Rottlerin Increases Cardiac Contractile Performance and Coronary Perfusion Through BK$_{Ca^{++}}$ Channel Activation After Cold Cardioplegic Arrest in Isolated Hearts

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Background—Cardioplegia and cardiopulmonary bypass (CP/CPB) subjects myocardium to complex injurious stimuli that can result in cardiomyocyte and vascular contractile abnormalities. Rottlerin, originally identified as a delta-protein kinase C inhibitor, has a number of known additional effects that may be beneficial in the setting of CP/CPB. We tested the hypothesis that rottlerin mitigates deleterious effects associated with CP/CPB.

Methods and Results—Langendorff-perfused isolated rat hearts were subjected to 2 hours intermittent cold (10°C) CP (St Thomas II) followed by 30 minutes normothermic reperfusion. CP was delivered every 30 minutes for 1 minute. Hearts were treated with rottlerin 1 μmol/L (CP+R) (n=7) or without rottlerin (CP) (n=9), and the BK$_{Ca^{++}}$ channel inhibitor paxilline 100 nmol/L was supplied in the CP. Hearts constantly perfused with KHB served as controls (n=6). Baseline parameters of cardiac function were similar between groups. CP resulted in reduced cardiac function (left ventricular diastolic pressure, 39±3.8%; ±dP/dt, 32±4.4%; −41±5.1% decrease compared to baseline). Treatment with rottlerin 1 μmol/L significantly improved CP-induced cardiac function (left ventricular diastolic pressure, 20±5.9%; ±dP/dt, 5.2±4.5%, −11.6±4.7% decrease versus baseline; P<0.05 CP+R versus CP). Rottlerin also caused a significant increase in coronary flow postreperfusion (CP, 34±4.2% decrease from baseline; CP+R, 26±9.6% increase over baseline; P=0.01). Independent of vascular effects, CP significantly decreased isolated myocyte contraction, which was restored by rottlerin treatment. The BK$_{Ca^{++}}$ channel inhibitor greatly reduced the majority of beneficial effects associated with rottlerin.

Conclusions—Rottlerin significantly improves cardiac performance after CP arrest through improved cardiomyocyte contraction and coronary perfusion. (Circulation. 2011;124[suppl 1]:S55–S61.)

Key Words: cardioplegia • potassium channels • protein kinase C • rottlerin • Akt • ischemia

Cardiac surgery using cardioplegia (CP) and cardiopulmonary bypass subjects myocardium to hypothermic reversible ischemic injury that can impair cardiac function (aka, myocardial stunning). The main protective benefits of CP are mediated through myocardial hypothermia and diastolic arrest, which preserve myocardial energy reserves. The ischemic insults associated with CP arrest during surgery include myocyte hypoxia, acidosis, oxidant-dependent damage, metabolic and structural alterations, and reduced cardiac function.1–4 In addition to direct effects on cardiomyocytes, CP can result in marked coronary vascular complications, including impaired vasodilation, propensity for spasm, and overall decreased perfusion.5

Although contractile impairment in the majority of patients resolves quickly, ≈10% can develop a cardiac low-output syndrome attributable in part to depressed left ventricular (LV) or atrial contractile function. Consequently, low-output syndrome prolongs recovery times and significantly elevates risk of mortality.6 Furthermore, the need for enhanced cardioprotection is required for specific high-risk patient populations (eg, prolonged surgical times, low ejection fraction, older age).

Rottlerin has been reported as a protein kinase C-δ (PKCδ) inhibitor. PKCδ has been implicated in depressed cardiac function and cell death after ischemia-reperfusion injury as well as in promoting vascular smooth muscle contraction.7–9 However, rottlerin as a true inhibitor of PKCδ has been called into question and has generated considerable controversy.10,11 Other PKCδ-independent effects of rottlerin recently have been recognized. Rottlerin has been reported as a potent large...
conductance potassium channel (BKCa⁺⁺) opener.12 Opening of BKCa⁺⁺ channels is beneficial for postischemic alterations in
vasomotor activity.13 In addition, other BKCa⁺⁺ channel
openers are reported to limit ischemia-related mitochondrial
Ca²⁺ overload.14,15 Finally, rottlerin is capable of reducing
oxygen radical formation.10 All these mechanisms of injury
occur during CP arrest and reperfusion. Therefore, through a
combination of targets, rottlerin may block many of the
deleterious side effects associated with CP arrest that limit
both vascular and cardiomyocyte function.

