Mechanism of reactive oxygen species generation after opening of mitochondrial K<sub>ATP</sub> channels

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OPENING of the ATP-sensitive K<sup>+</sup> (K<sub>ATP</sub>) channel mediates the cardioprotective effect induced by pathophysiological stressors such as ischemic preconditioning (IPC) (15, 29), heat shock (19), and pharmacological agents, including adenosine (5), ACh (26), opioids (12), monophosphoryl lipid A (31), phosphodiesterase 5A (PDE5A) inhibitors (24, 27), and mTOR inhibitor, rapamycin (20). In addition, direct opening of the mitochondrial K<sub>ATP</sub> (mitoK<sub>ATP</sub>) channels with diazoxide induces early and delayed preconditioning effects that are abolished by the channel inhibitor 5-hydroxydecanoate (5-HD) (23). The mitoK<sub>ATP</sub> channels are activated when intracellular ATP levels drop. Within 1–3 min of ischemia, there is a pronounced shortening of the action potential duration (APD) secondary to activation of the K<sub>ATP</sub> channels (6). Activation of K<sub>ATP</sub> channels has been reported to be partially responsible for the increase in outward K<sup>+</sup> currents, shortening of APD, and the increase in extracellular K<sup>+</sup> concentration during anoxic or globally ischemic conditions (4). Because there was a lack of correlation between the APD shortening and cardioprotection with the pharmacological openers of K<sub>ATP</sub> channels (17), Garlid et al. (14) first proposed that mitoK<sub>ATP</sub> channels were involved in the cardioprotective effect. By using reconstituted mitochondrial vesicles or isolated mitochondria and measuring potassium flux, these investigators demonstrated that heart and liver mitoK<sub>ATP</sub> channels shared pharmacological properties with the channels found in sarcolemma while possessing a distinct profile. Furthermore, it was shown that opening of mitoK<sub>ATP</sub> channels leads to the generation of reactive oxygen species (ROS) by the mitochondria and represents an important mechanism that is required for the cardioprotective effect of IPC (25, 30). Opening of these channels allowed potassium to enter the mitochondrial inner matrix, which causes generation and release of ROS from the respiratory chain (21). ROS then act as second messengers to activate a downstream pathway of protective kinases, including protein kinase C (PKC), that finally converge on the cardioprotective end effector as shown in Fig. 1. One of the principal downstream effectors of ROS is PKCε (2), which is translocated to the mitochondria (3). Cardioprotection conferred by IPC and pharmacological agents is blocked by ROS scavengers before the index ischemia (11, 25). In most earlier studies, mitoK<sub>ATP</sub> channels were proposed to be end effectors, and the channels were assumed to open during the index ischemia (13, 15). Recent studies, however, suggest that opening of mitoK<sub>ATP</sub> channels is also the initial trigger of the cardioprotective effect, promoting the generation of ROS and inducing the activation of PKCε (11, 25). Other studies have suggested that mitoK<sub>ATP</sub> channels act both as a trigger as well as an end effector of IPC (16). In contrast to these studies, Hanley and coworkers (10) recently challenged that diazoxide does not evoke superoxide (which dismutates to H<sub>2</sub>O<sub>2</sub>) from the respiratory chain by a direct mechanism. They reported that the stimulatory effects of this compound on mitochondrial respiration and oxidation of dichlorodihydrofluorescein (fluorescent probe for ROS) is not due to the opening of mitoK<sub>ATP</sub> channels. Moreover, these authors suggested that inhibitory effect of decanoate on diazoxide-induced flavoprotein oxidation supports the notion that 5-HD acts as a metabolic substrate rather than a mitoK<sub>ATP</sub> channel inhibitor. Clearly, there are controversial issues that need to be resolved in the future.

