Mitochondrial Reactive Oxygen Species and Vascular Function
Less Is More

Julie K. Freed, David D. Gutterman

Reactive oxygen species (ROS), conventionally known for causing cellular damage, are now accepted as important signaling molecules both physiologically and in the pathogenesis of cardiovascular disease. Elevated levels of ROS have been linked to the development of disorders, such as diabetes mellitus, hypertension, hypercholesterolemia, obesity, and atherosclerosis.1–4 Conversely, oxidative stress has been shown to stimulate and regulate multiple cell functions, including cell growth and proliferation, apoptosis, host defense, genomic stability, and vascular tone.5–8 An emerging concept is evolving of an optimal physiological range of ROS required to maintain cell homeostasis. Redox balance in the endothelium is a model example where ROS critically regulate vascular smooth muscle tone and tissue perfusion.

Endothelial cells produce an array of ROS, including superoxide (O$_2^-$), hydrogen peroxide (H$_2$O$_2$), peroxynitrite (ONOO$^-$), hydroxyl radicals (OH$^-$), lipid peroxides, and other radicals. O$_2^-$ production in the picomolar range reacts quickly with superoxide dismutase to form H$_2$O$_2$, a freely diffusible and stable form of ROS, with typical characteristics of a cell-signaling molecule that can participate in compensatory vasodilation in disease.9 Peroxynitrite, formed as the product of nitric oxide synthase and superoxide dismutase to form H$_2$O$_2$, a freely diffusible and stable form of ROS, with typical characteristics of a cell-signaling molecule that can participate in compensatory vasodilation in disease.9 Peroxynitrite, formed as the product of nitric oxide synthase and superoxide dismutase to form H$_2$O$_2$, a freely diffusible and stable form of ROS, with typical characteristics of a cell-signaling molecule that can participate in compensatory vasodilation in disease.

The various sources of oxidative stress within the vascular endothelial cell include xanthine oxidase, NAD(P)H oxidase, uncoupled endothelial nitric oxide synthase, and the mitochondrial electron transport chain (mETC), whereas antioxidant defense enzymes are located in peroxisomes (catalase), extracellularly (superoxide dismutase), within organelles including mitochondria (superoxide dismutase, glutathione peroxidase), or within the cytosol (glutathione peroxidase, superoxide dismutase, amino acids, peroxiredoxins).12 These varied distributions support the potential for regionally selective ROS production, an important characteristic of signaling molecules. Of the mentioned ROS-producing enzymes, the mETC is a significant source of ROS. Complexes I, II, and III within the mETC are all capable of producing O$_2^-$, which is rapidly converted to H$_2$O$_2$, but only complex III can generate ROS within the intermembrane space, which facilitates signaling to the cytosol.13,14 Mitochondrial-derived ROS carry the stigma of being linked to pathological conditions, for example, diabetes mellitus, alcoholic liver disease, Alzheimer, and ischemic heart disease, among others.15–18 However, more recent insights suggest that more constrained generation of ROS by the mitochondria is integral in physiological regulation as well.

The tight regulation of mitochondrial redox balance under normal conditions is supported by a number of observations. For example, NO protects against mitochondrial ROS production through a variety of mechanisms, including direct quenching of superoxide and direct inhibition of mETC components.19 In contrast, elevations in intracellular Ca$^{2+}$ in the presence of partial mETC inhibition or inner membrane depolarization promote ROS formation.20 Other known regulators and inducers of mitochondrial ROS include the inner membrane potential (ATP) regulated by potassium channels, including ATP-dependent K$^+$(mito K$_{ATP}$) channels and endogenous uncoupling proteins (UCP1, UCP2), sphingolipids, and isoflavones.21–24

Katakam et al provides new evidence for mitochondrial membrane potential as a critical vascular signaling mechanism by demonstrating mitochondrial-dependent stimulation of endothelial nitric oxide synthase in response to mitochondrial membrane depolarization. Interestingly, there was a ROS-dependent and ROS-independent component to this response, providing evidence of a novel redox negative feedback loop, as NO inhibits mitochondrial ROS production. The current study also implies that, whereas mitochondrial ROS in high concentrations or strategic cellular locations may quench and eliminate NO, under some circumstances (eg, treatment with mito K$_{ATP}$ openers), mitochondrial ROS can stimulate endothelial production of NO from nitric oxide synthase.

