Free Radicals, Mitochondria, and Oxidized Lipids
The Emerging Role in Signal Transduction in Vascular Cells

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Abstract—Mitochondria have long been known to play a critical role in maintaining the bioenergetic status of cells under physiological conditions. It was also recognized early in mitochondrial research that the reduction of oxygen to generate the free radical superoxide occurs at various sites in the respiratory chain and was postulated that this could lead to mitochondrial dysfunction in a variety of disease states. Over recent years, this view has broadened substantially with the discovery that reactive oxygen, nitrogen, and lipid species can also modulate physiological cell function through a process known as redox cell signaling. These redox active second messengers are formed through regulated enzymatic pathways, including those in the mitochondrion, and result in the posttranslational modification of mitochondrial proteins and DNA. In some cases, the signaling pathways lead to cytotoxicity. Under physiological conditions, the same mediators at low concentrations activate the cytoprotective signaling pathways that increase cellular antioxidants. Thus, it is critical to understand the mechanisms by which these pathways are distinguished to develop strategies that will lead to the prevention of cardiovascular disease. In this review, we describe recent evidence that supports the hypothesis that mitochondria have an important role in cell signaling, and so contribute to both the adaptation to oxidative stress and the development of vascular diseases. (Circ Res. 2006;99:924-932.)

Key Words: apoptosis ■ atherosclerosis ■ hypertension ■ diabetes ■ environmental tobacco smoke ■ endothelial cells ■ electrophilic lipids ■ mitochondria ■ prostaglandins ■ redox signaling ■ thiols

The “free radical hypothesis” for vascular dysfunction originally postulated that reactive oxygen and nitrogen species (ROS/RNS) led to nonspecific modification of lipids, proteins, and nucleic acids, which then contributed to the etiology of the disease.\(^1\)\(^,\)\(^2\) However, this view has changed in recent years with the recognition that these molecules can play a role in signal transduction through specific modification of cell signaling proteins.\(^3\)\(^,\)\(^4\) Overall this field has come to be known as “redox cell signaling” and describes how ROS/RNS can lead to the activation of pathways that control cell differentiation and apoptosis.\(^5\)\(^,\)\(^6\) These mechanisms are of particular relevance to cardiovascular diseases (CVD), such as atherosclerosis and hypertension, and have been studied intensively in vascular cells.\(^4\)\(^,\)\(^7\)\(^,\)\(^8\) During atherosclerosis, activation of the enzymes in both infiltrating macrophages and vascular cells generate high levels of ROS/RNS, thereby changing the oxidation status of thiols on signaling proteins: the redox tone.\(^8\)\(^,\)\(^9\)\(^,\)\(^10\)\(^,\)\(^11\) The redox cell signaling pathways that are activated are balanced between those that protect endothelial and vascular smooth muscle cells with those that initiate cell...
death through apoptosis. A major challenge at the present time is to understand how the localized production of ROS/RNS in the environment of the atherosclerotic lesion contributes to the control of this balance between resolution of inflammation or the evolution to a more advanced lesion. Considerable attention is now being made to the various mechanisms through which cells generate and detect ROS/RNS and their metabolic products, particularly oxidized lipids generated by enzymatic and nonenzymatic mechanisms. An increased understanding of how ROS/RNS contribute to cellular protection is now particularly important, because a number of therapeutic interventions based on decreasing these species have not demonstrated clinical benefit in vascular diseases. This is particularly striking in the case of low-molecular-weight antioxidants and inhibitors of the cyclooxygenase pathway. In both cases, we can hypothesize that these agents have limited therapeutic benefit, because ROS/RNS and oxidized lipids have potentially beneficial effects at the level of signal transduction.

The small molecules involved in redox signaling pathways can be generated from several families of enzymes, such as the NADPH oxidases and nitric oxide synthases (NOS), in a controlled manner within the cell. These ROS/RNS are derived from the metabolism of oxygen- or nitrogen-containing compounds and their subsequent reaction products. Although it has been known for some time that mitochondria are a source and target for ROS/RNS, it has been only recently that a role for the formation of these species in signal transduction has emerged. Mitochondrial ROS formation is associated with the cell signaling that controls proliferation, hypertrophy, hypoxia, and apoptosis. The cells of the vascular system provide an interesting stage on which to examine mitochondrial signal transduction in the pathophysiology of human disease. Interestingly, among the original tenets of the free radical hypothesis is that lipid oxidation products are implicated in the progression of atherosclerosis. Recent studies suggest that the mitochondrion may be the site at which redox signaling mediated by lipid oxidation products is coordinated.