Methods
Isolated Langendorff-Perfused Model of CP Arrest
Male Sprague-Dawley rats (Charles River; Wilmington, MA) were
anesthetized with 80 mg/kg ketamine IP and 5 mg/kg xylazine IP and
anticoagulated with heparin (2000 U/kg IV), and the heart was
placed in 10% formalin for confocal microscopy. A second section
was subsequently maintained at 37°C. Indices of ventricular func-

SDS-PAGE and Immunoblot
SDS-PAGE and immunoblot were performed using standard meth-
ology as previously described.16 Antibodies for immunoblot were as
follows: phosphospecific or total PKCδ, cardiac troponin I (cTNI),
Akt, 3-phosphoinositide-dependent kinase 1 (PDK1), phosphatase
and tensin homolog (PTEN), and extracellular signal-regulated
kinase (ERK) from Cell Signaling (Beverly, MA); phospholamban
(PLN) from Millipore (Billerica, MA); and phospho- and total heat
shock protein 27 (HSP27) and B-crystallin antibodies from Stress-
gen (Vancouver, BC).

Culture and Purification of Adult
Rat Cardiomyocytes
Adult rat cardiomyocyte cultures were obtained from hearts accord-
ing to a previously published protocol with modifications.18 Briefly,
hearts were excised from anesthetized adult rats, the aorta cannu-
lated, and hearts perfused with 0.3% collagenase solution in perfu-
sion buffer consisting of MEM (Joklik modification) supplemented
with creatine, BDM, taurine, and insulin for 45 minutes. After
perfusion, ventricles were removed and minced in the Ca²⁺-free
collagenase solution for 3 to 5 minutes. Chunks then were incubated
in 10 mL of perfusion buffer supplemented with BSA and 0.3 mmol/L
CaCl₂. Cells were washed in collagenase-free perfusion buffer 3
times with centrifugation. Myocytes were resuspended in DMEM
culture medium supplemented with creatine, carnitine,
taurine, penicillin/streptomycin, and insulin. Myocytes were plated
at a density of 2×10⁶ cells/cm² on 10 μg/mL laminin-coated dishes
for length measurements the following day.

In Vitro CP and Myocyte Length Recordings
Cultured rat myocytes were switched to crystalloid CP solution
bubbled with 5% CO₂/95% N₂ under anoxic conditions. Cells then
were placed in a hypoxia chamber evacuated with 5% CO₂/95% N₂
for the indicated times and retained at 4°C. For simulated reperfu-
sion, CP-treated cells were removed from the hypoxic chamber and
returned to the cell culture incubator, and CP solution was replaced
with a modified KHb containing NaCl, 118 mmol/L; KCl, 4.7
mmol/L; CaCl₂, 1.25 mmol/L; MgSO₄, 1.66 mmol/L; NaHCO₃, 24.88
mmol/L; KH₂PO₄, 1.18 mmol/L; Na-pyruvate, 2.0 mmol/L) for 30 minutes
to stabilize and record baseline measurements. During baseline mea-
surements, myocardial temperature was maintained at 37°C. Groups
subjected to cold crystalloid CP solution were perfused with St
Thomas II solution (NaCl, 110 mmol/L; KCl, 4.7 mmol/L; CaCl₂,
110 mmol/L; MgCl₂, 1.5 mmol/L; NaHCO₃, 10 mmol/L). Myocardial
cooling during CP was initiated at the onset of CP infusion through
rapidly switching the Langendorff organ chamber and perfusate to
a refrigerated circulator. Myocardial temperature was maintained
at 10°C for the duration of CP. CP groups were perfused initially for 2
minutes followed by a 1-minute infusion at 30, 60, and 90 minutes
respectively. After 120 minutes, the organ chamber and perfusate
were switched back to a heating circulator and the heart
perfused at 70 mm Hg with modified KHb. Myocardial temperature
was subsequently maintained at 37°C. Indices of ventricular func-
tion, perfusion pressure, myocardial temperature, and organ chamber
temperature were measured continuously throughout the experi-
ment using an LDS-Ponemah data acquisition system. At the conclu-
sion of the experiment, the heart was removed from the perfusion appar-
atus, and a small midtransverse slice was removed and immediately
placed in 10% formalin for confocal microscopy. A second section
was taken for a heart wet/dry weight ratio. Samples were weighed
directly after procurement and after desiccation for 24 hours at 50°C.
The remainder of the tissue was immediately placed in liquid N₂.

