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Review

Role of Reactive Oxygen Species in Pathophysiology of Various Disorders

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Abstract

Oxidative stress occurs when the body cannot efficiently eliminate reactive metabolic by-products, leading to excessive accumulation of reactive oxygen species (ROS) in cells and tissues. While ROS are normal metabolites that play essential signaling roles, various external factors-such as UV radiation, pollution, heavy metals, and certain drugs, including anticancer agents-can elevate ROS levels and disrupt redox balance. This imbalance induces cellular and tissue damage, triggering the activation of antioxidant defence mechanisms. Natural antioxidants like vitamin E, flavonoids, and polyphenols have gained research interest for their potential to counteract oxidative injury. Although the harmful effects of oxidative stress on human health are well established, its therapeutic targeting, particularly in oncology, remains debated since reducing ROS may influence treatment outcomes. This review summarizes recent insights into oxidative stress, highlighting both its detrimental and potentially beneficial roles in human health.

Keywords

Oxidative stress, Alzheimer's disease, Parkinson's disease, Reactive oxygen species

Article History

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1. Introduction

Oxidative stress is a pathological condition that occurs when the production of reactive oxygen species (ROS) exceeds the capacity of the body's antioxidant defenses to neutralize them. This imbalance leads to the accumulation of ROS, which can damage cellular components such as lipids, proteins, and DNA, ultimately impairing normal cell function and contributing to various diseases. ROS include singlet oxygen ($^1O_2$), hydrogen peroxide (H_2O_2), hydroxyl radicals (•OH), and superoxide anions ($O_2•^-$). These molecules are natural metabolic by-products generated in aerobic organisms [1,2]. Although traditionally associated with mitochondrial oxidative phosphorylation, ROS are also produced through various enzymatic pathways, such as those involving lipoxygenases, cyclooxygenases, and multiple immune and endothelial cell systems. In physiological conditions, ROS act as essential signaling molecules. They participate in regulating protein phosphorylation, transcription factor activation, immune responses, cell differentiation, and apoptosis, thereby helping maintain cellular homeostasis. Their production and elimination are normally kept in tight balance by antioxidant defenses [3]. However, when this equilibrium is disrupted due to environmental stressors, disease states, or hypermetabolic conditions, ROS levels can rise sharply, leading to oxidative stress. This pathological state reflects a disproportion between ROS generation and the cell's antioxidant capacity [4]. Excess ROS react with and damages lipids, proteins, and nucleic acids, ultimately compromising cellular integrity and function. Such oxidative injury has been implicated in the development and progression of numerous chronic and degenerative disorders [5,6].

In numerous instances, oxidative stress has been demonstrated to be strongly associated with numerous human diseases, such as cancer, diabetes mellitus, metabolic syndromes, atherosclerosis, as well as a variety of cardiovascular diseases. There is some debate over the exact role of oxidative stress in propelling these conditions, but one fact stands out, namely, it is an established pathogenic process. More specifically, mitochondrial impairment can be considered a significant contributor that elevates the levels of ROS both in the normal and diseased states [7]. Electron leakage through mitochondria during cellular respiration reacts with oxygen to produce superoxide radicals. Although antioxidant defense systems exist, such as manganese-dependent superoxide dismutase (MnSOD) such defenses are usually unable to handle the excessive burden of ROS. Living organisms have evolved robust antioxidant defense systems, involving both enzymatic and non-enzymatic pathways, to counteract the harmful effects of ROS. Superoxide dismutase (SOD) converts superoxide radicals into H_2O_2, which is subsequently broken down into water and oxygen, thereby preserving redox balance and safeguarding cells from oxidative damage [7,8].

Although oxidative stress may be detrimental, it represents a double-edged sword that may be used to advantage. The ROS functions are essential in various conditions which are involved in immune defense, redox regulation, and cellular homeostasis under physiological conditions, whereas excessive ROS generation leads to oxidative damage, mitochondrial dysfunction, inflammation, and tissue injury under pathological states. ROS can be employed in a controlled setting. Indicatively, a few cancer therapies make use of ROS mediated cytotoxicity to selectively kill cancer cells. Antineoplastic agents and radiation therapy tend to exploit the clinical potential of ROS in certain conditions and induce oxidative stress, which triggers the process of apoptosis in tumors [9]. In general, ROS are important markers; the acceptable balance in their levels is the basis of critical cellular activities. On the other hand, they cause disease pathogenesis when they are overproduced. This narrative review synthesizes literature identified via searches in PubMed and Google Scholar using keywords such as: 'oxidative stress,' 'reactive oxygen species, Neurodegeneration, Cancer, Cardiovascular, Sexual disease, etc. The comprehensive study of the phenomenon of ROS generation, a restriction of the endogenous antioxidant system, and methods of controlling the state of oxidative stress is one of the current hot topics in the realm of biomedical studies. Future research opportunities may lie in the investigation of how to exploit the ROS, such as increasing antioxidant defenses, or using ROS to their benefit in disease prevention and treatment. The review aims to (i) summarize ROS generation and antioxidant defense systems, (ii) compare ROS-mediated mechanisms across major disease categories, and (iii) critically assess therapeutic strategies targeting oxidative stress.

