Pathophysiology of myocardial reperfusion injury: preconditioning, postconditioning, and translational aspects of protective measures

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Submitted 31 May 2011; accepted in final form 15 August 2011

WHAT DO WE KNOW ABOUT ischemia-reperfusion injury? Because the morbidity and mortality due to ischemic heart diseases have come to the fore in developed countries and are still increasing, it is critically important, both scientifically and socially, to know how cardioprotection is achieved in ischemic myocardium. In fact, in the clinical setting, the application of coronary thrombolysis or immediate percutaneous coronary intervention for faster recanalization has been shown to dramatically improve the outcomes of patients with acute or chronic myocardial ischemia due to impaired coronary blood supply. This finding is founded on the premise that a shorter period of index ischemia causes less damage (212).

However, even if the ischemic period is short or limited, the functional recovery of a reperfused heart is often less successful than expected due to “reperfusion injury” (188), and we still do not have a definitive intervention to eliminate reperfusion-induced myocardial damage. Therefore, it is important to fully understand the mechanisms of ischemia-reperfusion injuries and to consider cardioprotective strategies.

Dynamic Sequence of Ischemia-Reperfusion Injury

ATP depletion as the original hypothesis. To maintain cellular homeostasis, the intracellular use of both ATP and high-energy phosphates is critically important. Cellular energy metabolism depends on acetyl-CoA, which is generated through aerobic/anaerobic glycolysis or β-oxidation of free fatty acids and is then metabolized through the tricarboxylic acid cycle, which supplies ATP. Cardiomyocytes are rich in mitochondria because the highest continuous amount of ATP is consumed within the myocardium, and this demand for ATP can only be met by aerobic metabolism. When hearts are exposed to ischemia, coronary arterioles and resistant vessels significantly
dilate to increase coronary blood flow up to three to five times above basal levels and to supply as much oxygen as possible and maintain aerobic needs. However, because of the lack of anaerobic metabolic pathways, the absence of a supply of oxygen leads to the depletion of intramyocardial ATP in a short period of time, making the myocardium very susceptible to ischemia.

Initial studies on ischemic myocardium revealed that contractile arrest generally occurs within several minutes of index ischemia, followed by cellular bulging and rupture of intracellular microstructures starting 15 to 30 min later (4). This discovery led to the ATP depletion hypothesis as a central cause of cell death because a 90% decrease in ATP results in irreversible structural changes in the myocardium (4). Therefore, supplementation of ATP in the myocardium was initially proposed as an effective therapy for the prevention of ischemic myocardial death.

However, a complete depletion of ATP within the myocardium takes ~40–60 min, whereas the intracellular inorganic phosphate level promptly increases just after the onset of ischemia (120), suggesting the rapid exhaustion of intracellular high-energy phosphate. Therefore, it was then thought that a change in the intracellular pH was a trigger for this lethal cascade.

Decreasing pH and counterbalancing Ca\(^{2+}\) accumulation. Anaerobic glycolysis prevails in ischemic myocardium, causing a rapid decrease in the intracellular pH and deactivation of troponin C sensitivity to phosphofructokinase and Ca\(^{2+}\). Within several minutes, this decrease results in contractile arrest and cellular bulging. To buffer this decrease in pH, excess H\(^+\) is excreted by accelerated Na\(^+\)/H\(^+\) exchange, which in turn causes substantial Na\(^+\) influx (152). Meanwhile, intracellular ATP depletion gradually inactivates ATPases, such as the Na\(^+\)/K\(^+\) ATPase, ATP-dependent Ca\(^{2+}\) reuptake, and active Ca\(^{2+}\) excretion, resulting in Ca\(^{2+}\) overload. These results have also been confirmed in vivo (121). These changes are also accompanied by a subsequent activation of intracellular proteases, such as calpain, which causes a fragile cellular structure, hypercontracture, which leads to contraction band necrosis, and the initiation of apoptotic cascades (Fig. 1) and mitochondrial transition pore opening, which will be discussed later. Each of these factors can occur within minutes, but they proceed gradually because a low intracellular pH slows or inhibits all of them (76). This idea agrees with the observation that reoxygenation within 5 min avoids irreversible cellular damage, whereas index ischemia for more than 15 min gradually affects intracellular structures (123).

Rapid normalization of pH and overload of Ca\(^{2+}\) and reactive oxygen species upon reperfusion. Prompt reperfusion or reoxygenation will bring about a rapid restoration of substrates essential for the generation of ATP, such as glucose or free fatty acids, an instantaneous increase in the oxygen supply, and prompt normalization of the extracellular pH by pericellular washout. Indeed, all of these factors are crucial for the prevention of further ischemic cellular injury and for restoration of cellular homeostasis; however, they can also concurrently cause reperfusion injury (188). Rapid normalization of the extracellular pH will instantly create an extreme H\(^+\) gradient across the plasma membrane that triggers a robust Na\(^+\)/H\(^+\) exchange and a massive Na\(^+\) influx. This unphysiological gradient can instantly trigger the passive, inverted action of the surface Na\(^+\)/Ca\(^{2+}\) exchanger, called “reverse mode,” which absorbs Na\(^+\) accumulation via excretion but, in turn, allows intracellular Ca\(^{2+}\) overload (179) (Fig. 2). Meanwhile, rapid normalization of intracellular pH disinhibits a low pH-derived inhibition of the Ca\(^{2+}\)-dependent protease calpain, hypercontracture, and the mitochondrial permeability transition all at once and promptly accelerates myocardial damage in the early stages of reperfusion (76). This also occurs when, upon reoxygenation, ectopic xanthine oxidase is activated by Ca\(^{2+}\)-sensitive proteases (89) and the intramitochondrial respiratory chain. This activation causes a sudden recovery of aerobic metabolism and results in an overload of reactive oxygen species (ROS), mainly superoxide. Physiologically, superoxide becomes hydrogen peroxide via superoxide dismutase (SOD) (53), which is then inactivated by catalase and becomes H\(_2\)O and O\(_2\). However, robust ROS generation beyond this catalytic process generates excessive hydroxyl radicals, which are very unstable but have a high potential to damage cellular structures, enzymes, or channel proteins on the cellular membrane (200). These events, together with activation of inflammatory cascades and facilitation of bioactive autacoids, such as cytokines or catecholamines, make cells more susceptible to death (Fig. 3) or myocardial contractile arrest.

Fig. 1. Ion exchanges during ischemia: 1) excretion of H\(^+\) due to pH lowering, 2) deactivation due to loss of ATP, and 3) reduction of Na\(^+\)/Ca\(^{2+}\) exchange due to lowered extracellular pH and intracellular accumulation of Na\(^+\).
dysfunction (183) immediately after the onset of reperfusion. Furthermore, impaired intracellular Ca\textsuperscript{2+} and ROS regulation can propagate to adjacent cells through gap junctions to further spread injury (159). Finally, after 30–60 min of reperfusion, a gradual recovery of Ca\textsuperscript{2+} excretion and ATP-dependent Ca\textsuperscript{2+} reuptake in sarcoplasmic reticulum takes place, and the cells return to homeostasis. This ischemia-reperfusion process makes the intracellular Ca\textsuperscript{2+} concentration dual peaked (120), with one peak occurring at 15–60 min after the onset of index ischemia and the other peak occurring within 30 min of reperfusion.

Various modes of death and their regulation under ischemia-reperfusion. During the above sequence of events, Ca\textsuperscript{2+} overload and excessive ROS generation can trigger multiple modes of cell death, such as necrosis and apoptosis (168). Myocardial necrotic changes generally include cellular swelling as an initial change, followed by rupture of cellular membranes, degradation of intracellular proteins or structures induced by Ca\textsuperscript{2+}-dependent proteases such as calpain (89), Ca\textsuperscript{2+}-induced hypercontracture [which induces mechanical rupture of muscle fibers (159)], and direct cleavage of DNA by free radicals originating from excessive ROS. Necrotic changes often require focal recruitment of inflammatory cells for subsequent scavenging activity.

