Transient Mitochondrial Permeability Transition Pore Opening Mediates Preconditioning-Induced Protection

Derek Hausenloy, MBChB; Abigail Wynne, BSc; Michael Duchen, PhD; Derek Yellon, DSc

**Background**—Transient (low-conductance) opening of the mitochondrial permeability transition pore (mPTP) may limit mitochondrial calcium load and mediate mitochondrial reactive oxygen species (ROS) signaling. We hypothesize that transient mPTP opening and ROS mediate the protection associated with myocardial preconditioning and mitochondrial uncoupling.

**Methods and Results**—Isolated perfused rat hearts were subjected to 35 minutes of ischemia/120 minutes of reperfusion, and the infarct-risk-volume ratio was determined by tetrazolium staining. Inhibiting mPTP opening during the preconditioning phase with cyclosporine-A (CsA, 0.2 μmol/L) or sanglifehrin-A (SfA, 1.0 μmol/L) abolished the protection associated with ischemic preconditioning (IPC) (20.2±3.6% versus 45.9±2.5% with CsA, 49.0±7.1% with SfA; P<0.001); and pharmacological preconditioning with diazoxide (Dzx, 30 μmol/L) (22.1±2.7% versus 46.3±3.0% with CsA, 48.4±5.5% with SfA; P<0.001), CCPA (the adenosine A1-receptor agonist, 200 nmol/L) (24.9±4.5% versus 54.4±6.6% with CsA, 42.6±9.0% with SfA; P<0.001), or 2,4-dinitrophenol (DNP, the mitochondrial uncoupler, 50 μmol/L) (15.7±2.7% versus 40.8±5.5% with CsA, 34.3±3.1% with SfA; P<0.001), suggesting that mPTP opening during the preconditioning phase is required to mediate protection in these settings. Inhibiting ROS during the preconditioning protocols with N-mercaptoptopropionylglycine (MPG, 1 mmol/L) also abolished the protection associated with IPC (20.2±3.6% versus 47.1±3.8% with MPG; P<0.001), diazoxide (22.1±2.7% versus 56.3±3.8% with MPG; P<0.001), and DNP (15.7±2.7% versus 50.7±6.6% with MPG; P<0.001) but not CCPA (24.9±4.5% versus 26.5±8.4% with MPG; P=NS). Further experiments in adult rat myocytes demonstrated that diazoxide induced CsA-sensitive, low-conductance transient mPTP opening (represented by a 28±3% reduction in mitochondrial calcine fluorescence compared with control; P<0.01).

**Conclusions**—We report that the protection associated with IPC, diazoxide, and mitochondrial uncoupling requires transient mPTP opening and ROS. (Circulation. 2004;109:1714-1717.)

**Key Words:** ischemia ■ myocardial infarction ■ free radicals ■ reperfusion

**Despite ongoing intensive investigation, the actual mechanism responsible for the powerful protective phenomenon that is ischemic preconditioning (IPC) has not yet been elucidated. Studies have implicated mitochondria in protective mechanisms associated with IPC. Pharmacological opening of the purported mitochondrial K\textsubscript{ATP} channel has been demonstrated to cardioprotect by preserving mitochondrial energy production during ischemia-reperfusion.**

We and others have implicated modest mitochondrial uncoupling as a critical event in preconditioning-induced protection. Mitochondrial reactive oxygen species (ROS) release may mediate the preconditioning signal. We have demonstrated that the prolonged (high-conductance) mitochondrial permeability transition pore (mPTP) opening, which mediates cell death at the time of reperfusion, can be inhibited by preconditioning.

The present study focuses on the physiological transient (low-conductance) form of mPTP opening, which does not lead to cell death and in fact may play several important functions that may contribute to IPC-induced protection. Transient (low-conductance) mPTP opening (1) can limit mitochondrial matrix calcium load by mediating mitochondrial calcium efflux; (2) can be induced by mitochondrial uncoupling; and (3) can mediate mitochondrial ROS release.