Vascular pathologies are multifactorial, but it is clear that mitochondrial dysfunction can contribute to the pathophysiology of these diseases. This appears to not only involve damage to the organelle and loss of bioenergetic function but also disruption of mitochondrial-dependent redox signaling pathways. In this review, we discuss (1) mitochondrial DNA damage in the etiology of vascular disease, (2) the mechanisms for mitochondrial ROS formation and influence on redox cell signaling events, and (3) the importance of oxidized lipids in mediating adaptation to stress or cell death in the endothelium.

**Damage to Mitochondrial DNA and Cardiovascular Disease**

In the mitochondrion, nonspecific modification of proteins, lipids, and nucleic acids can lead to damage of these molecules and change in mitochondrial function. Mitochondrial DNA (mtDNA) is particularly susceptible to modification by ROS/RNS because (1) mtDNA is in close proximity to the site of ROS/RNS production; (2) mtDNA lacks histone proteins, which can protect it from oxidative damage; and (3) mitochondrial polymerases lack specificity for base excision repair and are themselves modified by ROS, which can potentially lead to changes in polymerase function and increased mutation rates in mtDNA. Damage to mtDNA can rapidly lead to functional changes in the cell because it encodes 13 critical protein components of the mitochondrial respiratory chain. It has been shown that mtDNA damage occurs in CVD, and this is supported by findings in human subjects, as well as studies in animal and cellular models.

One of the important concepts from studies of genetic mitochondrial diseases is that there is a threshold at which damage to mitochondrial DNA results in loss of bioenergetic capacity. Because repair of mitochondrial proteins often requires new protein synthesis, damage to mtDNA is likely to lower this threshold (Figure 1A). Thus, the accumulation of mtDNA damage over a lifetime may increase the susceptibility to the development of pathology. In fact, the well known proatherogenic risk factors such as smoking, hypercholesterolemia, and obesity are all associated with increased mtDNA damage.

For example, smokers have an increase of 6-fold in the level of mtDNA damage and a 7-fold increase in mtDNA deletions in lung tissues compared with nonsmokers. Exposure to either environmental tobacco smoke or smoking decreases mitochondrial respiratory chain function and enhances lipid peroxidation. The mediators involved in these effects are not clear but could involve reactive lipid aldehydes in cigarette smoke that could directly modify DNA and proteins, or carbon monoxide. The mechanism of carbon monoxide may involve direct inhibition of cytochrome c oxidase, resulting in decreased mitochondrial respiration, an increase in oxidative stress and lipid peroxidation, and ultimately mtDNA damage (Figure 1B).

Accumulated mtDNA damage will hinder the replacement of respiratory chain proteins damaged by ROS production. These damaged proteins are more likely to generate ROS in an uncontrolled manner, thereby accelerating bioenergetic dysfunction. In this respect, intramitochondrial antioxidants have a critical role to play because they may alter the progression of the disease by preventing damage to existing proteins. Indeed, decreased manganese superoxide dismutase (MnSOD) activity promotes atherosclerotic lesion development and increases aortic mtDNA damage in apoE−/− mice. Recent studies suggest that activation of the NADPH oxidases leads to crosstalk with the mitochondrion and increased ROS formation from the organelle.

A further example of the link between accumulated mtDNA defects and susceptibility to CVD may be the impact of exposure to environmental tobacco smoke in utero. Gestational exposure to secondary tobacco smoke in mice increases the rate of development of atherosclerosis as the animals mature. In support of a role for mitochondria in this process, gestational exposure to cigarette smoke also increases mtDNA damage in the adult. The mechanisms of these effects likely involve the placental transfer of components of tobacco smoke, such as reactive lipid oxidation products, which may cause fetal mtDNA damage to liver,
vasculature may offer a source of endothelial cells containing undamaged mtDNA. However, little is known of the role of mitochondria in these progenitor cells.

**Formation of ROS/RNS and Their Interaction With Mitochondria**

At lower levels of ROS/RNS, damage to key targets in the mitochondrion, such as mtDNA, is prevented by the presence of intramitochondrial antioxidant defenses. The characteristics of specificity, localization, and reversibility, which are generally associated with cell signaling pathways, can now be identified in the formation of ROS at low rates from the respiratory chain. Mitochondrial superoxide is produced by the one-electron reduction of oxygen by complexes I and III of the respiratory chain and some components of the tricarboxylic acid cycle such as α-ketoglutarate dehydrogenase.46–48 Early studies using hyperoxia or mitochondrial toxins characterized the formation of mitochondrial superoxide or hydrogen peroxide as an electron “leak” from the respiratory chain.46,49 It is possible that uncontrolled ROS formation also occurs pathologically when mitochondrial respiratory proteins are damaged.50 However, hyperoxia and mitochondrial toxins do not model physiological ROS production pathways and therefore do not give insights into the mechanisms of mitochondrial redox signaling.