Apoptosis is usually triggered by intracellular Ca\textsuperscript{2+} overload, which induces the processing of procaspase-8 into active caspase-8 and the activation of Bax, which lead to the release of the apoptosis-inducing factor, Smac, and cytochrome-c from mitochondria. Apoptosis-inducing factor translocates into the nucleus and facilitates nonspecific DNA fragmentation. Smac inactivates X chromosome-linked inhibitor of apoptosis protein, which inhibits caspase-3, and cytochrome-c forms an apoptosome complex with procaspase-9 and apoptotic protease-activating factor-1, which activates caspase-9. Together, these cascades ultimately contribute to irreversible cellular dysfunction. Ca\textsuperscript{2+} accumulation (57) and ROS induction (175) are also crucial for opening the pore that enables trafficking of nonspecific, small molecules across mitochondrial membranes. Subsequently, H\textsuperscript{+} influx into mitochondria and a decrease in the mitochondrial membrane potential result in mitochondrial...
swelling and apoptotic changes (66). Histological findings of apoptosis include nuclear chromatin condensation, making cells nonfunctional, followed by cellular shrinking and fragmentation, usually independently of the inflammatory reaction, and subsequent phagocytic clearance (7).

Necrosis prevails within the ischemic myocardium and its adjacent regions, whereas apoptosis predominantly occurs in the ischemic border and in nonischemic regions (202), reflecting the differences in the focal magnitude of anoxia, ROS accumulation, neurohormonal activation, and mechanical stress. Recent reports propose that necrotic cell death prevails when the intramitochondrial Ca\(^{2+}\) level becomes extremely low or completely lost (14). Similarly, the intracellular ATP level might also serve as a “molecular switch,” with high levels resulting in apoptosis and low levels resulting in necrosis (105).

**Adaptation and therapeutic targets for ischemia-reperfusion injury.** Because the prompt recovery of intracellular pH and reoxygenation enhances Ca\(^{2+}\) overload or ROS generation and promotes reperfusion injury as described above in Rapid normalization of pH and overload of Ca\(^{2+}\) and reactive oxygen species upon reperfusion and Various modes of death and their regulation under ischemia-reperfusion, it has long been proposed that the transient acidosis during early reperfusion (97) as well as acidic or staged reperfusion procedures (67) buffer the Ca\(^{2+}\) or ROS overload upon reperfusion. They can lead to a smaller infarct size or preservation of myocardial function (96, 97) by inhibiting Na\(^+/\)Ca\(^{2+}\) exchange and Ca\(^{2+}\) overload (91) or by directly disrupting proapoptotic signals (229), all of which might be important therapeutic targets of cardioprotection.

Accordingly, some of the membrane ion channels, such as the Na\(^+/\)H\(^+\) exchanger (228), the Na\(^+/\)K\(^+\) ATPase (59), and the Ca\(^{2+}\)-activated K\(^+\) channel (185), are possible candidates for cardioprotection due to preconditioning because of their ability to directly inhibit intracellular Ca\(^{2+}\) accumulation.

Another key therapeutic target might be excessive ROS production or prolonged catecholamine release. When myocardial ischemia occurs, presynaptic vesicles release norepinephrine via the accumulation of Na\(^+\) and subsequent activation of reverse uptake-1 (180), which facilitates norepinephrine release. Norepinephrine activates both α-adrenoceptors that cause vasconstriction and β-adrenoceptors that increase myocardial oxygen consumption. Both of these may make the cells more susceptible to ischemic damage. Indeed, many reports show that the blockade of the β-adrenoceptor will protect the myocardium from prolonged ischemia-reperfusion. However, possible pharmacological mechanisms other than hemodynamic benefits are under discussion (9, 180, 238).

On the other hand, there are a number of adaptive responses to the various kinds of stresses induced by ischemia-reperfusion, i.e., Ca\(^{2+}\) overload, ROS accumulation, neurohormonal stimuli, focal mechanical strain, and endoplasmic reticulum stress from excessive production of unfolded or misfolded proteins. Autophagy, the lysosomal bulk digestion pathway of intracellular structural proteins, contributes to physiological turnover as well as pathological removal of intracellular proteins as a housekeeping system. The process of autophagy begins by recruiting Atg-5, -12, and -16 to the intracellular lipid bilayer. These proteins are then polymerized by LC-3 to form the autophagosome. The autophagosome sequesters proteins targeted for destruction and then fuses with the protease-rich lysosome, resulting in digestion of its contents. Mitochondria also have an adaptive system involving dynamic fusion and “fission” with each other (222). A shift toward fusion favors the generation of interconnected mitochondria that form large networks and are beneficial in metabolically active cells against the dissipation of energy. Alternatively, a shift toward fission produces numerous mitochondrial fragments as morphologically and functionally distinct small spheres or short rods with an increased distribution and surface area, which is usually beneficial in quiescent cells (222). Therefore, the facilitation of autophagy (69) and mitochondrial fusion (141) might also protect against ischemia-reperfusion injury by maintaining intracellular homeostasis. In addition, the blockade of cell-to-cell connections, such as gap junctions, by modulating connexin-43 (136) could also protect the myocardium by blocking the propagation of cellular damage to neighboring cells (159) or by modulating mitochondrial ATP-sensitive K\(^+\) (K\(_{ATP}\)) channel opening (164).

**Discovery of Preconditioning**

Before the concept of ischemic preconditioning arose, cardiologists observed that patients with severe, unstable angina or acute myocardial infarction and who had experienced at least one episode of prodromal angina often exhibited less chest pain, less variation in the ST segment of ECGs, less cardiac dysfunction, or even smaller myocardial infarct size. This was despite a paradoxical increase in the total period of time suffered from ischemia, and they called this the “cardiac warm-up phenomenon” (80). In 1986, Murry et al. (134) confirmed “preconditioning with ischemia” using an in vivo canine model and defined it as a phenomenon where brief periods of ischemia accompanied by reperfusion just before sustained ischemia exert 1) a delay in ATP depletion, 2) a reduction in oxygen consumption, 3) a retention of intracellular structure, and 4) a delay or reduction of cellular necrosis due to ATP expiration, finally resulting in delayed progression or reduction of infarct size, despite an increase in the total ischemic period. This is now recognized as a narrow definition of ischemic preconditioning. The concept of cardioprotection due to preconditioning currently prevails and has been expanded on to include not only acute irreversible injuries, such as necrosis and apoptosis, but also chronic disorders, such as myocardial hibernation or remodeling, although it appears to be irrelevant to acute myocardial contractile dysfunction, such as stunning (98).

**Critical Dual Time Window: Early and Late Phases**

The original report on preconditioning (134) also mentioned that the strength of protection by ischemic preconditioning critically depends on the duration from the end of preconditioning ischemia to the onset of index ischemia. Later, the existence of dual periods for this duration was reported (123). The first period is more than several seconds and <3 h and the second one, associated with the increased expression of cardioprotective heat shock proteins (HSPs) (123), is 24–72 h. These are now widely recognized as “early and late phase” preconditioning. The two phases appear to involve different types of reactions; the former involves reactions that are completed in a short period of time, such as activation of ion channels, phosphorylation/activation of existing enzymes, or...
rapid turnover/translocation of substances, whereas the latter involves more time-consuming reactions, such as genomic modulation and expression of channel proteins, receptor proteins, enzymes, molecular chaperon proteins, or immunotransmitters.

Although these two phases differ in timing, they share some common triggers, mediators, and effectors. Finally, myocardial injury at the time of reperfusion might be a major target of both types of preconditioning as well as postconditioning; this will be discussed later (64).