There has also been considerable interest in the role of the nitric oxide (NO)-cGMP-protein kinase G (PKG)-pathway in protection of the heart against ischemia-reperfusion injury (18). PKG is a serine/threonine protein kinase and is one of the major intracellular receptors for cGMP. Inhibition of cGMP-specific PDE5A with selective potent inhibitors, sildenafil citrate (Viagra) and yardenafil (Levitra), induced protective effects against ischemia-reperfusion injury in the intact heart (24, 28) and adult cardiomyocytes (9). Conceptually, these drugs inhibit the enzymatic hydrolysis of cGMP, which in turn maintains the tissue accumulation of cGMP, leading to downstream protective mechanisms involving activation of PKG and opening of mitoK<sub>ATP</sub> channels. Our studies showed that sildenafil induces IPC through NO generated from endothelial and/or inducible nitric oxide synthase, activation of PKC, and opening of the mitoK<sub>ATP</sub> channels (reviewed in Ref. 22). Similarly, bradykinin mimics IPC by generating ROS, and it does so via cGMP activation of PKG (8). Furthermore, Costa et al. showed that PKG + cGMP induce mitoK<sub>ATP</sub> channel opening via an endogenous PKC-ε in isolated mitochondria (7).

It is quite obvious from the above review that there is overwhelming evidence for the involvement of ROS in cardioprotection. However, there is no direct demonstration that mitoK<sub>ATP</sub> channel opening actually leads to ROS production in the mitochondria. Moreover, the mechanism and the site of ROS generation are unknown. What Garlid and associates (1) have proposed in this issue of the American Journal of Physiology-Heart and Circulatory Physiology is a novel mechanism of ROS generation with the opening of mitoK<sub>ATP</sub> channel. By using a series of fluorescent probes that are sensitive to hydrogen peroxide and pH, they measured their changes in suspensions of isolated rat heart and liver mitochondria. The data suggest that the K<sup>+</sup>-specific ionophore valinomycin quantitatively reproduced the ROS production similar to that observed by the mitoK<sub>ATP</sub> opens diazoxide and chromakalim. They further show that alkaline pH but not increasing the matrix...
Consequent increase in steady-state superoxide production. Results in the increase in reduction at the flavin site and chain. The increase of matrix pH causes retardation of the (NADH:ubiquinone oxidoreductase) of the electron transport pose that electrons are passed to ubiquinone from complex I.

volume itself enhanced ROS production. These results are supported by carefully and systematically presented data. Neutralization of the matrix pH with acetic acid led to the blockade of the stimulatory effect of valinomycin on ROS production. Furthermore, ROS production exhibited a biphasic dependence on valinomycin concentration, with peak production occurring at valinomycin concentrations that catalyze about the same K⁺ influx as mitoK<sub>ATP</sub> channel openers. The ROS production decreased with higher concentrations of valinomycin and with all concentrations of a classical protonophoretic uncoupler.

These data suggest that the increase in ROS is due specifically to K⁺ influx into the matrix and is mediated by the attendant matrixalkalinization. The authors went on to demonstrate the applicability of this mechanism with PKG-directing and mitoK<sub>ATP</sub>-dependent manner. The authors propose that electrons are passed to ubiquinone from complex I (NADH:ubiquinone oxidoreductase) of the electron transport chain. The increase of matrix pH causes retardation of the electron flow at the F MnH2 or FMN semiquinone sites. This results in the increase in reduction at the flavin site and consequent increase in steady-state superoxide production.

Overall, this study offers a provocative mechanism by which ROS are generated with the opening of the mitoK<sub>ATP</sub> either directly with the use of pharmacological openers or signaling pathway(s) involving activation of PKG and PKC. Obviously, one of the limitations of this study is that it was performed in vitro in the isolated heart and liver mitochondrial preparations. Therefore, it is far too soon to make predictions of the relevance of these findings in explaining the mechanism of ROS generation in vivo with the cardioprotective modalities, including ischemic and pharmacological preconditioning. Clearly, future investigations are needed to address this important issue.

Editorial Focus

CADIOPROTECTION

Fig. 1. Flow diagram showing the signal transduction steps that lead to cardioprotection after ischemic and pharmacological preconditioning. See text for a detailed explanation. PED5A, phosphodiesterase 5A; PKG, protein kinase G; ROS, reactive oxygen species.

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GRANTS

The study was supported in part by National Heart, Lung, and Blood Institute Grants HL-51045, HL-59469, and HL-79424.

H2042

AJP-Heart Circ Physiol • VOL 291 • NOVEMBER 2006 • www.ajpheart.org

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