2. Production or Preparation of Free Radicals

ROS are produced by both enzymatic and non-enzymatic approaches with each attributed to a specific oxidative signature. on the biological systems. On the one hand, ROS generation is closely associated with core processes such as mitochondrial respiration, the production of prostaglandins, phagocytosis, catalysis in cytochrome P450 [10,11] in the context of enzyme enzymes NADPH oxidase, xanthine oxidase, and a host of different peroxidases Environmental factors can also generate a wide range of reactive intermediates. This is followed by the generation of molecules like H_2O_2, •OH and hypochlorous acid (HOCl) and peroxynitrite (ONOO-) which individual downstream species have distinct reaction kinetics and physiological outcomes [12].

Xanthine oxidase, amino-acid oxidase and other oxidases produce non-radical ROS, H_2O_2. Even though H_2O_2 has lower intrinsic reactivity than free radicals, it is a good penetrator of cell membranes and, therefore, plays an important role in redox signal transduction. The hydroxyl radical is the strongest and most harmful ROS, which is formed through the fenton reaction as present H_2O_2 is oxidized by $O_2•^-$ and in the presence of transition metals like Fe^{2+} or Cu^{2+} [13]. The example process demonstrates catalytic enhancement of oxidative stress caused by impaired metal-ion homeostasis. Besides, nitric oxide synthase (NOS) is a pivotal accelerator of the generation of ROS; this enzyme involved in the

transformation of arginine to citrulline also produces nitric oxide (NO) as a by-product concomitant [14]. NO plays essential functions in the vascular homeostasis, neurotransmission, and immunity, but a fast response with $O_2^{\bullet -}$ produces ONOO-, a strong oxidant agent that is involved in cell damage and inflammation [15,16].

ROS are also formed in non-enzymatic channels aside from the enzymatic ones. Such mechanisms include direct contact of molecular oxygen and organic substrate, exposure to ionizing radiation and free leak of electrons during the mitochondrial electron transport spontaneously [17]. Non-enzymatic pathways gain increased prominence when cellular stress/environmental injury occurs and significantly increases overall oxidative load. The occurrence of ROS is predetermined by the combination of endogenous and exogenous factors; these processes may lead to the formation of free radicals both endogenously during physiological and pathological activity, as well as exogenously due to the influence of ageing of the organism, immunological reaction, inflammation, ischemia -reperfusion damage, infection, malignant cell formation, vigorous exercise, stress in a person, and the ageing process itself [18]. These intrinsic instigators have capability of derailing redox homeostasis, and this leads to pathophysiological cascades.

Extrinsic contributors of ROS include environmental contaminants, heavy metals (e.g., cadmium, mercury, lead, iron, arsenic), pharmaceuticals (e.g., cyclosporine, tacrolimus, gentamicin, bleomycin), solvents and food-related substances-including processed or smoked foods and cooking oils [19,20]. Oxidative stress is further increased by lifestyle factors like smoking, alcoholism and exposure to ionizing radiation. These xenobiotics are metabolically transformed into highly reactive intermediates when entering the organism and, thus, put an additional burden on the oxidative stress on the cells. The contribution to the health and disease of ROS heavily relies on their multidimensional nature of the production process that requires a thorough understanding. This multifacetedness of oxidative stress along with its extensive impact on biological systems is supported by the fact that the processes of enzymatic and non-enzymatic mechanisms are controlled by external and internal stimuli which interact with each other in a complex way as shown in Figure 1 [21-25].