Factors Underlying the Mechanisms of Preconditioning

G protein-coupled receptor agonists: adenosine, α- and β-adrenoceptor activation, and others. Downey and colleagues (109) opened the door to the investigation on mechanisms of preconditioning with a report showing that protection by ischemic preconditioning was abolished by the inhibition of the adenosine receptor before sustained ischemia in vivo. This suggested that adenosine was a trigger of ischemic preconditioning. However, they later reported a conflicting result in vitro that preischemic treatment with either adenosine or selective adenosine-A1 receptor agonist, 2-chloro-N6-cyclopentyladenosine, exerted minimal protection (49), implying that adenosine is not a candidate for pharmacological preconditioning. This inconsistency was highlighted by later reports from other groups showing successful pharmacological preconditioning with selective adenosine-A1 receptor agonist, 2-chloro-N6-cyclopentyladenosine or R-phenylisopropyladenosine, in early phase (130, 233) and late phase (91) infarct limitations in vivo, strongly suggesting the inclusion of adenosine receptor activation in ischemic preconditioning.

Later reports proposed α (68, 214)- and β (193, 209)-adrenoceptor activation as a putative trigger of ischemic preconditioning, based on the findings that receptor blockade abrogated ischemic preconditioning-induced cardioprotection. However, there were contradictory findings. Downey and colleagues reported that neither specific catecholamine receptor antagonists (207) nor depletion of intramyocardial catecholamine storage and release (8) blocked ischemic preconditioning, whereas exogenous catecholamine or adrenoceptor agonists did precondition the heart (207, 214). Vatner and colleagues also reported a similar observation that cardiac denervation did not block early phase but did blunt late-phase ischemic preconditioning via α1-adrenoceptor signaling (102).

In search of effective receptor subtypes, Tsuchida et al. showed the direct involvement of α1b-adrenoceptor in ischemic preconditioning (214), but studies using transgenic mice support α1a rather than by α1b (160). On the other hand, the β2-adrenoceptor is reported to confer cardioprotection in ischemic preconditioning (209), whereas preischemic β1-activation could be an alternative (193).

Indeed, reasons for such contradictions between the receptor blockade of ischemic preconditioning and pharmacological preconditioning with receptor agonists, or the inconsistency of positive or negative cardioprotection among the reports, are not fully understood. One reason for these differences may be due to the experimental models used; however, we should consider other reasons.

First, a feasible explanation is that there are multiple, parallel mechanisms induced by preconditioning ischemia, all of which can exert cardioprotection by themselves or in harmony. Accordingly, adenosine-dependent and α1-adrenoceptor mechanisms might reflect this relationship (12, 214).

Second, pharmacological interventions do not necessarily mimic ischemic preconditioning accurately because of the half-life of mimetic agents; the majority of the agents might act for a longer period of time than the brief period of time required for preconditioning ischemia. Because the increased endogenous adenosine production induced by ischemic preconditioning confers cardioprotection in both preconditioning and reperfusion periods (95) and because adenosine-A1 receptor activation around the onset of reperfusion also protects the myocardium (111), the preischemic administration of agents might still be effective beyond the sustained ischemic period.

Third, a critical time window for the involvement of the respective receptor activation is considered. For example, sustained transgenic activation of α1b-adrenoceptor did not elicit cardioprotection (160), whereas temporal blockade during the preconditioning period protected the myocardium (68, 214). Also, β1-adrenoceptor activation is reported to be beneficial during the preconditioning period but deleterious after reperfusion (193).

Finally, some reports do not support the contribution of adenosine in ischemic preconditioning-induced cardioprotection, because they failed to show that preconditioning-induced cardioprotection resulted in an increase in the intramyocardial level of adenosine. One possible reason for this failure might be due to how the level of adenosine was measured and the extremely short biological half-life of adenosine. We have also experienced this inconsistency when collecting samples without the prompt usage of a stop solution containing EDTA, adenosine deaminase inhibitors, and dipyridamole. Therefore, this may be due to the prompt intracellular uptake or ultrarapid degradation of adenosine under physiological conditions. Accordingly, this idea might be further supported by the observation that the loss of cardioprotection by the addition of exogenous adenosine was restored by extending its biological half-life by either a coadministration with dipyridamole to delay clearance through intracellular uptake (11) or a sustained targeting release using a liposomal envelope (201).

Further pharmacological analyses revealed the importance of other G protein-coupled receptor (GPCR) members, opioid receptors (22, 181), and bradykinin-B2 receptors (52, 101) in pharmacological and ischemic preconditioning-induced cardioprotection in both the early (181) and late (22) phases of ischemic preconditioning. For example, the contribution of each opioid receptor (δ-, κ-, and μ-subtypes) has been reported in direct (107), remote, (144) or secondary protection of cardiac myocytes by acting on the central nervous system (106). However, the protection in the clinical setting still remains controversial (206, 219). As is summarized in Fig. 4, top left, various endogenous as well as exogenous stimulants cause their respective cardioprotective effects via the activation of unique or combined GPCR subtypes.

Downstream of GPCR: PKC, PKA cascades, and more. GPCRs couple to G proteins, consisting of a Gα- and a Giβγ-subunit, and the overall properties of each GPCR upon activation are generally defined by Gα-subtypes, such as Gs, Gi, and Gq. Gi and Gq positively and negatively modulate, respectively, cAMP production, whereas Ga activates phospholipase C and leads to PKC activation (Fig. 4).
Many reports have shown that ischemic preconditioning activates PKC (93, 237) and that PKC blockade abrogates infarct limitation induced by ischemic preconditioning (194, 237). In addition, repeated ischemic preconditioning instantly increases intramyocardial cAMP levels; moreover, either transient β-adrenoceptor stimulation (110) or intramyocardial pharmacological cAMP accumulation (167) mimics the cardioprotective behavior of preconditioning, and PKA inhibition significantly and substantially reduced the preconditioning-induced cardioprotection (167). Among PKC subtypes, PKC-δ inhibition or PKC-ε activation have been reported to be relevant to preconditioning-induced cardioprotection (186) in human myocardium, whereas we have previously reported the importance of Ca²⁺-dependent, classic PKC in animal models (236).

As a possible downstream effector, we have previously reported that PKC directly activates ecto-5'-nucleotidase, located on the cell membrane (92), suggesting that adenosine could benefit the myocardium as not only a trigger but also a mediator of ischemic preconditioning (94). This has been supported by reports from other groups (95, 196). Recent reports also revealed that adenosine is an endogenous bioactive substance with multiple cardiovascular effects, including a negative inotropic effect, a negative contractile effect, and promotion of coronary blood flow and anti-platelet activity (90), as well as inhibition of apoptosis (158) and enhancement of autophagy (233). However, the role of elevated intramyocardial cAMP levels and PKA activation in cardioprotection of ischemic preconditioning has been reported (110), but they were both shown to be independent of PKC (117, 170, 176). Instead, mitochondrial ion channel (176) or p38 MAPK activation (170) was reported as a putative downstream mechanism in vivo. The reason for transient activation of p38 MAPK by PKA can be explained by PKA phosphorylation of the catalytic site of protein tyrosine phosphatase and inhibition of the dephosphorylation of p38 MAPK, leading to physiological augmentation of p38 MAPK activity (178). We also reported that Rho kinase plays an important role downstream of PKA during sustained ischemia to confer cardioprotection (167). Other reports support the involvement of SOD induction (48).