Statistical Analysis
All statistical analyses were performed with Sigma Stat software
(Systat Software Inc; Chicago, IL). For analysis of CP and
CP+rottlerin (CP+R) functional time courses, 2-way repeated-
measures ANOVA with Student Newman-Keuls post hoc analysis
was performed. A 2-way ANOVA with Student Newman-Keuls
was performed for isolated myocyte experiments. All other statistical
tests were 1-way ANOVA with Student Newman-Keuls. P<0.05
determined significance.

Results
Rottlerin Alleviates CP-Induced Myocardial
Stunning in the Isolated Heart
Cold crystalloid CP for 2 hours in the isolated rat hearts
caused depressed cardiac contractile function on reperfusion.
During CP, myocardial temperature was maintained at
10°C, followed by rewarming to 37°C during 30 minutes of
reperfusion as described previously.14 A representative experi-
ment is presented in online-only Data Supplement Figure 1.
On reperfusion, there were significant reductions in systolic
pressure, developed pressure, and ±dP/dt compared with
baseline (Figure 1A through 1D). Inclusion of rottlerin
1 μmol/L in the CP solution significantly improved indices
of cardiac function, including developed pressure (Figure
1A), ±dP/dt (Figure 1B and 1C), and tau (Figure 1D).
There were no significant changes in heart rate between groups (Figure 1E).

**Rottlerin Improves CP-Induced Reductions in Coronary Perfusion**

CP arrest and 30 minutes reperfusion reduced coronary flow compared with baseline. Hearts treated with rottlerin 1 μmol/L in the CP solution showed significant improvements over CP alone (Figure 2A and 2B). At 30 minutes of reperfusion, the CP+R group showed a significant increase in flow over baseline, whereas CP and sham hearts showed overall reductions in flow (Figure 2B). There were no significant increases in wet/dry tissue weight ratios between groups, indicating no deleterious increases in tissue edema (online-only Data Supplement Figure 2).

**Rottlerin Blocks CP-Impaired Myocyte Contractility In Vitro**

To explore whether rottlerin alleviates CP-induced depressed contractile function solely through vascular effects, isolated rat cardiac myocytes were subjected to in vitro CP and simulated reperfusion with reoxygenation and rewarming. In vitro CP resulted in depressed myocyte contraction as determined by decreased myocyte length.
shortening (Figure 3A and 3B). Inclusion of rottlerin 1 μmol/L completely rescued CP-induced changes in myocyte length shortening (Figure 3A and 4B), indicating direct effects on cardiomyocytes.

Cardioprotective Effects of Rottlerin Are Independent of PKC
PKCδ phosphorylation is known to correlate with increased PKCδ activity. However, CP did not increase the phosphorylation of PKCδ on Y311, T505, or S643. There was an insignificant trend for CP-induced phosphorylation of PKCδ-T505, but treatment with rottlerin 1 μmol/L did not attenuate this trend or decrease basal phosphorylation on any of the residues examined (Figure 4A and 4B). Phosphorylation of ERK and p38-MAPK have been implicated as downstream of PKCδ activation. HSP27 is a downstream target of p38-MAPK that also may regulate contractile deficits associated with CP-induced stunning. Although CP induces phosphorylation of ERK and HSP27, these effects were independent of rottlerin (Figure 4C and 4D).