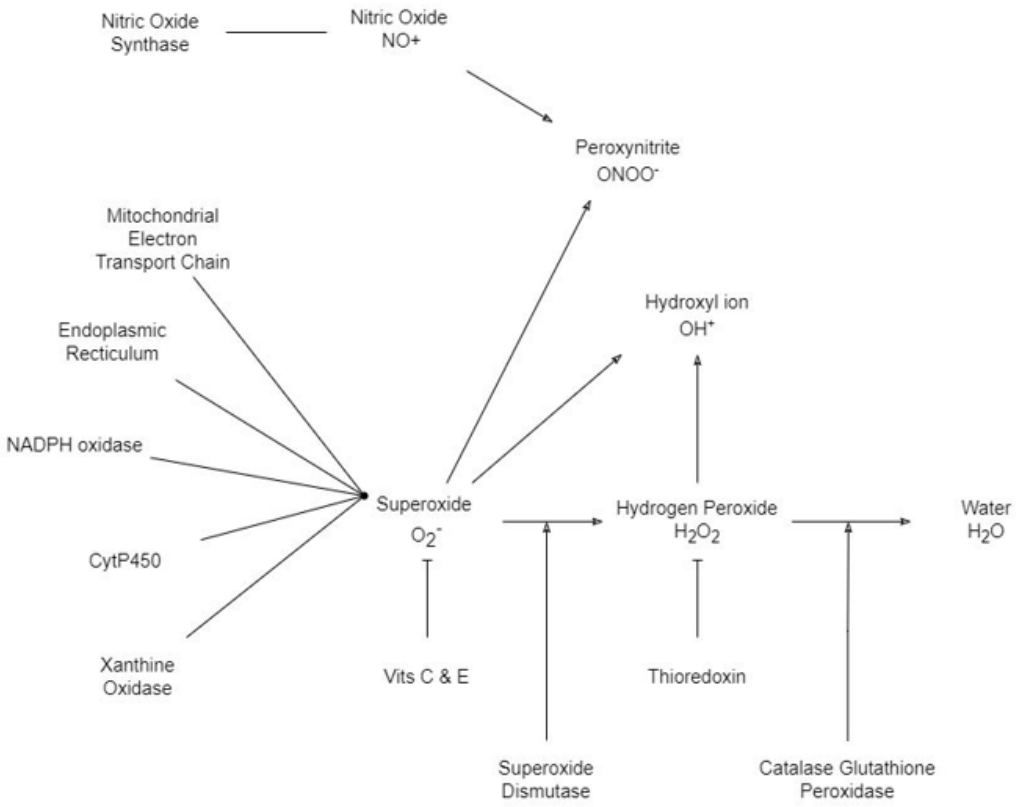

Figure 1. Schematic representation of major ROS sources and detoxification pathways. Superoxide arises from mitochondrial and enzymatic systems and converts to H_2O_2 via SOD. Antioxidants and enzymes (catalase, glutathione peroxidase (GPx), thioredoxin) neutralize ROS. Superoxide also reacts with nitric oxide to form ONOO-, contributing to oxidative stress.

2.1 Physiological functions of Free Radicals in the Body

At the physiological range, free radicals have a range of necessary functions that maintain cell integrity to maintain a delicate balance between the various roles of free radicals. The best contribution is in the host defense whereby such reactive species have significant roles in the viral suppression and biosynthesis of diverse cellular components [16-21]. Neutrophils and macrophages, which are phagocytic lineages, are considered both radical generators and scavengers and coordinate the production, sequestration, and a temporally regulated release to eliminate the invading pathogens. Historical clinical evidence indicates that ROS are an integral part of immunological processes, which is supported by

clinical cases of granulomatous disorders [22-25]. Pathogenic mutations or malfunctions of the NADPH oxidase complex neutralize the ability of these individuals to form the $O_2^{\bullet -}$ in many of them, a biochemical impairment that renders these people susceptible to chronic, repeated infections. In turn, the paramount role of the ROS-mediated pathogen eradication is considerable [26].

In addition to their antimicrobial significance, the free radicals participate actively in signal transduction. The isoforms of NADPH oxidase generate reactive species in a diverse range of non-phagocytic cells, such as fibroblasts, endothelial cells, vascular smooth muscle cells, cardiomyocytes and thyroidocytes, and therefore play central roles as regulators of intracellular signaling cascades [27]. Through these processes, radicals control gene expression, cell proliferation and cell death [28]. NO, a presumptive free radical, can serve as a central intercellular messenger, which adjusts vascular tone to achieve optimal hemodynamics as well as protective effects against thrombosis and cerebral malfunction. Besides, NO gives an impetus to immune mechanisms by enhancing reactions that get rid of tumor and intracellular pathogens. Communication in the promotion of cell proliferation and muscular tissue repair is also facilitated by the manipulation of mitogenic signaling induced by free radicals [29,30]. Their ubiquitous nature is integral to maintaining homeostatic balance and coordination of complex physiological events. Thus, the multifaceted roles of free radicals underscore their essential contribution to immune defense, cellular signaling, and overall physiological homeostasis as shown in Table 1.