Taken together, while adenosine or α₁b-adrenoceptor stimulation could activate PKC (68) and while β₂-adrenoceptor or some unknown mechanism could activate PKA and cAMP response element-binding protein (119) following ischemic preconditioning, both mechanisms might independently but synergistically mediate preconditioning in response to various stimuli, including brief periods of ischemia (168). This might include a switch in second messenger signaling; cardioprotection that was induced by PKA activation through β₂-adrenoceptor stimulation was observed together with a switch of the second messenger from Gs to Gi (209). Also, α₁b-adrenoceptor stimulation resulted in PKC activation that was mediated by Gβ and not Gα (68). Furthermore, a recent report (87) regarding heat-induced preconditioning intriguingly proposes p38 MAPK activation as a common cardioprotective mechanism in the PKC and PKA pathways.

p38 MAPK, ERK, and phosphatidylinositol 3-kinase/Akt cascades. The first report supporting the role of p38 MAPK activation during indexed ischemia in preconditioning-induced cardioprotection (221) was followed by opposing reports, in vivo (113) and in vitro (115), suggesting that p38 MAPK activation during prolonged ischemia could promote ischemic damage. In fact, continuous hypoxia causes biphasic activation of p38 MAPK in rat neonatal cardiomyocytes (115), with a transient peak within 30 min, followed by continuous activation after 4 h, leading to the hypothesis that p38 MAPK activation might have diverse effects; transient activation is protective, whereas continuous activation is harmful. We observed in vivo (171) that brief preconditioning ischemia causes transient but robust activation of p38 MAPK, followed by inactivation of p38 MAPK during sustained ischemia. The inhibition of p38 MAPK during the preconditioning period substantially blunted infarct limitation by ischemic preconditioning, implying a major role for p38 MAPK activation before...
index ischemia in preconditioning-induced cardioprotection. However, Marber and colleagues (177) have shown in vitro a p38 MAPK subtype specificity in cardioprotection and that ischemic preconditioning reversed p38 MAPK activation during index ischemia, whereas p38 MAPKβ was inhibited during index ischemia in the presence and absence of ischemic preconditioning. They have also shown that TGF-β-activated kinase-1-binding protein-1 might be important in this subtype-specific action of p38 MAPK (205). While we also documented partial cardioprotection by nonspecific pharmacological p38 MAPK inhibition during index ischemia in the above study (171), the critical role of MAPKs during sustained ischemia in preconditioning-induced cardioprotection remains obscure (17).

As downstream effectors, p38 MAPK and phosphatidylinositol 3-kinase (PI3K) induce expression, membrane transportation, and activation of glucose transporter-4, which facilitates glucose uptake (191), partly regulated by 5′-AMP-activated kinase (138). Furthermore, MAPK-activated protein kinase-2 and HSP27 are also activated in the preconditioned myocardium at the onset of sustained ischemia (171). HSP27 binds to the z-bands of myofibrils and prevents ischemic myofilament degradation and the interaction of apoptotic protease-activating factor-1 with procaspase-9 by binding to cytochrome-c and reducing apoptotic changes (24). Interestingly, MAPK-activated protein kinase-2 also potentially activates Akt, another possible antagonist of apoptotic signals (157).

By contrast, the pharmacological and ischemic preconditioning-induced activation of ERK, another component of MAPKs, also plays an important role in cardioprotection. Initial findings showed that the inhibition of ERK during preconditioning and after reperfusion blunted the infarct size of ischemic preconditioning (196). Later reports indicated limited or enhanced MAPK contribution to cardioprotection during sustained ischemia (17) or after reperfusion (155), respectively, supporting the protective role of postischemic ERK activation in preconditioning-induced cardioprotection. Intriguingly, a counteracting effect of Rho-kinase activation at reperfusion is raised as a putative mechanism downstream of ERK (241). We have also observed this in vivo downstream of preischemic p38 MAPK activation (167). The cross talk between p38 MAPK and ERK in preconditioning-induced cardioprotection might be an important issue for further analysis.

PI3K and Akt, which are activated by ischemic preconditioning, are denoted as “reperfusion injury salvage kinase (RISK) pathways” (63), a set of signals together with ERK that confer cardioprotection against ischemia-reperfusion. They are also reported to induce nitric oxide (NO) production upon both ischemic preconditioning (211) and reperfusion (21); additionally, they are reported to protect the myocardium. We will discuss this later.

Finally, the cascades shown above are summarized in Fig. 4, right.

**NO and cGMP pathways.** NO is reported as a major factor that primarily provides cardioprotection (20). Unlike adenosine, NO can activate guanylate cyclase to use cGMP as a second messenger while exerting similar cardiovascular effects. The sources of NO can be both endogenous and exogenous. Although it still remains somewhat controversial (137), endogenous NO generated by either activated endothelial NO synthase (NOS) or upregulated inducible NOS can confer cardioprotection both immediately and long after the triggering signal, respectively (20). This supports the idea that NO works as both a signal mediator and an effector (90, 109), both immediately after ischemic insult and at later time points.

Recently, numerous reports revealed that the cardioprotective properties of NO are partly induced by vasodilation hemodynamic effects or anti-inflammatory effects (142), which are generally cGMP dependent (33) and similar to adenosine (168). However, they also include direct cGMP-independent effects: the inhibition of GSK-3β (30), which might cause the aforementioned cardioprotection as well as the inhibition of mitochondrial permeability transition pore (mPTP) (143) and the opening of the mitochondrial K_ATP channel, which are both dependent on (25) and independent of (30) cGMP-mediated signaling. It is likely that the direct effects of NO largely target mitochondria. NO might also protect the myocardium by preventing mitochondrial fission (35, 141), opening mitochondrial K_ATP channel, and inhibiting mPTP to maintain energy metabolism against ischemic energy disturbances. We will discuss these issues in detail later.

While NO confers many aspects of cardioprotection as described above, the induction of NO synthesis colocalizes with the site of Ca^2+ and ROS in action. NO could act as a double-edged sword when simultaneously exposed to excessive oxidative stress, resulting in both the uncoupling and generation of further oxidative/nitrosative stress (142).

**K_ATP channels.** The K_ATP channel, usually an octamer [4 inward rectifier K^+ channel (Kir) family and 4 sulfonylurea receptor (SUR) subunits] on the membrane modulated by Mg and ATP (190), was first identified by cardiovascular physiology studies as a relaxing and negative inotropic factor (234). K_ATP channels, which are inward rectifiers (190), can raise a depolarization threshold and reduce the excitation of either vascular smooth muscle or cardiomyocytes, resulting in intracellular Ca^2+ unloading and reduced metabolic demand (190, 234). However, Inoue et al. (75) also found ATP-sensitive inward rectifier activity on the inner mitochondrial membrane, suggesting the existence of “mitochondrial K_ATP channels” in contrast to “sarcoplasmic K_ATP channels.” Cardioprotection derived from both subtypes has been previously reported (172). The concept of the mitochondrial K_ATP channel as a final effector of cardioprotection involves the stabilization of the mitochondrial inner membrane and the prevention of membrane uncoupling (57), which provides similar benefits with the inhibition of mPTP due to preconditioning (32). For example, δ-opioid receptor signaling might also contribute to preconditioning with K_ATP channels as a putative downstream mechanism, but it is also reported to be involved in GSK-3β inhibition (53) or mitochondrial PTP-induced cardioprotection (32). Accordingly, pharmacological K_ATP opening prevents not only ischemic damages but also cardiac remodeling due to chronic nonischemic stimuli (169), suggesting that this may be a putative therapeutic strategy.

**GSK-3β and mPTP.** In search of the downstream cascades of PI3K, Tong et al. (210) reported on the involvement of GSK-3β inhibition (53) or mitochondrial PTP-induced cardioprotection (32). Accordingly, pharmacological K_ATP opening prevents not only ischemic damages but also cardiac remodeling due to chronic nonischemic stimuli (169), suggesting that this may be a putative therapeutic strategy.
subsequently confers either triggered or immediate cardioprotection and serves as a downstream effector of the Wnt/ Frizzled pathway-induced cardioprotection (16). These roles implicate this developmental signal in cardioprotection afforded by preconditioning. It has also been reported to target the mammalian target of rapamycin, one of the major common downstream effectors of the PI3K/Akt pathways (217).

