Remifentanil Preconditioning Protects against Ischemic Injury in the Intact Rat Heart

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Background: Opioid receptors mediate cardiac ischemic preconditioning. Remifentanil is a new, potent ultra-short-acting phenylpiperidine opioid used in high doses for anesthesia. The authors hypothesize that pretreatment with this drug confers cardioprotection.

Methods: Male Sprague-Dawley rats were anesthetized and the chest was opened. All animals were subjected to 30 min of occlusion of the left coronary artery and 2 h of reperfusion. Before the 30-min occlusion, rats received either preconditioning by ischemia (ischemic preconditioning, 5-min occlusion, 5-min reperfusion × 3) or pretreatment with remifentanil, performed with the same regime (3 × 5-min infusions) using 0.2, 0.6, 2, 6, or 20 µg·kg⁻¹·min⁻¹ intravenously. The experiment was repeated with naltrindole (a selective δ-opioid receptor antagonist, 5 mg/kg), nor-binaltorphimine (a selective κ-opioid receptor antagonist, 5 mg/kg), or CTOP (a selective µ-opioid receptor antagonist, 1 mg/kg) administered before remifentanil-induced preconditioning or ischemic preconditioning, respectively. Infarct size, as a percentage of the area at risk, was determined by 2,3,5-triphenyltetrazolium staining.

Results: There was a dose-related reduction in infarct size/area at risk after treatment with remifentanil that was similar to that seen with ischemic preconditioning. This effect was prevented or significantly attenuated by coadministration of a µ, κ, or δ-opioid antagonist. The infarct-sparing effect of ischemic preconditioning was abolished by blockade of κ-opioid receptors or δ-opioid receptors but not by µ-opioid receptors.

Conclusion: Remifentanil mimics cardioprotection via all three opioid receptors. This differs from ischemic preconditioning, which confers cardioprotection via κ- and δ-, but not µ-opioid receptors. Part of the protective effect of remifentanil may be produced by µ-agonist activity outside the heart.

OPIOID receptors (OR) are involved in cardiovascular regulation,1–3 and several studies have found that activation of certain ORs can induce a cardioprotective effect similar to classic and delayed ischemic preconditioning (IPC).4–6 It is believed that opioid-peptides exert this effect by interaction with Gi-protein coupled receptors.7–9 There is evidence that both δ- (especially δ₁)10,11 and κ12,13-ORs are involved in opioid-induced cardioprotection. Several studies have found that intravenous administration of morphine can mimic the effect of IPC to reduce infarct size (IS) in anesthetized open-chest rats.9,10,14 Combined administration of isoflurane and morphine produces a synergistic reduction in myocardial IS in rats.15 Fentanyl has been shown to alleviate postischemic ventricular dysfunction in rats with this cardioprotective effect apparently mediated by δ-ORs.16,17 Remifentanil is a new ultra-short-acting phenylpiperidine opioid analgesic agent that is rapidly metabolized by nonspecific blood and tissue esterases.18 It has an analgesic potency similar to that of fentanyl and 100 times greater than morphine,19 the opioids that have been most extensively studied in cardioprotection. Li- gand-binding data show that remifentanil has a high degree of µ-OR selectivity (EC₅₀ = 2.6 nm) with a lower affinity for δ (EC₅₀ = 66 nm) and κ (EC₅₀ = 6.1 µM) ORs,20 and its effect on postischemic myocardium is still unknown.

The heart has δ-ORs and κ-ORs.3,21,22 It has been shown that the cardioprotection of morphine preconditioning is mediated via the δ-OR,11 and there is also evidence that it is mediated via both δ-ORs and κ-ORs.13,25 This study aimed to determine whether remifentanil, like morphine and fentanyl, confers cardioprotection against ischemia-induced injury and, if so, which ORs mediate this effect. We also compared the effects of remifentanil with those of ischemic preconditioning.

Materials and Methods

This study was conducted in accordance with our institutional guidelines on the use of live animals for research and the experimental protocol was approved by the Animal Care and Use Committee of the University of Hong Kong.