A likely mechanism through which mitophagy may transduce and regulate cellular redox signals is through thiol switching. For example, it has been shown that the mitochondrial glutaredoxin 2 pathway modulates the redox couples that control the S-glutathionylation of proteins in the respiratory chain.51 Taken with the finding that S-glutathionylation of the 70-kDa subunit of complex I leads to superoxide formation, these data suggest there is crosstalk between thiol status and controlled formation of ROS.46,51

Mitochondrial superoxide formation can also be regulated by uncoupling proteins (UCPs), and several recent studies suggest they play a role in the etiology of CVD, although the effects appear to depend on the specific UCP isoform. Overexpression of UCP-1 in aortic smooth muscle cells increases superoxide formation, hypertension, and exacerbates atherosclerotic lesion formation.52 However, overexpression of UCP-2 in the vasculature decreases ROS generation and prevents mitochondrial overload in cardiomyocytes,53 and UCP-2 knockout is associated with increased atherosclerotic lesion formation in vivo.54 Nonetheless, these studies do suggest that changes in UCP activity (and thus superoxide formation) can contribute to vascular dysfunction.

Once formed, the mechanisms leading to superoxide signal transduction remain largely unknown but four possibilities can be proposed with some supporting evidence. The most direct of these is that superoxide itself is detected by iron–sulfur proteins such as aconitase. This “receptor” for superoxide may then release iron into the mitochondrion.55,56 This in turn could promote lipid peroxidation and the consequent formation of electrophilic lipids57 capable of modifying protein thiols (Figure 2). The second mechanism is the conversion of superoxide to hydrogen peroxide by the action of superoxide dismutases, which are present in both the mitochondrial matrix and intermembrane space. An important
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Effects of ROS/RNS on Mitochondrial Signaling

Mitochondrially generated ROS are important for many of the signaling pathways, which contribute to cardiovascular pathologies. In some cases, the primary stimulus for activation of these pathways has been identified. For example, the property of hydrogen peroxide is that it readily crosses membranes and can regulate cytosolic redox-sensitive signaling pathways. Whether the hydrogen peroxide acts intramitochondrially or in the cytosol is not clear. Evidence for a role of mitochondrial hydrogen peroxide in cell signaling is supported by studies with mitochondrially targeted catalase and overexpression of MnSOD. For example, mitochondrially targeted catalase decreases hydrogen peroxide and protects cells from cytokine-mediated or hypoglycemic cell death. The third mechanism is the competitive reaction of superoxide with NO to form peroxynitrite (Figure 2). Although a role for peroxynitrite in signal transduction has been identified in a number of studies, the link to the mitochondrion remains to be fully elucidated. Lastly, an emerging concept is that the combined interaction of hydrogen peroxide and RNS with peroxidase enzymes can lead to posttranslational modification of proteins. For example, tyrosine residues can be nitrated by myeloperoxidase in the presence of both nitrite and hydrogen peroxide. This may be particularly important in cardiovascular disease because myeloperoxidase levels are an increased risk factor for CVD, and protein targets include fibrinogen and apolipoprotein A1. Because the reactivities of superoxide, hydrogen peroxide, and peroxynitrite are distinct, this allows the possibility of activation of different signaling pathways depending on the relative proportions of each of these ROS/RNS.

Recently, the potential for crosstalk between NO and ROS at the level of the mitochondrion has been proposed. NO can bind to a number of the respiratory complexes, but the most sensitive target is the heme group in cytochrome c oxidase. Partial inhibition of electron transport by NO leads to backup of electrons in complexes I to III, and these reduced forms of the complexes generate more ROS. In this context, reports of a mitochondrial NOS or mitochondrial targeting of cytosolic NOS isoforms are particularly interesting because of the potential for linking NO formation with control of mitochondrial ROS production. The function of the NO-cytochrome c oxidase pathway appears to be intimately related to the maintenance of oxygen gradients within tissues. This occurs at one level, through the acute modulation of actively respiring mitochondria; at a second level, through the regulation of mitochondrial biogenesis in a cGMP-dependent manner; and at a third level, through the impact of NO on the response to hypoxia. Because loss of the NO/cGMP pathway is an early event in the development of atherosclerosis, it is interesting to speculate that this loss could enhance mitochondrial dysfunction in the vessel wall through decreased mitochondrial biogenesis.