This would suggest that low-conductance transient mPTP opening may contribute to the mechanism of IPC-induced protection. In this regard, the preconditioning mimetic diazoxide has been demonstrated to induce mPTP opening. On this basis, we hypothesized that both transient (low-conductance) mPTP opening and ROS, during the preconditioning phase, mediate both preconditioning and mitochondrial uncoupling–induced protection.

**Methods**

**Isolated Perfused Rat Heart**

Hearts excised from male Sprague-Dawley rats were Langendorff-perfused with Krebs-Henseleit buffer and subjected to 35 minutes of...
ischemia followed by 120 minutes of reperfusion, and the infarct-risk-volume ratio was determined by triphenyltetrazolium-chloride staining.2

**Treatment Protocols for Infarct Studies**
The hearts were treated as follows (n=6/group):

1. Control hearts were perfused with 0.02% DMSO or 0.005% ethanol, or Krebs-Henseleit buffer alone during stabilization.
2. IPC hearts were treated with two 5-minute periods of global ischemia with a 10-minute intervening reperfusion.
3. Hearts underwent IPC in the presence of diazoxide or CCPA in the presence of CsA/SfA.
4. Hearts were preconditioned with diazoxide or CCPA in the presence of CsA/SfA.
5. Hearts were perfused with MPC during washout.
6. Hearts were perfused with DNP in the presence of NPC.

**Model for Detecting mPTP Opening in Intact Cells**
We used an established method for detecting transient (low-conductance) mPTP opening in the intact cell.12,13 Adult rat myocytes isolated by collagenase perfusion from Sprague-Dawley rats, with the use of a previously described method,14 were incubated with calcine-AM (1.0 μmol/L) and cobalt-chloride (CoCl₂, 1.0 mmol/L), resulting in mitochondrial localization of calcine fluorescence. mPTP opening was indicated by a reduction in mitochondrial calcine fluorescence.

**Results**
Ischemic preconditioning, diazoxide, CCPA, or DNP reduced infarct size from 49.9±3.8% in control to 20.2±3.6% with IPC, 22.1±2.7% with diazoxide, 24.9±4.5% with CCPA, and 15.7±2.7% with DNP (P<0.001; Figure 1A). Inhibiting mPTP opening during the preconditioning protocol, with the use of CsA/SfA, abolished the protection associated with IPC (20.2±3.6% versus 45.9±2.5% with CsA, 49.0±7.1% with SfA; P<0.001; Figure 1A), diazoxide (22.1±2.7% versus 46.3±3.0% with CsA, 48.4±5.5% with SfA; P<0.001; Figure 1A), CCPA (24.9±4.5% versus 54.4±6.6% with CsA, 42.6±9.0% with SfA; P<0.001; Figure 1B), and DNP (15.7±2.7% versus 40.8±5.5% with CsA, 34.3±3.1% with SfA; P<0.001; Figure 1B), implicating that mPTP opening is required to mediate the protection in these settings. Given alone, neither cyclosporine-A nor sanglifehrin-A influenced infarct size (43.9±1.4% in control versus 42.8±3.5% with CsA, 48.0±4.2% with SfA; P=NS; Figure 1B).

**Reactive Oxygen Species Are Required for Protection**
The presence of the ROS scavenger MPG during the preconditioning protocols abolished the protection associated with IPC (20.2±3.6% versus 47.1±3.8% with MPG; P<0.001; Figure 1A), diazoxide (22.1±2.7% versus 56.3±3.8% with MPG; P<0.001; Figure 1A), and DNP (15.7±2.7% versus 50.7±6.6% with MPG; P<0.001; Figure 1B), implicating ROS as a mediator of protection in these settings. However,
Diazoxide Induces Low-Conductance Transient mPTP Opening

Treatment of calcine-loaded myocytes with diazoxide resulted in a reduction in mitochondrial calcine fluorescence to 72±3% of baseline values (P<0.01; Figure 2), indicating that diazoxide induces low-conductance transient mPTP opening in quiescent cells. This effect of diazoxide was abolished by cyclosporine-A (the mPTP inhibitor, confirming that the reduction in mitochondrial calcine fluorescence was due to mPTP opening) and by 5-HD (the mitochondrial KATP channel blocker) (Figure 2).