Table 1. Various sources of ROS and its pathological consequences in various diseases.

ROS Source	Pathological Consequences	Major Antioxidant Systems	Representative Diseases Linked to oxidative stress
Mitochondrial electron transport chain (ETC)	Excess superoxide formation; mitochondrial membrane depolarization; ATP depletion; activation of intrinsic apoptosis	SOD2 (Mn-SOD), GPx, catalase, glutathione (GSH)	Parkinson's disease, Alzheimer's disease (AD), amyotrophic lateral sclerosis , myocardial ischemia
On the NADPH oxidase (NOX) activation	Enhanced ROS burst; vascular inflammation; endothelial dysfunction	SOD1, catalase, Nrf2-mediated enzymes	Atherosclerosis, hypertension, diabetic vasculopathy
Xanthine oxidase	Uric acid and ROS overproduction; tissue inflammation; microvascular injury	SOD, catalase, GPx	Cardiovascular disease, chronic kidney disease, and gout-associated oxidative stress
nitric oxide synthase (uncoupled NOS)	ONOO- formation; nitrosative stress; lipid/protein/DNA damage	GSH, thioredoxin, catalase	Neurodegeneration, stroke, metabolic syndrome
Cytochrome P450, cyclooxygenase, Lipoxygenase	Lipid peroxidation; generation of toxic lipid radicals; inflammation	GPx, vitamin E, carotenoids	Cancer, inflammatory disorders, liver injury
Environmental toxins and xenobiotics (metals, pollutants)	DNA strand breaks; protein oxidation; mitochondrial toxicity	GSH, metallothionein's, and catalase	Chronic obstructive pulmonary disease (COPD), lung fibrosis, nephrotoxicity, carcinogenesis
UV and ionising radiation	Hydroxyl radical formation; DNA mutations; oxidative stress	Vitamin C, vitamin E, GSH, catalase	Skin cancer, photoaging, and immune dysregulation
Inflammatory cell respiratory burst (neutrophils, macrophages)	Massive ROS release; tissue injury; chronic inflammation; fibrosis	SOD, GPx, catalase	Autoimmune disorders, rheumatoid arthritis, COPD
NADPH oxidase (NOX) activation	Enhanced ROS burst; vascular inflammation; endothelial dysfunction	SOD1, catalase, Nrf2-mediated enzymes	Atherosclerosis, hypertension, and diabetic vasculopathy

3. Harmful Effects of Oxidative Stress on Human Health

As has been mentioned above, the excessive accumulation of free radicals and oxidants will lead to oxidative stress, which is an inflammatory condition that adversely affects cellular integrity. This is an irregularity that attacks basic cellular building blocks such as plasma membranes, lipids, proteins, lipoproteins, and deoxyribonucleic acid (DNA) and becomes activated when the formation of reactive species surpasses the antioxidant activity of the cell, thus triggering oxidative damage [16,17]. For example, enhanced levels of reactive species like ONOO- and •OH catalyze lipid peroxidation, which destroys lipoproteins and impairs the structural and functional integrity of cellular membranes. The resultant peroxidative attack gives cytotoxic and mutagenic products, such as malondialdehyde (MDA) and conjugated dienes. These metabolites not only undermine membrane stability but also contribute to the development of genomic mutation and malfunctioning of the cell, thus making them one of the major contributors to the pathogenesis of many diseases, as shown in Figure 2 [18,19].