Surgical Preparation

Male Sprague-Dawley rats weighing 300–350 g were used. The rats were anesthetized by intraperitoneal administration of pentobarbitone (50 mg/kg body weight) and maintained by repeat doses of 25 mg/kg every 60–90 min. All of the animals underwent tracheotomy and tracheal intubation. Mechanical ventilation was provided with a Harvard Apparatus Rodent Respirator (Harvard Apparatus, Boston, MA), and the rats were ventilated with room air at 60–70 breaths/min. Body temperature was monitored and maintained at 37 ± 1°C (mean ± SD) using a heating pad. The carotid artery was...
its myocardial infarct size, rats were randomly assigned
remifentanil (GlaxoSmithKline Limited, Hong Kong) lim-
ments. To determine whether the administration of
and cardiac cyanosis. After surgical preparation, the rat
pericardium, a 6
artery. Regional ischemia was achieved by pulling the
occluder, was placed at the origin of the left coronary
heart at the
stat. Ischemia was con
loss. Ischemia preconditioning (IPC) hearts were subject to three 5-min cycles of
interspersed with 5 min of drug-free periods. Remifentanil preconditioning (RPC) hearts were subject to three 5-min cycles of infusion of remifentanil (0.2, 0.6, 2, 6, or 20 μg·kg⁻¹·min⁻¹) interspersed with 5-min drug-free periods. Occ = occlusion of the left coronary artery; rep = reperfusion; rem = infusion of remifentanil, and free = drug-free periods.
cannulated to measure mean blood pressure via a pres-
sure transducer, and a Lead-II electrocardiogram moni-
tored heart rate via subcutaneous stainless steel elec-
trodes. These were connected to a PowerLab monitoring
system (ML750 PowerLab/4sp with MLT0380 Reusable
BP Transducer; AD Instruments, Colorado Springs, CO).
The right jugular vein was cannulated to infuse saline or
drugs. A left thoracotomy was performed to expose the
heart. After removing the
fth intercostal space. After removing the
plicature, along with a snare
rmed by a substantial decrease in
hemorrhage. Ischemia was confirmed by a substantial decrease in
left ventricular pressure, electrocardiographic changes,
and cardiac cyanosis. After surgical preparation, the rat
was allowed to stabilize for 15 min.

**Study Groups and Experimental Protocol**

The current study consisted of two series of experi-
ments. To determine whether the administration of
remifentanil (GlaxoSmithKline Limited, Hong Kong) lim-
its myocardial infarct size, rats were randomly assigned
to receive one of seven treatments (fig. 1): control (CON, saline vehicle), ischemic preconditioning (IPC) and
remifentanil preconditioning (RPC) using five doses: 0.2,
0.6, 2, 6, and 20 μg·kg⁻¹·min⁻¹. All animals received 30
min of occlusion of the left coronary artery followed by
2 h of reperfusion. Before the 30-min occlusion, rats
were subjected to either preconditioning by ischemia
(IPC, 5-min occlusion, 5-min reperfusion × 3) or pre-
treatment with remifentanil with the same regimen (3 ×
5-min infusions). These experiments will be referred to
as Series 1.

Subsequently, to test which opioid receptor was in-
volved in mediating the effects of remifentanil and isch-
emic preconditioning, rats were randomly assigned to
one of 12 groups (fig. 2) as follows:

1. Control (CON, saline vehicle).
2. Naltrindole (NTD, a selective δ-OR antagonist) 5
mg/kg intravenously 10 min before ischemia.
3. Nor-binaltorphimine (nor-BNI, a κ-OR selective
antagonist) 5 mg/kg intravenously 15 min before
ischemia.
4. CTOP (D-Phe-Cys-Tyr-D-Trp-Orn-Thr-Pen-Thr-NH₂,
a μ-OR selective antagonist) 1 mg/kg intravenously 10
min before ischemia.
5. RPC.
6. IPC.
7. NTD + RPC.
8. NTD + IPC (5 mg/kg intravenously 10 min before
RPC or IPC).
9. Nor-BNI + RPC.
10. Nor-BNI + IPC (5 mg/kg, intravenously 15 min be-
fore RPC or IPC).
11. CTOP + RPC.
12. CTOP + IPC (CTOP 1 mg/kg intravenously before
RPC or IPC).

The chemicals were purchased from Sigma Chemical
Company (St. Louis, MO). These experiments will be
referred to as Series 2.

**Determination of Infarct Size**

On completion of the reperfusion period, the heart
was excised, transferred to a Langendorff apparatus,
and perfused with normal saline for 1 min at a pressure of
100 cm H₂O to flush out blood. The snare was securely

**Fig. 1.** All group hearts were subject to 30 min of occlusion and
120 min of reperfusion. Before ischemia, ischemic precondition-
ing (IPC) hearts were subject to three 5-min cycles of occlusion
interspersed with 5 min of reperfusion, whereas remifentanil preconditioning (RPC) hearts were subject to three 5-min cycles of
infusion of remifentanil (0.2, 0.6, 2, 6, or 20 μg·kg⁻¹·min⁻¹) interspersed with 5-min drug-free periods. Occ = occlusion of the
left coronary artery; rep = reperfusion; rem = infusion of remifentanil, and free = drug-free periods.