These findings have led us, and others, to propose that increased levels of NO derived from inducible NOS can substantially inhibit the respiratory chain to the detriment of adequate ATP production. This is effectively an NO-dependent hypoxia (ie, “nitroxia”) in which the generation of high levels of ROS/RNS is likely to occur. Furthermore, the sensitivity of the respiratory chain to NO inhibition changes in response to stress by mechanisms that have yet to be defined. For example, in a model of cardiac pressure overload, the concentration of NO at which cardiac function is impaired is decreased. Initially, this may be an adaptation to the hypoxic stress associated with cardiac failure. Later, the reaction of NO with superoxide increases protein nitration and may lead to mitochondrial dysfunction and progression of the disease. An interesting series of studies have also supported the concept that NO derived from endothelial NOS (eNOS) under physiological conditions is beneficial through a mechanism involving the modulation of myocardial oxygen consumption.

Although evidence implicates peroxynitrite in mitochondrial protein and DNA damage, it is also clear that it may be important in signal transduction. Although it is clear that NO is derived from NOS, the source of superoxide is not known, but may be mitochondrial. Examples of signaling proteins that can be activated by peroxynitrite include some of the mitogen activated protein kinases (MAPKs), S-AMP-activated kinase (AMPK), and p21 ras.
vascular agents angiotensin II, epidermal growth factor (EGF), transforming growth factor (TGF)-β, and tumor necrosis factor (TNF)-α are capable of modulating mitochondrial ROS (Figure 3). The mitochondrial contribution to growth factor signaling appears to involve the trans-activation of the growth factor receptors and is associated with the protection against oxidative stress.

Studies of the mechanisms through which mitochondria integrate cell death and survival signals support the hypothesis that mitochondrial ROS/RNS play a role in these signaling pathways, particularly the MAPKs (Figure 3). Specific examples include both the extracellular signal-regulated kinases 1 and 2 (ERKs), c-jun N-terminal kinase (JNK), and p38 MAPK. The downstream effects of MAPK activation via the mitochondria are dependent on the cell type and conditions. An interesting mechanism has emerged linking mitochondria with hypertension through the control of mitochondrial K₈ channels. In vascular smooth muscle cells, it has been shown that mitochondrial ROS can be stimulated by angiotensin II through opening of the K₈ channel, and this results in the redox activation of MAPKs.

Diabetes is associated with increased ROS/RNS production from vascular cells, mitochondrial dysfunction, and is a risk factor for the subsequent development of atherosclerosis. It has been suggested that a single mtDNA mutation is responsible for modifying metabolic pathways and thus contributes to the etiology of diabetes. Importantly, hyperglycemia can also lead to mtDNA damage through increased mitochondrial ROS formation. These results suggest that mitochondria may not only be important in the initiation of processes leading to diabetes but may also establish a feed-forward mechanism that exacerbates the pathology. An interesting example with implications for cardiovascular disease is the potential role of peroxynitrite and mitochondrial ROS in the responses of the cell to hyperglycemia. It has been suggested that the antidiabetic drug metformin may exert its effects by promoting ROS formation at complex I, which in turn leads to peroxynitrite formation and activation of AMPK, as previously described. Because these signaling pathways are protective, this could represent an example of the beneficial effects of peroxynitrite in signal transduction.

Investigators in the cancer field have also recognized the potential importance of mitochondrial ROS formation in the development of this disease, and these concepts may apply to cancer. In cancer, cellular proliferation can be stimulated by mitochondrial ROS, which in turn can be promoted by the accumulation of mtDNA damage. The resultant ROS can then cause the uncontrolled activation of proliferative signaling pathways. For example, oxidative stress in both cancer and cardiovascular disease can enhance angiogenesis by decreasing MnSOD activity, thereby altering the regulation of MAPKs and the subsequent expression and activation of matrix metalloproteinases 2 and 9.

**Lipid Oxidation in Atherosclerosis and Adaptation to Stress**

The oxidative hypothesis for atherosclerosis has been critical in the development of our current understanding of the molecular mechanisms of the disease. The central concept is that oxidative modification of low-density lipoprotein (LDL) promotes a proinflammatory response, recruitment of macrophages, and the development of atherosclerotic lesions. However, it is becoming increasingly clear that vascular cells also have the capacity to adapt to oxidative stress through cellular antioxidant glutathione (GSH). Early studies with oxidized LDLs (oxLDLs) showed that low levels were cytoprotective, through mechanisms involving increasing levels of the intracellular antioxidant glutathione (GSH). Later studies revealed that this response was mediated by the transcriptional control of genes regulated by the electrophile response element, including heme oxygenase-1.