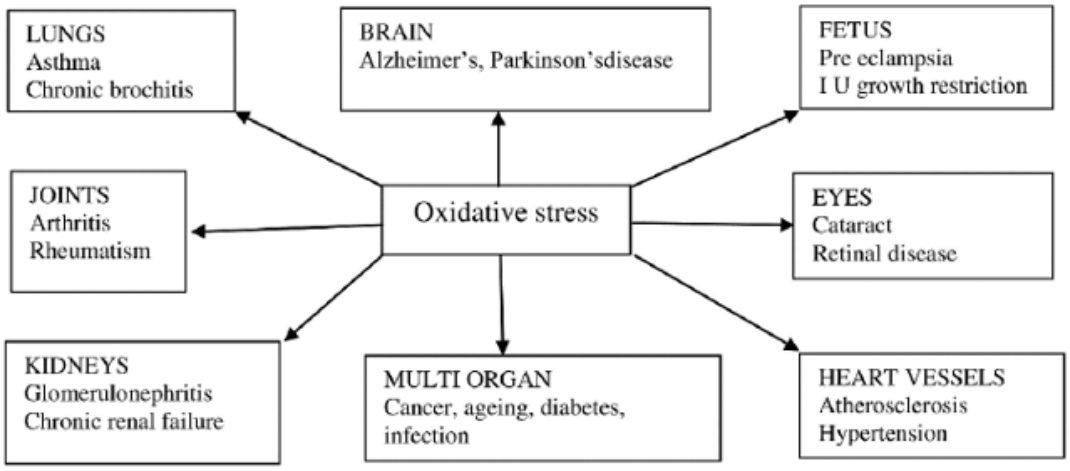

Figure 2. Overview of diseases linked to oxidative stress. Oxidative stress contributes to disorders across multiple organs, including lungs (asthma, chronic bronchitis), joints (arthritis, rheumatism), kidneys (glomerulonephritis, renal failure), brain (AD, Parkinson's disease), eyes (cataract, retinal disease), heart vessels (atherosclerosis, hypertension), fetus (preeclampsia, IUGR), and multi-organ conditions like cancer, ageing, diabetes, and infections.

Lipid peroxidation is a chain reaction that is self-propagating; hence, it is very destructive and destroys a tremendous number of lipid molecules, thus causing damage to the structure and the functioning of cell membranes. In addition to the lipidic damage, proteins are also prone to oxidative changes; these changes may also disrupt their three-dimensional conformations, and as such, disrupt their enzymatic activity and a myriad of other vital functions [15-20]. Even DNA is susceptible to oxidative damage, a situation where 8-oxo-deoxyguanosine (8 -OHdG) has become one of the most extensively studied of oxidative DNA damage markers. This lesion is specifically detrimental as it can promote mutagenesis and induce carcinogenesis. Besides, oxidative damage can result in loss of epigenetic content, most specifically interference with the methylation ability of CpG clusters within the promoter of genes, which subsequently influences the regulation of genes. In fact, 8-OHdG tissue concentrations have been suggested as a convenient Biomarker of oxidative stress [16-26]. To counter such perturbations, cells take up various defence systems to maintain genome integrity through the mobilization of different defense systems, such as base excision repair (BER) pathways and antioxidant systems. Thus, the widespread molecular damage driven by oxidative stress highlights its critical role in the initiation and progression of numerous human diseases, underscoring the importance of robust cellular defense and repair systems.

3.1 Implication of Oxidative Stress in Cancer

Development of cancer is a complex process that involves cellular and molecular alterations, and it may be a consequence of a fragile equilibrium between internal and external factors. Oxidative DNA damage has been known to be a major pathogenic agent. The oxidative stress may cause chromosomal aberration and also oncogene activation, resulting in or accelerating tumorigenesis [27]. Chemical carcinogenesis is characterized by the production of hydrolyzed bases of DNA, frequent products of DNA oxidation, as shown in Figure 3. The presence of such adenine-type lesions induces genomic instability, which results in changes to the transcriptome that produce gene mutations that interfere with normal cell functions. The range of oxidative stress-induced changes includes the base lesions, sugar lesions, cross-linkages of DNA and proteins, strand breaks, and apurinic/apyrimidinic sites. These genomic alterations could be occasioned by exposure to environmental poisonous substances, tobacco smoke or by the type of inflammatory condition involved in the formation of tumors [17-20]. The epidemiological evidence also suggests a connection between large dietary fat consumption, which is one of the activities that enhances the lipid peroxidation levels, and increased cancer mortality. This correlation indicates the possibility of lifestyle-acquired radical oxidative stress as a contributing factor to cancer pathogenesis and progression [25]. Therefore, oxidative stress emerges as a pivotal driver of genomic instability and tumor progression, reinforcing its central role in both the initiation and advancement of cancer.