BKCa++ Channels Mediate Rottlerin-Induced Improvements in Post-CP Cardiac and Vascular Function
To determine whether rottlerin mediates its effects through the opening of BKCa++ channels, hearts were treated with rottlerin 1 μmol/L and the BKCa++ channel blocker paxilline 100 nmol/L and 1 μmol/L, both supplied in the CP condition. Paxilline blocked the majority of beneficial effects of rottlerin at 100 nmol/L and all the measured beneficial effects at 1 μmol/L (Figure 5). However, treatment with rottlerin and paxilline 1 μmol/L caused significant increases in LV end-diastolic pressure and tau compared with CP treatment alone. Full-time courses of the paxilline-treated groups are presented in online-only Data Supplement Figure 3.

Rottlerin Enhances CP-Induced Akt Phosphorylation Through BKCa++ Channels
CP caused significant phosphorylation increases in members of the Akt signaling cascade, including Akt ser473, Akt thr308, ser241 PDK1, and ser380 PTEN (Figure 6). Compared with CP alone, rottlerin significantly increased the phosphorylation of Akt on thr308. All targets of the Akt pathway measured were significantly reduced in the rottlerin groups cotreated with paxilline 100 nmol/L (Figure 6), indicating that this pathway is controlled by BKCa++ channel modulation.

Rottlerin Does Not Reduce Protein or Lipid Oxidation
To determine whether rottlerin mediates its effects through antioxidant mechanisms, tissue protein and lipid oxidation were indirectly measured by carbonyl and malondialdehyde content, respectively. Neither CP nor addition of rottlerin significantly altered protein (online-only Data Supplement Figure 4A) or lipid oxidation (online-only Data Supplement Figure 4B) compared with sham treatment.
Rottlerin Does Not Alter PLN or cTnI Phosphorylation

Phosphorylation of PLN and cTnI are implicated in regulation of myocardial contractility. Neither CP nor CP/R 1 μmol/L changed basal levels of cTnI or PLN phosphorylation (online-only Data Supplement Figure 5).

Discussion

The principle findings of the current study indicate that rottlerin improves functional recovery of isolated hearts after cold CP arrest. As an additive to CP, rottlerin (1) increased isolated heart contractile performance, (2) enhanced significantly myocardial perfusion, and (3) directly increased contractile performance of cardiac myocytes independent of vascular effects. All of these beneficial effects appeared to be independent of PKCδ activation as measured by phosphorylation status and screening of potential downstream targets. In contrast, the beneficial effects of rottlerin were reduced by paxilline, implicating an important role for BKCa channels.

Figure 4. Rottlerin does not alter phosphorylation of PKCδ. A. Immunoblot analysis of isolated heart left ventricle tissue probed with phosphospecific antibodies to PKCδ. B. Graph displays normalized percent increase in PKCδ phosphorylation over sham. C. Phosphorylation of ERK1/2, HSP27, and cryAB (reported indirect downstream targets of PKCδ). D. Graph displays normalized percent increase in phosphorylation over sham. Minimum number per group, 6. *Statistical significance versus sham at $P<0.05$, 1-way ANOVA with Student Newman-Keuls. cryAB indicates αB-crystallin; ERK1/2, extracellular signal-regulated kinase 1/2; PKCδ, delta-protein kinase C. Other abbreviation as in Figure 1.