However, mitochondrial protection against ischemia-reperfusion is necessary to ensure cellular respiration and aerobic ATP generation and to inhibit the release of cytotoxic agents such as ROS and proapoptotic factors (such as cytochrome-c) from mitochondria upon myocardial stress (57). There were two great breakthroughs in the understanding of mitochondrial protection: the discovery of the mitochondrial KATP activity as described above in KATP channels and the discovery of mPTP (56, 57).

The mitochondrial outer membrane contains a pore protein called the voltage-dependent anion channel (VDAC) that lets nonspecific small substances of less than ~5 kDa into the intermembrane space and cytosol, whereas the inner membrane is less permeable and may let only molecules such as H2O, O2, CO2, or NH3 go through. Therefore, the mechanism that induces mitochondrial release of larger molecules, such as cytochrome-c under stress, was not well understood. Originally, VDAC was considered to be a crucial component of this canal but was ruled out later because the intrinsic apoptotic pathway was also induced in VDAC knockout mice (13). Currently, Halestrap et al. (56) propose that mPTP is composed of adenine nucleotide translocase, mitochondrial phosphate carrier, and their regulator cyclophilin-D. Ca2+ overload (57) or ROS (175) is crucial to open the pore that enables small molecules to pass between the mitochondrial matrix and cytosol, allowing for an H+ influx into mitochondria. This cancels the membrane potential across the mitochondrial membrane and results in mitochondrial swelling and subsequent apoptotic changes (66).

Cyclosporine A binds to cyclophilin D, located on the mitochondrial inner membrane, and inhibits mPTP opening by causing its dissociation from mPTP and thereby facilitating pore opening induced by Ca2+ and ROS (27, 57). Ischemic preconditioning is also reported to prevent, upon ischemia-reperfusion, the mPTP opening downstream of GSK-3β (84) or PKC-ε (15), possibly through the modulation of cyclophilin D (62). Finally, these models conform well to the idea that both necrotic (128) and apoptotic (32, 238) cell death occurs upon ischemia-reperfusion injury, and both are reduced by ischemic preconditioning (70).

Further investigation of the intersectional relationship between the RISK/survival and Wnt/developmental pathways, as well as mPTP (a putative contributing mechanism), in cardioprotection is necessary.

Ca2+ and free radicals. Importantly, it is widely recognized that both Ca2+ and ROS serve as signaling mediators under physiological conditions, while the dose, time period, and location are critical (43). It is well known that intracellular Ca2+ overload or induction of ROS causes cellular damage because of ischemia-reperfusion injury, especially when it is prolonged or intense. Moreover, as described above in NO and cGMP pathways, even a typically beneficial signal such as NO could cause deleterious effects when colocalized with excessive oxidative stress (142). However, short or transient exposure to them is reported to be beneficial because of their ability to trigger ischemic preconditioning (139, 198) and postconditioning (29). In preconditioning mechanisms, intracellular Ca2+ is required to activate classical PKC, an important component for triggering the preconditioning signal (139). Also, the Ca2+-activated K+ channel protects the myocardium when it is activated at the time of reperfusion (176, 185). Furthermore, Ca2+ is indispensable for myocardial twitching (142) and for the generation of ROS from mitochondria (43) within physiological range. On the other hand, ROS can reciprocally modulate intracellular Ca2+ homeostasis (43), and the transient increase in ROS through the increase in NO levels can trigger both early (24, 137) and late (198) phases of ischemic preconditioning. However, the role of ROS as a final effector of cardioprotection is rather controversial, especially in postconditioning, as discussed in the next section.

We finally summarized these mitochondria-oriented protective mechanisms in Fig. 4, bottom left.

Cardioprotection Afforded by Postconditioning

Postconditioning, defined as brief periods of ischemia alternating with brief periods of reflow applied at the onset of reperfusion following sustained ischemia (143), has recently been shown to have potential as a novel cardioprotective intervention against ischemia-reperfusion injury (197, 218). Ischemic postconditioning results in cardioprotection similar to preconditioning and provides a variety of crucial clues to cardioprotective mechanisms that can be directly applied in the clinic (28). In contrast to preconditioning, cardioprotection from postconditioning requires the instant sequence starting from triggers, through mediators and leading to effectors. The question as to whether cardioprotection from preconditioning and postconditioning use different mechanisms is currently under discussion (143), together with supportive (230) or negative (242) reports for additional cardioprotection from postconditioning beyond concomitant ischemic postconditioning.

Critical conditions for ischemia and reperfusion/reoxygenation in postconditioning. Because the prompt recovery of intracellular pH and reoxygenation upon reperfusion causes Ca2+ overload or excessive ROS generation and enhanced reperfusion injury, reduction of the levels of intracellular Ca2+ or ROS is one of the critical strategies for preventing reperfusion injuries. The initial successful attempts to reduce these levels were done using acidic (97) or staged (67) reperfusion, which can temper the promptness of pH recovery and reoxygenation upon reperfusion. On the other hand, recent studies have proposed that postconditioning can also elicit cardioprotection; however, it might instead induce the chances of repeated overshooting of intracellular Ca2+ and ROS levels at the time of reperfusion when preventive action has to take place. Accordingly, the latest reports have revealed that the benefits of postconditioning require the following conditions to be optimal: the duration of the index ischemia (118), the duration between the onset of reperfusion and the first brief ischemia, the duration and number of ischemias, and the duration of the interspersed reperfusion (143). First, postconditioning reduced the infarct size after index ischemia longer than 45 min in vivo, whereas it adversely impaired injury after index ischemia shorter than 30 min (118), possibly because the
ischemia-reperfusion postconditioning maneuver per se causes some extent of ischemia-induced damage, and the injury made by relatively short-index ischemia was too small to be substantially rescued by ischemic postconditioning. Second, a short time period of <1 min after the onset of reperfusion/ reoxygenation before the onset of the brief ischemia postconditioning might protect the myocardium (230), whereas a longer time period invalidates cardioprotection from the following brief ischemia (88, 230). While time periods longer than 1 min fail to exert cardioprotection in small rodent models (88), it is still effective after 3 min in large animal models (189), whereas a 5-min interval seems to be beyond the cardioprotective limit (218) even in the human. Third, the duration and number of ischemic postconditioning procedures that could affect the strength of stimulus might also be critical (143). In vivo, the predominant findings across the species are that at least three cycles of brief occlusion and reperfusion are needed to elicit substantial cardioprotection as measured by reduced myocardial cell death (71, 118, 143), but additional cycles did not seem to provide further protection (88, 230). Also, a 10-s to 1-min period appears to be the optimal duration for an ischemic postconditioning mechanism to limit infarct injury (88, 143), and this tends to be shorter in small animals (26, 230).

Role of brief ischemia in putative mechanisms of postconditioning. Taken together, the postconditioning procedure should start within a few minutes after index ischemia, and periods of ischemia, <1 min, should be repeated at least several times within the total duration of several minutes (230). Because preconditioning ischemia and reperfusion periods do not require such strict time windows as postconditioning, preconditioning and postconditioning transient ischemia might use different mechanisms and conditions: postconditioning brief ischemia at the moment of reperfusion injury activates triggers or mediators that cause “instant” cardioprotection, whereas the brief preconditioning ischemia has additional time before the final effectors are activated, either during index ischemia or upon reperfusion. Therefore, limited signals and events, which are caused by brief ischemia and altered within seconds or a few minutes, could actually confer the same cardioprotection as postconditioning.