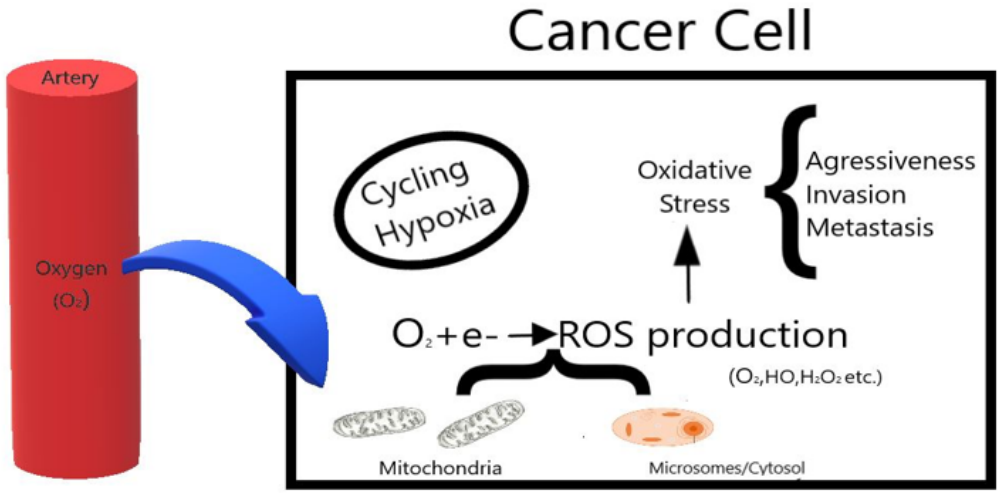

Figure 3. Cycling hypoxia in cancer cells promotes excessive ROS generation from mitochondria and microsomes, triggered by oxygen fluctuations. Elevated ROS induces oxidative stress, driving tumor aggressiveness, invasion, and metastasis. The figure illustrates oxygen supply from the artery, ROS formation ($O_2^{\bullet -}$, $HO^{\bullet}$, H_2O_2), and its role in malignant progression.

3.2 Oxidative Stress and Cardiovascular Disease

Elastic cardiovascular diseases are clinically heterogeneous entities that are commonly etiologically complex, associated with a typically long list of risk factors. These situations are hypercholesterolemia, hypertension, smoking, diabetes mellitus, unbalanced diet, psychosocial strain and sedentary lifestyle, which are the most generally recognized [11,30-32]. Oxidative stress has been more recently reasoned to be both a primary and a secondary etiological cause of many CVDs [18]. Oxidative processes, specifically atherosclerosis, are mostly oxidative; it is a widely accepted view that the endothelial inflammation triggers resident macrophage recruiting processes, which, in turn, produce ROS. These ROS then oxidize circulating low density lipoprotein, which in turn facilitates the growth of foam cells and deposition of lipids. So, the development of atherosclerotic plaque is a result of such cascade events. *In vivo* and *in vitro* research has revealed that oxidative stress can play a role in the pathogenesis of atherosclerosis, ischemia, hypertension, cardiomyopathy, cardiac hypertrophy, and congestive heart failure [11,16,25,30,31]. Thus, oxidative stress plays a central role in initiating and accelerating cardiovascular diseases by promoting inflammation, lipid oxidation, and plaque formation as shown in Figure 4.

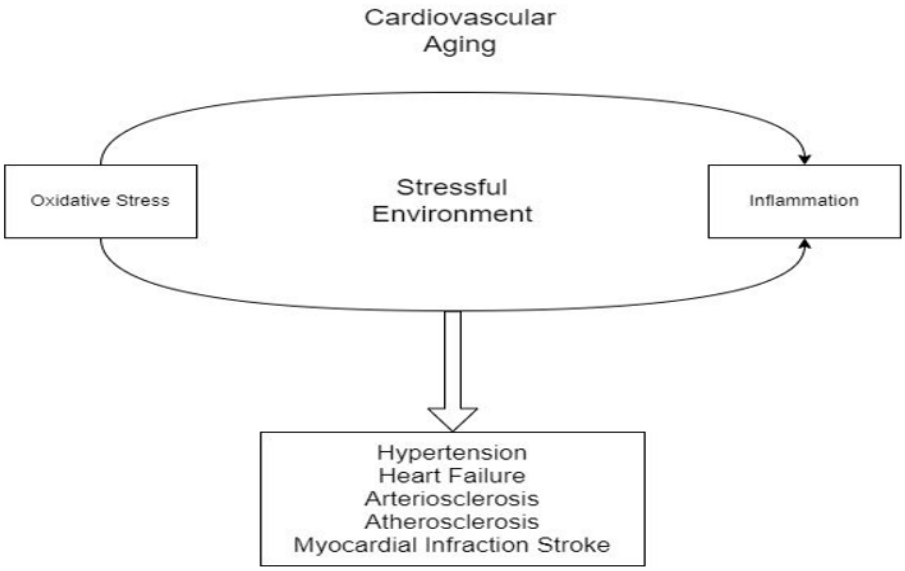

Figure 4. Cardiovascular ageing creates a stressful environment marked by oxidative stress and inflammation, which reinforce each other. This persistent stress response contributes to major cardiovascular disorders, including hypertension, heart failure, arteriosclerosis, atherosclerosis, myocardial infarction, and stroke, highlighting the interconnected pathways driving age-related vascular decline.