Discussion

We report that transient (low-conductance) mPTP opening and ROS, during the preconditioning phase, are required to mediate the protection associated with ischemic and pharmacological preconditioning and mitochondrial uncoupling. In the infarct studies, we demonstrated that pharmacologically inhibiting mPTP opening during the preconditioning phase completely abrogated the protection associated with IPC, diazoxide, and CCPA, indicating that mPTP opening is required for protection in these settings. In the myocyte model of mPTP opening,12,15 we demonstrated that diazoxide induces transient (low-conductance) mPTP opening, confirming the findings of previous studies.12,17 We confirm that IPC and diazoxide-induced protection is ROS-dependent and found that CCPA-induced preconditioning is ROS-independent, supporting the findings of Cohen and colleagues.6

We have previously demonstrated that modest mitochondrial uncoupling is a critical event in preconditioning-induced protection.4,5 In the present study, we show that this protection can be abolished by inhibiting mPTP opening, suggesting that mPTP opening occurs downstream of mitochondrial uncoupling, which is supported by the fact that mitochondrial uncoupling can induce mPTP opening.10 Transient mPTP opening can induce mitochondrial ROS release,11 which may explain why we found mitochondrial uncoupling–induced protection to be ROS-dependent.

Transient mPTP opening during the preconditioning phase may mediate protection by (Figure 3) reducing mitochondrial calcium load6; in this regard, diazoxide has been shown to induce mitochondrial calcium efflux through mPTP opening.12 Transient mPTP opening during the preconditioning phase also may mediate protection by mediating mitochondrial ROS release/signaling.11 We are undertaking further studies to determine whether preconditioning-induced mitochondrial ROS release occurs through mPTP opening.

Because transient mPTP opening can be induced by uncoupling, oxidation of NADH,10 and an alkaline pH,8 the

Figure 2. Mitochondrial calcine fluorescence (expressed as percentage of baseline fluorescence) in myocytes loaded with calcine and cobalt chloride demonstrate Dzx-induced reduction in mitochondrial calcine fluorescence, indicating transient (low-conductance) mPTP opening, which is abolished in the presence of either 5-HD (a mitochondrial KATP channel blocker) or CsA (an mPTP inhibitor) (*P<0.05).

Figure 3. Hypothetical scheme outlining role for transient (low-conductance) mPTP opening in myocardial preconditioning. mPTP comprises the voltage-dependent anion channel (VDAC), adenine nucleotide translocase (ANT), and cyclophilin D. Preconditioning induces transient mPTP (low-conductance) opening through mitochondrial uncoupling, ROS, and increasing matrix pH, which then protects the heart by reducing mitochondrial calcium load and facilitating ROS signaling.
preconditioning stimulus may induce transient mPTP opening by mediating uncoupling, producing mitochondrial ROS, which then oxidize NADH, or by increasing matrix pH through activation of the mitochondrial K<sub>ATP</sub> channel.

In conclusion, we report for the first time that IPC, diazoxide, CCPA, and mitochondrial uncoupling all protect by inducing transient mPTP opening during the preconditioning phase. Given that the adenine nucleotide translocase (ANT) is believed to be a component of the mPTP and the recent suggestion that the ANT forms part of the mitochondrial K<sub>ATP</sub> channel, it would be intriguing to speculate on whether agents that reportedly protect through opening of the mitochondrial K<sub>ATP</sub> channel actually protect through transient (low-conductance) opening of the mPTP.

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References
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