Figure 5. Beneficial effects of rottlerin are mediated through large conductance potassium channels. Cotreatment with rottlerin 1 μmol/L and paxilline 100 nmol/L and 1 μmol/L in CP blocks the protective effects of rottlerin alone. The graph shows experimental data as in Figure 2, with the percent change from baseline of the 30-minute reperfusion time point. Minimum number per group was 6, except for CP+rottlerin+paxilline 1 μmol/L where n=4. *Different from CP. #Different from both CP and CP+rottlerin groups ($P<0.05$, 1-way ANOVA with Student Newman-Keuls). LVDP indicates left ventricular diastolic pressure. Other abbreviations as in Figure 1.
channels with paxilline greatly reduced the vasodilatory effect of rottlerin, indicating that rottlerin also works through smooth muscle BK$_{Ca^{++}}$ channels to improve coronary flow after CP. Second, rottlerin-induced activation of BK$_{Ca^{++}}$ channels may directly alleviate stunning of cardiac myocytes. Classical mechanisms of myocardial stunning associated with CP and cardiopulmonary bypass include the oxidant radical and Ca$^{2+}$ overload hypothesis. The nonexclusive views propose (1) oxidant-dependent damage/oxidant-dependent activation of signaling, which negatively modulate the contractile apparatus, and (2) alterations in Ca$^{2+}$ homeostasis, which promote contractile abnormalities and metabolic alterations through mitochondrial damage. BK$_{Ca^{++}}$ channels reside in the cardiomyocyte inner mitochondrial membrane. BK$_{Ca^{++}}$ channel activation is proposed to increase mitochondrial K$^+$ accumulation, which, in turn, electrochemically limits mitochondrial Ca$^{2+}$ influx and reduces mitochondrial depolarization and permeability transition pore opening. Known cardioprotective effects associated with the BK$_{Ca^{++}}$ channel openers NS1619, NS11021, and DiCl-DHAA after ischemia-reperfusion injury include reductions in mitochondrial Ca$^{2+}$ overload, mitochondrial membrane depolarization, increased cell viability, and improved function in whole hearts. Indeed, adaptation to hypoxia alone can partially activate the mitochondrial BK$_{Ca^{++}}$ channels, which is recognized as a protective response.

In addition, we found that rottlerin treatment greatly enhanced the CP-induced phosphorylation of Akt on the required activation residue thr308. Akt activation is reported to be an upstream mediator of mitochondrial K$^+$ channel function as well as a modulator of the mitochondrial depolarization and permeability transition pore. However, the present data indicate that Akt functions downstream of rottlerin-dependent activation of BK$_{Ca^{++}}$ channels because BK$_{Ca^{++}}$ channel inhibition with paxilline blocked the CP and CP+R-induced increases in Akt pathway activation (Figure 6). Although activation of Akt signaling is considered beneficial and prosurvival after ischemia-reperfusion injury, it is unclear what specific role (if any) Akt may play in modulating the acute increases in myocardial function after CP+R treatment. Further studies will need to address whether this aspect of improved function associated with rottlerin is necessary.

Rottlerin has demonstrated antioxidant properties, although it is unclear whether these effects are due to BK$_{Ca^{++}}$ opening or other additional mechanisms. However, we did not find any evidence that rottlerin directly influences oxidant-dependent damage as measured by total lysate protein and lipid oxidation. Specific investigation of these effects may be required in isolated mitochondria and with more sensitive methods. Finally, it is highly likely that the dose of rottlerin used in the present studies did not inhibit PKC$\delta$. Previous studies demonstrated that PKC$\delta$ inhibitory doses are significantly $> 1 \mu$mol/L. Numerous reports indicated that rottlerin may indirectly alter PKC$\delta$ activation but at concentrations (ie, $> 10 \mu$mol/L) that lead to mitochondrial uncoupling and global reductions in ATP and subsequent kinase activity. However, the dose of rottlerin used in the current study is considerably less than any dose that was previously shown to alter cellular ATP levels and lead to activation of AMPK. In addition, we found no activation of AMPK with or without rottlerin in the CP-treated groups, indicating preservation of myocardial energy reserves (data not shown). We also found no phosphorylation of PKC$\delta$ or potential downstream targets. Conversely, rottlerin 0.5 $\mu$mol/L significantly increases BK$_{Ca^{++}}$ channel opening in cell and cell-free systems.

**Limitations**

Although the present model sought to faithfully reproduce injury associated with CP arrest in patients, a number of important shortcomings exist. First, we did not address injury associated with extracorporeal circulation and reperfusion injury associated with blood components. Second, the most common form of CP currently in use is cold blood crystalloid CP; thus, the effect of blood as a CP additive on our results is unclear. Future studies will need to address the potential benefit of rottlerin with a model that incorporates CP arrest and reperfusion after cardiopulmonary bypass.