3.3 Role of Oxidative Stress in Various Neurological Disorders

Oxidative stress has been linked to many neurological disorders that include Parkinson's disease, Alzheimer's disease, amyotrophic lateral sclerosis, multiple sclerosis, depression, and loss of memory [33,34]. There are reports of numerous experimental and clinical studies that have revealed that oxidative damage is an important condition in neuronal death and dementia progression in AD [34].

It is also known that the toxic amyloid peptide, which is often found in the brains of AD patients, is at least a partial cause of the neurodegeneration that is witnessed on the onset of AD and during the progression of AD [35]. Thus, oxidative stress plays a crucial role in the onset and progression of major neurodegenerative disorders, making it a key target for therapeutic intervention, as shown in Figure 5.

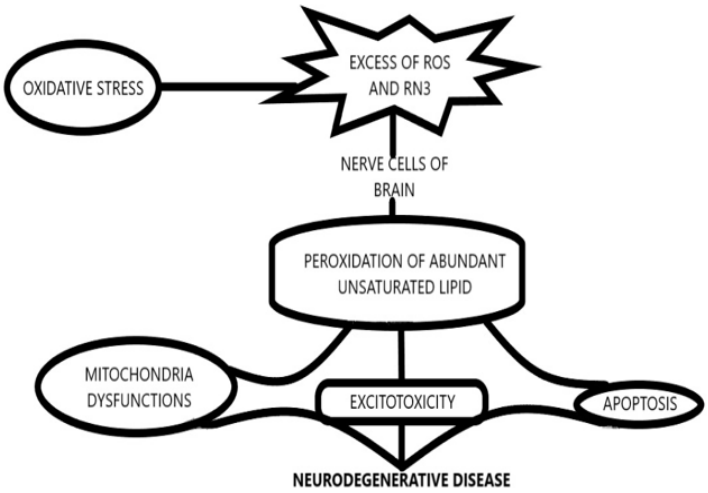

Figure 5. Oxidative stress elevates ROS/RNS in brain nerve cells, causing peroxidation of abundant unsaturated lipids. This leads to mitochondrial dysfunction, excitotoxicity, and apoptosis, collectively contributing to neurodegenerative disease progression. The diagram highlights interconnected pathways through which oxidative damage drives neuronal decline.

3.4 Respiratory Disease and Oxidative Stress

Many studies have explained a strong association between oxidative stress and pulmonary conditions like asthma, chronic obstructive pulmonary disease, with each of them characterised by systemic, as well as localized chronic inflammation [36,37]. It is already known that ROS increase inflammation by stimulating several different kinases, which interact with signaling cascades and transcription factors, in particular, NF-κB and AP-1 [38,39]. Rheumatoid Arthritis is recognized as a chronic and debilitating autoimmune disorder that impacts the brain as well. On the one hand, the brain is also affected by an immune disease known as Rheumatoid Arthritis. Rheumatoid arthritis is a long-term inflammatory disease of the joints and the tissues that surround them, the infiltration of which is accompanied by the infiltration of macrophages and activated T cells [15,40,41]. Agreement on high levels of isoprostane and prostaglandins in the synovial fluid of patients with the syndrome highlights the critical role played by the free radicals at the site of inflammation, both in the development and progression of this syndrome [41]. Thus, oxidative stress plays a major role in driving inflammation and tissue damage in respiratory diseases and rheumatoid arthritis, underscoring its importance in disease progression.

4. Pre-diabetes and Oxidation of the Kidneys

Oxidative stress alters a range of diseases of the kidney (glomerulonephritis, tubulointerstitial nephritis, renal failure, proteinuria, and uremia) [16,42]. Oxidative stress triggers the inflammatory cells and the production of proinflammatory cytokines, and thus contributes to an early inflammatory step. This initial phase is dominated by tumor necrosis factor-α (TNF-α) and interleukin-1α (IL-1α), which are coupled with NF-κB, which is a transcription factor that is imperative in maintaining the inflammatory response. The increases in transforming growth factor-b later on enhance the extracellular matrix production, which is a later pathogenic process. This results in sustained oxidative stimuli creating an initial inflammation cascade after which there is a collective development of excessive fibrosis tissue to the extent of affecting organ activity, and which in the long run leads to renal failure. Well-known immunosuppressant agents like cyclosporine, tacrolimus, gentamicin and bleomycin are also known to increase the levels of free radicals and cause oxidative stress through lipid peroxidation [42-47]. Strong oxidative stress inducers implicated in several nephropathies, as well as some malignancies, are heavy metals and transition metals (Cd, Hg, Pb, As) [22,23]. Thus, oxidative stress plays a central role in initiating inflammation and promoting fibrosis in kidney diseases, ultimately contributing to progressive renal dysfunction.