Indeed, transient acidosis, which may result from the brief ischemic period, might directly confer cardioprotection by attenuating intracellular Ca^{2+} levels, regional ROS generation (88, 118), and mPTP opening (29), independent of subcellular kinase signaling pathways (135). However, accumulating evidence shows that postconditioning strictly requires a brief ischemic/anoxic phase to activate the RISK pathways (ERK and Akt) (118, 230), produce NO, and open mitochondrial K_{ATP} channels (230), thereby preserving mitochondrial function (143) and preventing apoptotic changes (149). This requirement implies a common cardioprotective mechanism for ischemic preconditioning and postconditioning because postischemic activation of RISK pathways is also important for preconditioning, as we described in p38 MAPK, ERK, and phosphatidylinositol 3-kinase/Akt. Prompt activation of the RISK pathways (63) could also subsequently inhibit mediators, such as GSK-3β, prevent mPTP opening, or induce NO synthesis, and most of these are common to ischemic preconditioning (242) and reduce ROS production and Ca^{2+} overload (197).

Role of transient reperfusion in the postconditioning mechanism. Meanwhile, Cohen et al. (29) reported that the restoration of oxygenation is necessary to activate PKC and cardioprotective cascades, while maintaining an acidic myocardial pH for several minutes until RISK cascades can be activated. Other reports also showed that the paradoxical effects of postconditioning might be related to the divergent effects of postconditioning on Akt phosphorylation and ROS production (118). Such mechanisms are recognized as the reason why brief ischemia and reperfusion should be frequently repeated upon reperfusion to obtain the unique protection of postconditioning. Accordingly, cotreatment with the ROS scavenger N-(2-mercaptopropionyl)glycine is reported to blunt cardioprotection by ischemic postconditioning (29).

Subsequent cardioprotective mechanisms of postconditioning. Furthermore, Garcia-Dorado and colleagues (76) reported that the activation of the cGMP/PKG pathway is upstream of delayed normalization of intracellular pH upon reperfusion via PKG-dependent inhibition of Na^{+}/H^{+}-exchange. This indicates that the pre- and postconditioning mechanisms differ substantially because the Na^{+}/H^{+} exchange inhibition seems distant from cardioprotection that is induced by ischemic preconditioning (55).

In addition, the contribution of some endogenous autacoids, such as adenosine and opioids as well as their receptors (mostly GPCR), on postconditioning-induced cardioprotection is also expected (143). Adenosine is increasingly released or focally accumulated upon reperfusion (90), and it is recognized to cause cardioprotection before index ischemia as a trigger of preconditioning, as well as at reperfusion as an effector of both preconditioning (95) and postconditioning (143). In a rodent model, the nonselective opioid receptor antagonist naloxone, as well as the selective antagonists of specific (δ, κ, or μ) opioid receptors, blunted cardioprotective postconditioning; however, the nonselective agonist morphine exerted pharmacological postconditioning (239). There are other possible mediators of postconditioning-induced cardioprotection such as bradykinin or tyrosine kinase receptors (143), but their mechanisms of action are still under discussion.

Clinical Translational Trials Based on Cardioprotection of Pre- and Postconditioning

It would be extremely beneficial if direct or mimicking procedures of cardioprotection by preconditioning and postconditioning in the clinical fields are successful. Confirmation of a clinical presence of cardioprotection induced by ischemic preconditioning (78) and postconditioning (58) against ischemia-reperfusion injury has warranted recent clinical investigations.

Preconditioning procedures for elective ischemia-reperfusion. Yellowon et al. initially found in open-heart surgery that intermittent cross clamping preserved cardiac ATP levels (231) and protected the myocardium (81). Accordingly, unstable angina during the last 48 h before surgery mimicked preconditioning in the early postoperative period (224). Furthermore, ischemic preconditioning significantly reduced lethal postoperative ventricular arrhythmia (225) as well as postoperative atrial fibrillation (226). However, because scheduled cardiac surgeries usually employ cardioplegia and anesthesia, which have the potential to provide cardioprotection (42), the added benefit of
additional treatments seems controversial even after prospective clinical trials (216). Even in the case of elective percutaneous coronary intervention, the preceding use of some drugs such as statins was reported to reduce myocardial injury (132), but the application of its putative downstream mediator by nitroglycerin before ischemic insult failed to exert any significant cardioprotection (82). One of the reasons it may be difficult to identify preischemic pharmacological strategies mimicking “triggers of preconditioning” could be the critical timing and intensity required for procedures in clinical situations.

By contrast, in a procedure called “remote preconditioning,” promising results have been obtained in recent trials where cardioprotection was successfully achieved by applying repeated cycles of transient ischemia on distant organ(s), such as limb muscles (23, 220).

**Postconditioning mimetics for predictable or unexpected ischemia-reperfusion.** Because cardioprotection by both preconditioning and postconditioning mainly focuses on the reduction of ischemia-reperfusion injury and because the accessibility of sudden unexpected ischemia-reperfusion, such as acute coronary syndrome, is usually quite convenient after the onset of ischemic insult, most of the recent translational therapeutic strategies are applied at the time of reperfusion. This protocol is followed because of findings of “final effectors of preconditioning” and “contributors of postconditioning” at reperfusion, which share some common pathways (64). Unfortunately, very few large clinical trials to date have successfully shown sufficient cardioprotection (129). As the initial translational application in the clinical field, the Acute Myocardial Infarction Study of Adenosine (AMISTAD) trial (116a) proposed cardioprotection by adenosine, which is considered to be a final effect of preconditioning at reperfusion. It revealed that patients with acute myocardial infarction who underwent continuous intravenous adenosine infusion together with percutaneous transluminal coronary recanalization had a smaller infarct size and a better functional recovery than those without adenosine infusion, especially in the instances of anterior wall infarction. However, a following AMISTAD-II trial (162), which specifically evaluated anterior wall infarction, found no difference in the primary end point of new congestive heart failure, rehospitalization for CHF, or death from any cause within 6 mo, although the infarct size tended to decrease in a dose-dependent manner. Cohen and Downey (31) addressed an important limitation in the AMISTAD-II study regarding the method for calculating the infarct size and the different measurements of infarction in the placebo group (45 and 27% in AMISTAD-I and -II, respectively). Similarly, the Japan-Working Groups of Acute Myocardial Infarction for the Reduction of Necrotic Damage (J-WIND) trial (89a) successfully found cardioprotection when recombinant human atrial natriuretic peptides (ANP) were administered at reperfusion as adjunctive therapy just after successful percutaneous coronary intervention in acute phase, which reduced myocardial creatine kinase (CK) release and increased left ventricular (LV) ejection fraction at 6–12 mo. In another portion of this study, a hybrid of the K_{ATP} channel opener and the NO donor nicorandil failed to show any infarct limitation in the acute phase, although oral administration during follow-up increased LV ejection fraction. Differences in the results among these studies might be due to differences in the details of the protocols used, but the favorable outcome, especially in chronic phase, is also supported by other clinical trials (79, 89a), as well as the preceding Impact of Nicorandil in Angina (IONA) study (77), demonstrating chronic cardioprotection due to nicorandil by reducing coronary heart disease death, nonfatal myocardial infarction, or unplanned hospital admission for angina heart attack. Therefore, at least the chronic use of nicorandil as well as the adjunctive use of ANP might be recognized as evidence-based medicine in the clinical field, originated in the knowledge of pre- and postconditioning-induced cardioprotection. On the other hand, following the initial success in protecting the myocardium in both the acute (195) and chronic phase (206) in patients suffering from left anterior descending coronary artery or right coronary artery infarction within 6 h of the onset with four cycles of 60 min ischemia-reperfusion, the direct application of postconditioning brief ischemia-reperfusion is also intensively evaluated. Actually, the salvage impact varies among the studies, probably depending on critical requirements in postconditioning maneuvers, and it seems less protective by the protocols that have fewer cycles or longer intermission (143).

Among recent studies using the cardioprotective signaling of postconditioning, the use of 3-hydroxy-3-methylglutaryl-CoA inhibitors (statins) is reported as a readily available, safe, and hopeful option to date. The immediate use of statins either before the onset of ischemia (72, 215) or around the reperfusion period (173) reduced infarct size regardless of hyperlipidemia. This result was also shown in humans (125); in addition, immediately using statins at these time point also reduced adverse outcomes when used as late as 24 h after reperfusion (182). This evidence strongly suggests that cardioprotection induced by statins goes beyond lipid lowering and involves the signaling cascades of postconditioning, such as Akt activation (173) and oxidative stress reduction (72).

