expression of HDAC2.

In addition to reducing the expression and activity of HDAC2, oxidative stress has been reported to exacerbate other pathogenic mechanisms of COPD. Therefore, the use of antioxidant agents potentially reduces the direct damage to lung tissue caused by oxidative stress and the exacerbating effect of oxidative stress on the other mechanisms involved in COPD, as well as reversing the resistance of inflammation to steroids. To date, few antioxidant agents have been tested in the treatment of patients with COPD. It has been shown that N-acetylcysteine, a glutathione precursor, is able to reduce the concentration of $\text{H}_2\text{O}_2$ in the EBC of patients with COPD; however, it was not able to prevent the deterioration of pulmonary function or to reduce the frequency of exacerbations. N-acetylcysteine is a relatively weak antioxidant, susceptible to inactivation by oxidative stress. It is likely that substances that have a more potent...
antioxidant effect and are more stable, that is, substances that do not participate in the redox cycle, can lead to a significant decrease in oxidative stress, thus preventing the progression of the disease.

**Final considerations**

Oxidative stress plays an important role in the pathogenesis of COPD, since it can directly damage the components of the respiratory tract and exacerbate the other mechanisms involved. A better understanding of the cellular and molecular events involved in the pathogenesis of COPD will create the basis for new approaches that will allow the diagnosis of COPD at early stages and provide appropriate monitoring of disease activity, as well as leading to the development of novel therapeutic agents to prevent the progression of the disease.

**References**

The role of oxidative stress in COPD: current concepts and perspectives


About the authors

Antonio George de Matos Cavalcante
Physician in the Department of Pulmonology. Walter Cantidio University Hospital, Federal University of Ceará, Fortaleza, Brazil.

Pedro Felipe Carvalhido de Bruin
Associate Professor. Department of Clinical Medicine, Federal University of Ceará School of Medicine, Fortaleza, Brazil.

J Bras Pneumol. 2009;35(12):1227-1237