5. Oxidative Stress and Sexual Maturation

Several studies suggest that oxidative stress may contribute to delayed puberty and impaired sexual development. Evidence from pregnant women and prepubertal children exposed to cadmium, a metal known to increase free radical generation, supports this association. Cadmium-induced oxidative imbalance has been linked to disruptions in hormonal regulation and developmental timing. Overall, the impact of oxidative stress and reactive species extends widely across human health, demonstrating their capacity to initiate or exacerbate numerous clinical disorders affecting multiple

organs and systems. Consequently, oxidative stress emerges as an important factor influencing reproductive maturation and a broader determinant of disease susceptibility. Thus, oxidative stress plays a significant role in disrupting reproductive maturation, underscoring its broader impact on human health and disease vulnerability.

6. Exogenous Antioxidants and Human Health

The human body uses non-enzymatic antioxidants like lipoic acid, GPx, GSH, arginine, and coenzyme Q10 in combating free radicals and also reducing oxidative stress. Besides that, various exogenous antioxidant molecules, which may be of animal or plant origin, are commonly consumed either within the diet or in the form of a supplement. The table below is a discussion on the most salient dietary antioxidants and clarifies their protective effects on human health. Thus, both endogenous and dietary antioxidants play a vital role in neutralizing free radicals and protecting the body from oxidative damage.

7. Vitamin E

Vitamin E is an umbrella term that covers a series of lipophilic molecules such as tocopherols, tocotrienols and other similar molecules produced by plants [48]. Such compounds can be found in food fortified with α-tocopherol, in cooking oils, and in vegetables [49,50]. Among others, RRR-α-tocopherol is thought to be the most biologically active; *in vitro* research has shown that the product has antiproliferative effects on smooth vascular muscle cells through the regulation of protein kinase C [51]. Whereas the activity is stimulated by low-density lipoproteins [52], *in vivo* experiments with a mouse and rabbit models of atherosclerosis support these observations [53-55]. While vitamin E shows protective potential in preclinical models, clinical outcomes remain inconsistent due to limitations such as poor bioavailability, highlighting the need for targeted delivery systems, including nanoparticle-based formulations. Thus, vitamin E, especially RRR-α-tocopherol, plays a significant protective role by regulating cellular pathways involved in vascular health and atherosclerosis.

8. Limitations and Future Directions

Although this manuscript provides a comprehensive overview of ROS biology and oxidative stress-mediated pathology, several limitations remain. The discussion synthesises existing evidence but lacks quantitative comparisons across disease models, and mechanistic differences specific to tissue types require deeper investigation. Additionally, most cited studies rely on correlational data, making causality between oxidative stress and disease progression difficult to establish. Future research should prioritise longitudinal, multi-omics approaches to map redox alterations dynamically, develop more specific biomarkers for early diagnosis, and design targeted antioxidant therapeutics with improved bioavailability. Integrating experimental, clinical, and computational models will further advance translational applications in oxidative stress-related diseases.

9. Conclusion

Oxidative stress, defined as the imbalance between the excessive production of ROS and the body's ability to neutralize them through antioxidant defences, plays a crucial role in determining cellular health. While controlled ROS levels are essential for normal physiological signaling and adaptive responses, their uncontrolled accumulation leads to damage to lipids, proteins, and DNA. This oxidative imbalance contributes significantly to the onset and progression of multiple diseases, including cancer, cardiovascular disorders, neurodegenerative diseases, respiratory complications, and metabolic dysfunctions. Recognizing the dual nature of ROS as both vital signaling molecules and potent cellular stressors is fundamental for developing effective therapeutic strategies. Enhancing endogenous antioxidant mechanisms, regulating redox pathways, and optimizing antioxidant interventions will be essential for maintaining cellular homeostasis. Ultimately, maintaining a precise balance between ROS generation and antioxidant defenses is critically essential for sustaining health, as restoring this equilibrium offers promising opportunities for preventing oxidative damage and improving therapeutic outcomes.

Conflict of Interest

The authors declare that there is no conflict of interest.

Generative AI Statement

All authors declare that no artificial intelligence (AI) tools or software were used in the preparation of this manuscript.

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