Wortmanin reduced dilation to 2 distinct mito K$_{ATP}$ openers, Bristol Meyers Squibb-191095 (BMS) and diazoxide, showing commonality of the phosphoinositide-3 kinase/endothelial nitric oxide synthase pathway in dilator signaling for both agents. Interestingly, mitochondrial ROS generation was necessary only for the dilation to diazoxide, but not BMS. The authors explain that both agents act on mito K$_{ATP}$ channels to initiate this depolarization, based on their previous work.

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However, other explanations may be relevant. As the response to each was different, it is difficult to elucidate which response, if either, is most physiologically relevant. A major obstacle is the fact that the molecular identity of mito K$\text{ATP}$ remains unknown, precluding selective genetic manipulation of channel expression, which might answer these questions. Additional investigation is needed to reveal the non-ROS–mediated pathway of nitric oxide synthase activation by mito K$\text{ATP}$ channel openers. Perhaps, BMS has nonspecific pleotrophic effects beyond mitochondrial membrane depolarization.

Numerous studies have shown that hyperpolarization of the mitochondria (elevation of $\Delta \psi$) triggers release of O$_2^{-}$, predominantly at complex III. Combined with evidence that mitochondrial uncoupling proteins can inhibit formation of ROS, it is plausible that depolarization of the mitochondria would prevent ROS release. However, more recent studies show that the situation is more complex. Depending on the respiratory state of the mitochondria and redox state of the cell, either depolarization or hyperpolarization can stimulate oxidative stress within the mitochondria. It has been proposed that there is a U-shaped curve representing the relationship between mitochondrial $\Delta \psi$ and ROS formation, with physiological levels of ambient oxidant production spanning the nadir of the curve.

The role of intracellular Ca$^{2+}$ on mitochondrial ROS formation is similarly complex. Mitochondria respond to elevations in cytosolic Ca$^{2+}$ by acting as a high-capacity, low-affinity buffering system. Based on previous studies, increases in mitochondrial Ca$^{2+}$ can increase ROS production through stimulation of the mETC, as well as promoting release of cytochrome C. Katakam et al reported increases in intracellular Ca$^{2+}$ levels from both diazoxide and BMS, both attributed to mito K$\text{ATP}$ channel activation. However, a necessary role for mitochondrial membrane depolarization in cytosolic calcium elevation was not proved in the current study. Furthermore, it is possible that increased Ca$^{2+}$ levels are buffered by the mitochondria to effect ROS production. Of note, there was a greater increase in intracellular Ca$^{2+}$ after diazoxide versus BMS treatment, consistent with the greater rise in mitochondrial superoxide (MitoSOX; m-hydroethidine fluorescence) seen with diazoxide treatment. Future studies can evaluate whether diazoxide-induced increases in Ca$^{2+}$ are buffered by the mitochondria, resulting in an increase in mitochondrial Ca$^{2+}$-stimulated ROS production. BMS appeared to have a greater effect on mitochondrial membrane depolarization. Future studies are needed to clarify the exact signaling sequence linking mitochondrial membrane depolarization, cytosolic calcium elevation, and mitochondrial ROS generation.

In summary, the report by Katakam et al suggests that mitochondrial membrane depolarization, through mitochondrial ROS-dependent and -independent mechanisms, generates endothelium-derived relaxing factors, including NO, that promote tissue perfusion. This study supports the role of mitochondrial ROS as signaling molecules that regulate endothelial cell function, and ultimately cerebral vascular tone. Although the connection involving the mito K$\text{ATP}$ channel and mitochondrial-derived ROS has proven to be key in limiting ischemia/reperfusion damage in myocardium, the current study supports prior work that sets the stage to explore these beneficial mechanisms in the cerebral vasculature as well, contributing to the concept of targeting mitochondria as a novel therapeutic target in the treatment of stroke.

Disclosures

None.

References


Key Words: superoxide • mitochondria • nitric oxide • oxidative stress • vasodilation • cerebral circulation • potassium channels
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