Although oxLDL contains a mixture of distinct lipid peroxidation products, it is likely that many of these effects are mediated by specific electrophilic lipids. In support of this hypothesis: (1) electrophilic lipids regulate GSH levels, and polymorphisms in the proteins controlling GSH synthesis are associated with increased inflammatory disease in human populations; (2) depletion of GSH or loss of heme oxygenase in animal models of cardiovascular disease enhances susceptibility to the disease process; (3) electrophilic lipids derived from both enzymatic and nonenzymatic lipid peroxidation can be detected in the vasculature in both humans with cardiovascular disease and in animal models.

One of the challenges in understanding how oxidized lipids mediate these biological effects has been the difficulty in following the fate of these lipids in the cell and monitoring the protein adducts that are formed by these molecules. We have approached this by synthesizing tagged lipids so that both protein adducts and intracellular localization can be addressed. The example shown in Figure 4 is the fluorescent

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**Figure 3.** Overview of mitochondrial redox signaling pathways. Mitochondria respond to a variety of stimuli, including extracellular and cytosolic ROS, as well as pathways initiated by growth factors and inflammatory mediators. They respond by further producing ROS, which can promote pathways leading either to cell death or adaptation to stress. In the case of cytoprotection, mitochondrial ROS can control MAPKs and mitochondrial ion channel activation and thereby regulate cell signaling. However, depending on the conditions, mitochondrial ROS can also cause cell death through mtDNA damage, protein modification, and bioenergetic dysfunction. Antioxidants, which decrease mitochondrial ROS formation, will have effects on these pathways that will be determined by the location, concentration, and specificity of the antioxidant.
derivative of the cyclopentenone prostaglandin 15-deoxy-Δ(12,14)-prostaglandin J2 (15d-PGJ2).28 The reticular mitochondrial network in endothelial cells is shown by the staining of the mitochondrial-specific dye Mitotracker, which colocalizes with the green fluorescence of the BODIPY-tagged 15d-PGJ2 (Figure 4). The mechanism for the mitochondrial association of the oxidized lipid is unknown but is saturable and associated with increased stimulation of mitochondrial ROS formation.28 We have also recently shown that oxLDL induces mitochondrial ROS formation but the mediator in this case has not been identified.27 These data have led to the hypothesis that mitochondria can detect changes in extracellular oxidative processes and modulate cell function through the regulation of cell signaling. It is now clear from our own work and that of others that the reactivity of lipid peroxidation products with cellular subproteomes, including the electrophile-responsive proteome, leads to distinct biological responses.122–124 Depending on the reactive lipid, these protein modifications may contribute to protection against vascular damage or, alternatively, to the development of cardiovascular diseases.

Future Prospects

It is now becoming clear that the mitochondrion is not only integrated into the metabolic function of the cell but also the signal transduction pathways that control cellular responses. The loss of control of free radical formation from the mitochondrion can contribute to the pathology of CVD through a number of mechanisms including damage to mtDNA. The challenge is now to determine the precise molecular switches and second messengers which transduce mitochondrial ROS to cell signals. These emerging concepts also provide the impetus to determine how mitochondrial dysfunction contributes to human disease. Of particular interest are lipid oxidation products that can be generated both nonspecifically and through the cyclooxygenase and lipoxygenase pathways. These compounds interact with the mitochondrion and induce the formation of ROS. Some of these signaling pathways contribute to the adaptive antiatherogenic responses of the endothelium. Interestingly, the electrophilic lipids, which at high concentrations are toxic to cells, play a critical role in mediating the adaptive response of endothelial cells. It is now known that pharmacological inhibition of the cyclooxygenase pathway can remove potentially vasculoprotective prostaglandins, and we speculate that the electrophilic lipid metabolites from this pathway are also cytoprotective through the induction of antioxidant defenses. Fully defining the electrophile-responsive proteome in endothelial cells will provide the molecular basis of the distinction between adaptive and proapoptotic responses in the vasculature. Because lipid peroxidation products are also formed in response to exercise, we suggest that it is the activation of this adaptive response that contributes to the beneficial effects of physical activity for cardiovascular health.18,125 Perhaps the most exciting prospect is the development of specific targeting strategies to deliver redox active molecules to the mitochondrion, which offers the possibility of a therapeutic intervention to correct defects in mitochondrial redox signaling.126

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Disclosures

None.

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