**Conclusions**

The present study demonstrates that rottlerin, as an additive to cold crystalloid CP, improves CP-induced myocardial stun-
ning and vasomotor regulation likely through direct activation of BKCa channels and not PKCδ-dependent effects. To our knowledge, this is the first use of rottlerin and a BKCa activator in a whole-heart model of CP arrest, and we demonstrate improved cardiomyocyte and vascular function after reperfusion. These results indicate that rottlerin as a CP additive with no requisite before and after treatment may demonstrate improved cardiomyocyte and vascular function.

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Disclosures
None.

References
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Supplemental Material:

Supplemental Methods

**Protein and Lipid Oxidation:** Protein carbonyl formation was measured using the Oxyblot system (Millipore) according to the manufacturer's instructions and as described previously \(^1\). Malondialdehyde (MDA) content indicative of lipid peroxidation was measured using a Bioxytech MDA-586 kit (OxisResearch, Burlingame, Ca) according to the manufacturer's instructions and as described previously \(^1\).

Supplemental Figure Legends

**Figure Legends:**

Supplemental Figure 1 – Cold crystalloid cardioplegia reduces cardiac performance. A) Representative experiment of cardioplegia/reperfusion in isolated rat hearts. a. – baseline measurement b. – induction of cardioplegia (2 min delivery), c) Cardioplegic arrest 30 min (1 min CP delivery) d 60 min Cardioplegic arrest (1 min CP) e. 90 min CP (1 min delivery) f. Start reperfusion. g-h: 5, 10, 20 ,30 min reperfusion. B) Tracings from individual hearts subjected to CP and reperfusion with or without 1 uM Rottlerin.

Supplemental Figure 2. Rottlerin does not alter wet/dry tissue weight. None of the treatments significantly effected wet/dry tissue weights indicating no gross increases in tissue edema. Minimum n=6, except CP + Rott + Paxilline 1 uM , n=4. One Way Anova,

Supplemental Figure 3. The BKCa++ channel inhibitor paxilline blocks beneficial effects of rottlerin on post-CP cardiac function. Experimental conditions similar to figures 1 and 2. Cotreatment with rottlerin (1 uM) and Paxilline (100 nM or 1 uM) supplied as an additive to cardioplegia. A) Developed Pressure, B) +dP/dt, C) –dP/dt, D) Tau, and E) LVEDP F) Heart rate and G) Coronary Flow. X-axis time : Baseline – pre CP
function, CP – Cardioplegia, 5 - 30 – min reperfusion. n = minimum of 6 per group, except Rottlerin + 1 uM Pax, n=4. One Way ANOVA, Student Newman-Keuls.

**Supplemental Figure 4– Rottlerin does not significantly alter protein or lipid oxidation.** A) Representative oxyblot and graph of normalized fold increase over sham in protein carbonyl content measured by oxyblot. B) Graph of lipid oxidation measured by tissue MDA content. Graphs minimum n=6 / group. One Way ANOVA.

**Supplemental Figure 5– Rottlerin does not significantly alter phospholamban or troponin I phosphorylation.** Graph displays normalized fold increase in phosphorylation over sham. Minimum n=6 / group. One Way ANOVA.

Reference List

Supplemental Figure 1

A

LVP (mmHg)

dP/dt (mmHg)

myocardial temp (deg C)

baseline  cardioplegia 2 hours  reperfusion 30 min

B

CP

CP + Rott

Perfusion pressure

LVP

dP/dt
Supplemental Figure 2

The bar chart represents the wet to dry weight ratio under different conditions. The conditions are labeled as follows:

- Sham
- CP
- CP + Rott
- CP + Rott + 100nm Pax
- CP + Rott + 1uM Pax

The y-axis represents the wet to dry weight ratio ranging from 0 to 7, while the x-axis lists the different conditions.
Supplemental figure 3

A

B

C

D

- Developed Pressure (mmHg)

- \( \frac{\text{dP}}{\text{dt}} \)

- Tau

Legend:
- CP
- CP + Rottlerin
- CP + Rottlerin + 100 nm Pax
- CP + Rott + 1 uM Pax

Graphs showing changes in developed pressure, \( \frac{\text{dP}}{\text{dt}} \), and Tau under different conditions.
Supplemental figure 4

A

B

Normalized Protein Oxidation

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<th>CP + Rottlerin</th>
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μM MDA

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Supplemental figure 5