Another emerging target is the use of the mPTP inhibitor cyclosporine A, a noteworthy and quite reasonable pharmacological intervention to date, which exhibited cardioprotection in acute phase (153) by infarct-limitation, measured in terms of CK release and MRI image on day 5 after infarction, as well as in chronic phase (126) by restoring LV function. The findings of protection by cyclosporine are now expanded in endothelial function upon reperfusion in humans (140) but seem still immature and need further confirmation in large-scale clinical trials to establish evidence-based medicine.

**Comorbidities and Cardioprotection: Prevailing Knowledge into Real-World Clinical Medicine**

The most important issue is to bridge the results of basic research with clinical medications or therapeutic procedures. It is unfortunately true that there is an inevitable gap in the scientific approaches used in basic science and in clinical medicine. Clinical science largely relies on statistics because of heterogeneity of disease conditions and individuals, such as age, sex, background diseases, and their comorbidities (45).

**Hypertension and cardiac hypertrophy.** Hypertrophied myocardium is at greater risk of exacerbating myocardial injury after ischemia-reperfusion through the development of rigor contracture during ischemia, resulting in reduced contractile function and increased CK release (45). Also, epidemiologic (165) and experimental studies (17) show that ventricular...
tachyarrhythmias are highly associated with hypertensive LV hypertrophy (LVH), probably via abnormalities in ectopic ion channel currents (45) and increased dispersion of action potential duration through reentrant mechanisms induced by increased interstitial fibrosis (221). Accordingly, the preconditioning effect of prodromal angina is reportedly attenuated in acute myocardial infarction patients with hypertensive LVH (203). It also seems to be the case with cardioprotection by ischemic (150) and pharmacological (151) postconditioning, although few studies have been published on this point.

It is important to distinguish between the primary benefits of regression of LVH or the reduction of blood pressure from those of acute treatments during ischemia-reperfusion when considering the effects of cardioprotective interventions. The regression of LVH by lowering blood pressure leads to a reduction in the susceptibility to negative outcomes, especially arrhythmias. In fact, the pharmacological reduction of acute blood pressure with LVH reduced mortality and infarct size to control levels (74), supporting the contribution of perfusion pressure rather than LVH to potentiating irreversible injury in hypertensive animals. Also, classic ischemic preconditioning preserved cardioprotection in the isolated model (40) of rats with pressure-overloaded LVH. On the other hand, there is evidence that normalization of myocardial action potential duration is related to a restoration of transient outward current density after LVH regression (235), and pharmacological cardioprotection by bradykinin was attenuated in the isolated pressure-overloaded hypertrophied hearts (40), even though the isolated effects of either high blood pressure or LVH are still arguable.

Although the influence of acutely applied cardioprotective procedures on reducing injury in established LVH has been immature to date, Rajesh et al. (156) propose the effectiveness of opening K$_{ATP}$ channels in the protection of preconditioning.

**Heart failure.** The unfavorable situations are quite similar in long-duration hypertension in the status of cardiac remodeling and in heart failure. Studies in isolated hearts of aged rats showed that preconditioning is protective in control hearts collected from normotensive animals, but in hearts collected from age-matched hypertensive animals, it neither enhanced postischemic functional recovery nor attenuated creatine phosphate release during global ischemia-reperfusion (41, 131). This finding highly suggests a reduced efficacy of preconditioning in chronic hypertension or in the presence of aging and hypertension. In rabbits, ischemic preconditioning failed to reduce infarct size in postinfarction remodeled hearts, whereas cardioprotection by pharmacological preconditioning with diazoxide was not affected (127). Accordingly, in right atrial appendages obtained from patients, ischemic preconditioning reduced myocardial injury in the myocardium in the presence of mild LV failure but failed to rescue those with severe LV failure. By contrast, diazoxide treatment resulted in similar protection for all groups (51).

These data are consistent with a defect within the upstream cardioprotective signal transduction pathway of failing hearts that does not interfere with direct activation of the downstream cardioprotective signaling cascade of preconditioning. In this way, an insufficiency in the signal transduction cascade in failing hearts might occur upstream of mitochondrial K$_{ATP}$ channels. Ferdinandy et al. (45) have described an important potential modification of upstream cardioprotective signaling in diseased hearts at the level of adenosine metabolism. These authors found that in patients with heart failure, increased ecto-5'-nucleotidase activity results in an increased serum adenosine level (90) and leads to the loss of cardioprotection by ischemic preconditioning due to tachyphylaxis (60). These observations could potentially explain the failure of the adenosine A$_1$/A$_2A$ receptor agonist, AMP579, to reduce the infarct size in patients with impaired LV function in the AMP579 Delivery for Myocardial Infarction Reduction (ADMIRE) study. In line with this, pharmacological postconditioning with isoflurane reduced infarct size (112) and activated the salvage kinase pathway (44) in the post-myocardial infarction-remodeled heart.

Another possible explanation could be found in mitochondrial malfunction (161), such as decreased electron transport chain activity in the status of cardiac remodeling and the failing heart. Recent studies reveal that mPTP can modulate mitochondrial function in the heart (37) and that ischemic pre- and postconditioning effects might be impaired under mitochondrial insufficiency (62) but that the direct pharmacological restoration of mitochondrial function by inhibiting cyclophilin D might protect against the failing heart (108).

**Hyperlipidemia.** It was initially reported that protection conferred by classic preconditioning against myocardial stunning and electrophysiological changes was lost when rabbits developed hypercholesterolemia, irrespective of atherosclerosis, which was restored by normalization of serum lipid levels (46) or the administration of statins (215). Other more recent reports (83) have shown that increasing the number of preconditioning cycles can aggravate infarct size in isolated rabbit hearts that are subjected to ischemia-reperfusion after 8 wk of experimental hypercholesterolemia. However, a number of recent studies have shown a limited impact of hypercholesterolemia on the cardioprotective effects of ischemic preconditioning (38). Taken together, it is likely that hyperlipidemia modifies the effect of preconditioning to some extent but that the net result of this effect is critically dependent on the strength of the cardioprotective signals. This also applies to late preconditioning (199) and postconditioning (73). In fact, the same rabbit in the ischemia-reperfusion model was used to show the loss of the infarct limitation in response to late preconditioning (204).

The use of statins has been reported to reduce myocardial injury regardless of hyperlipidemia both before the onset of ischemia (72, 215) and around the reperfusion period (173), suggesting that the cardioprotection induced by statins is not merely the result of a lipid-lowering effect.

**Diabetes and hyperglycemia.** The reduced protective effect of classic preconditioning in vivo on infarct size, ischemia-reperfusion-induced arrhythmias, and contractile dysfunction in experimental streptozotocin-induced diabetic hearts have been shown in a variety of species including rats, dogs, and sheep (45). Resistance to the protective effect of preconditioning in this experimental model has also been described for late preconditioning (39), isoflurane-induced pharmacological preconditioning (240), and postconditioning (243). Some clinical observations also suggest that patients with diabetes and ischemic heart disease might present a reduced response to preconditioning-like events, such as prodromal angina (78) and brief ischemic events, which can produce infarct limitation and increase survival after coronary angioplasty (104) in normal...
hearts. Furthermore, hyperglycemia per se has been shown to be a significant risk factor for mortality in a very large cohort of hospitalized patients with acute myocardial infarction (100), as well as a determinant of infarct size, irrespective of the presence of diabetes (86).

Mitochondrial dysfunction (6) or rather mitochondrial $K_{\text{ATP}}$ dysfunction (51) has been proposed to be the mechanism underlying this characteristic behavior of diabetic or hyperglycemic hearts. This might entail an impaired integrity of mitochondrial DNA (124), impaired Akt phosphorylation in response to ischemic preconditioning (213), increased oxidative or nitrosative stress (47) caused by impairment of mitochondrial respiratory capacity (114), as well as enhanced susceptibility to mPTP opening, caspase activation, and apoptosis (223).

In the experimental conditions described above, PKC or p38 MAPK activation were still protective, suggesting that insufficiency in the cardioprotective signaling cascade arises upstream of PKC and p38 MAPK (61). Accordingly, treatment of diabetes with insulin or pioglitazone has been suggested as a way to overcome the negative effects on cardioprotection by activating ERK and Akt, the downstream effectors and central mediators of the RISK pathway (227).

Antidiabetic drugs might have an effect on cardioprotection, beyond their direct effect on diabetes and hyperglycemia. Insulin-secreting drugs such as sulfonylureas and glinides increase insulin secretion by blocking $K_{\text{ATP}}$ channel on the pancreatic $\beta$-cell (SUR1/Kir6.2). However, in coronary smooth muscle cells (SUR2b/Kir6.1), the $K_{\text{ATP}}$ channel modulates coronary blood flow at rest and in hypoxia, and myocardial sarcolemmal $K_{\text{ATP}}$ channels (SUR2a/Kir6.2) contribute to the adaptation of the myocardium to stress. Interestingly, the inhibition of cardiovascular $K_{\text{ATP}}$ channels by sulfonylureas increases mortality in diabetic patients after coronary angioplasty (50, 104). In particular, despite the absence of structural information, mitochondrial $K_{\text{ATP}}$ channels have been suggested to play an important role in cardioprotective mechanisms. This is thought to occur because nonselective $K_{\text{ATP}}$ channel blocker glibenclamide and the selective mitochondrial $K_{\text{ATP}}$ channel blocker 5-hydroxydecanoate block, at least in part (172), the cardioprotection of classic as well as late preconditioning. This has been shown in several species including humans (45). Interestingly, the selective pancreatic $K_{\text{ATP}}$ channel blocker gliclazide does not appear to have any negative effect on cardioprotection, even when clinical data were analyzed (104).

Aging. The morbidity and mortality due to ischemic cardiovascular diseases are significantly higher in the elderly than in young adults (99). It is also generally recognized that aged hearts are resistant to cardioprotection from various kinds of preconditioning procedures (18), although there is still some controversy about the specific effects of classical, late-phase, and pharmacological preconditioning in certain animal models (34, 184).

Besides changes in structural components of the myocardium, such as increased fibrosis (174), the aged myocardium displays functional alteration of the cardiomyocytes (18). Intriguingly, telomere dysfunction even in quiescent cells, such as cardiomyocytes, produces aging-induced impaired mitochondrial biogenesis and function that lead to reduced respiratory capacity (114). This produces insufficient gluconeogenesis, cardiomyopathy, and increased ROS through the p53-PGC axis (166). The aging-induced increase in ROS generation is also the product of NADPH oxidases (116) and increased cardiac monoamine oxidase-A activity (18), as well as of reduced antioxidant capacity (187). In addition, in the aged myocardium the expression of several genes is altered (19). Among these, the decreased expression of IGF-IGF receptor, PKC-ε, ERK, Akt, MnSOD, and catalase might not only weaken the impact of the protective effect of preconditioning or postconditioning but also increase susceptibility to ROS. Furthermore, increased inducible NOS and decreased connexin-43 expressions (19) might be considered as an adaptation to continuous stress. Finally, aged myocardium shows a reduced tolerance to ischemic injury (1).

Ischemic preconditioning reduces infarct size and LV remodeling and therefore potentially improves the prognosis of patients with an acute myocardial infarction (78, 232). However, these benefits seem diminished in patients older than 65 yr (2). Ischemic postconditioning failed to reduce infarct size (154), but a longer and more intense postconditioning procedure restored protection (20). In accordance with this, chronic opioid treatment confers cardioprotection in both the young and senescent mouse heart via PKA activation, independently of acquisition of analgesic tolerance (145), whereas protection with acute morphine treatment, which is PKC dependent (146), is lost in aged hearts (147). Therefore, prolonged or stronger preconditioning stimuli might provide a powerful cardioprotection for the aging heart.

Regular exercise, especially endurance exercise, protects against ischemia-reperfusion injury in both young and old animals through the induction of myocardial HSPs and endothelial NOS, and either improves cardiac antioxidant capacity or restores mitochondrial function (10). Aging-induced increases in LV cardiomyocyte apoptosis and subsequent remodeling are improved by exercise, which also normalizes the Bax-to-Bcl-2 ratio in the LV of the aged rat heart (103). In the clinical setting, the protective effect of prodomal angina against subsequent acute myocardial infarction was reported to be preserved in aged patients with a high level of physical activity (3).

Sex difference. Premenopausal women have a reduced risk for cardiovascular disease, but this risk arises after menopause (65). However, a large clinical trial unexpectedly showed that hormone replacement therapy increases cardiovascular events in healthy postmenopausal women (163).

In most animal studies, no sex difference in ischemia-reperfusion injury has been observed, except in the rat model where injury was smaller in female than in male hearts (148). Furthermore, estrogen administration, at least for short duration, has been shown to reduce ischemia-reperfusion injury via acute nongenomic responses that involve the activation of Akt pathway (192). Also, nuclear estrogen receptor activation has been shown to result in an altered expression of a number of cardioprotective genes, such as NOS and HSPs, and a number of genes involved in metabolism, such as lipoprotein lipase, PGD2 synthase, and PGC-1α (133). Recently, the third category of G protein-coupled estrogen receptors has been shown to protect the myocardium regardless of sex (36), allowing us to reconsider sex-induced differences in ischemia-reperfusion injury as well as in preconditioning-induced cardioprotection.
Summary and Future Directions

In this review, we first discussed the original hypotheses and current findings regarding the nature of ischemia–reperfusion injury. Based on both basic and clinical findings, ischemic pre- and postconditioning with a cardioprotective potential has been discovered and established. We summarized here the ongoing investigation on the protective mechanisms of ischemic pre- and postconditioning as well as its potential application for molecular, pharmacological, or mechanical treatments against ischemia–reperfusion injury and subsequent adverse outcomes. Among various factors, Ca2+ overload and ROS generation are recognized as the key players of injury, whereas modulation on mitochondrial homeostasis as well as activation of intracellular salvaging kinase signaling (such as RISK pathway) is thought to be the emerging target of therapeutic interventions. We also reviewed major previous and upcoming translational clinical trials upon such basic findings, but we still need to further optimize such trials along with clinical comorbidities to make these trials more applicable and adaptive in clinical medicine.

Although further work is needed to understand the mechanism of cardioprotection and to make it fully applicable in the clinical setting, the connection between the bench and the bedside can be achieved by additional translational studies and established by large-scale clinical trials. We need to facilitate the creation of large clinical trials in variable situations to bring the results obtained by basic research into the real world.

GRANTS

This work is supported by grants-in-aid from the Ministry of Health, Labor, and Welfare (Japan) and the Ministry of Education, Culture, Sports, Science, and Technology (Japan) and by grants from the Japan Cardiovascular Research Foundation, the Japan Heart Foundation, the Suzuken Memorial Foundation, and the Banyu Life Science Foundation International.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the author(s).

REFERENCES


29. Cohen MV, Yang XM, Downey JM. Acidosis, oxygen, and interference with mitochondrial permeability transition pore formation in the early


and preconditioning on infarct size in hypercholesterolemic and normal anesthetized rabbits. 


76. Inserte J, Barba I, Poncelas-Nozal M, Hernando V, Agulló L, Ruiz-


Penna C, Tullio F, Moro F, Folino A, Merlino A, Pagliaro P. Effects of a protocol of ischemic postconditioning and/or captopril in hearts of...


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