**Fig. 2.** Experimental protocol used to determine which opioid
receptor mediates the cardioprotective effect of ischemic pre-
conditioning (IPC) and remifentanil preconditioning (RPC, 20
μg·kg⁻¹·min⁻¹). Naltrindole (NTD, a selective δ-OR antagonist,
5 mg/kg) and CTOP (a selective μ-OR antagonist, 1 mg/kg)
intravenously 10 min before ischemia, IPC, or RPC. Nor-binal-
torphimine (nor-BNI, a selective κ-OR antagonist, 5 mg/kg)
intravenously 15 min before ischemia, IPC, or RPC. Occ = occlu-
sion of the left coronary artery; rep = reperfusion; rem = infu-
sion of remifentanil, and free = drug-free periods.
RPC hearts were subject to three cycles of 5 min infusion periods of remifentanil (0.2, 0.6, 2, 6 or 20 μg·kg⁻¹·min⁻¹) interspersed with drug-free periods. After, the slices were stained by incubation at 37°C for 20 min in 1% 2,3,5-triphenyltetrazolium (Sigma Chemical Co.) in phosphate buffer (pH 7.4), and then were immersed in 10% formalin to enhance the contrast of the stain. The areas of infarct (2,3,5-triphenyltetrazolium stained) and risk zone (2,3,5-triphenyltetrazolium stained) for each slice were traced and digitized using a computerized planimetry technique (SigmaScan 4.0, Systat Software Inc., Richmond, CA). The volumes of the left ventricles, IS, and AAR were calculated by multiplying each area with slice thickness and summing the product. The IS was expressed as a percentage of the AAR (IS/AAR).

**Statistical Analysis**

Data analysis was performed with a personal computer statistical software package (Prism v4.0; GraphPad Software, San Diego, CA). Data were expressed as mean ± SD. Homodynamics were analyzed using two-way analysis of variance with Bonferroni post hoc test for multiple comparisons if significant F ratios were obtained. IS (expressed as percentage of the area at risk) were analyzed between groups using analysis of variance with a Student-Newman-Keuls post hoc test for multiple comparisons. Sigmoid dose-response nonlinear regression was used for remifentanil-treated rats. Statistical differences were considered significant if the P value was <0.05.

**Results**

A total of 107 animals were used in the study. Animals were omitted from further data analysis if severe hypotension (arterial mean blood pressure less than 30 mmHg) or intractable ventricular fibrillation occurred. Consequently, five were excluded because of intractable ventricular fibrillation: one each in the control, RPC (0.2 μg·kg⁻¹·min⁻¹), NTD, NTD+IPC, and NTD+RPC groups. One animal in the CTOP+RPC group and one in the nor-BNI+IPC group were excluded because of severe hypotension. One animal in the IPC group was excluded because of an excessively large AAR volume (>0.550 mm³). A total of 99 animals completed the study.

**Effects of Remifentanil or Ischemic Preconditioning on Myocardial Infarct after Ischemia and Reperfusion**

As shown in table 1, remifentanil at 6 and 20 μg·kg⁻¹·min⁻¹ significantly reduced the heart rate. At 0.6–20 μg·kg⁻¹·min⁻¹ it also significantly reduced the mean blood pressure and rate pressure product. There was no difference in any of the hemodynamic parameters between control and treatment groups during ischemia and reperfusion with two exceptions: a slight, but significant drop in mean blood pressure in the groups preconditioned with 0.6 and 2 μg·kg⁻¹·min⁻¹ RPC. The AAR ranged from 0.384 ± 0.084 cm³ to 0.434 ± 0.117 cm³. There was no difference between the control and treatment groups. As shown in figure 3 the IS, expressed as a percentage of the AAR, of the control group was 52.7 ± 5.5% (n = 9). In groups subjected to IPC and RPC the infarct sizes were significantly reduced. The reduction in IS in groups subjected to remifentanil PC in the range of 0.6–6 μg·kg⁻¹·min⁻¹ were dose related, with a peak reduction at 6 μg·kg⁻¹·min⁻¹. The ED₅₀ was 2.69 μg·kg⁻¹·min⁻¹ according to the sigmoid equation $Y = 15.18 + 17.76/[1 + 10^{(-2.57 - 5.18})]$, $r = -0.898$. 

Table 1. Hemodynamic Parameters in Series 1

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Treatment</th>
<th>30-min occlusion</th>
<th>2-h reperfusion</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No.</td>
<td>HR</td>
<td>MBP</td>
<td>RPP</td>
</tr>
<tr>
<td>Control</td>
<td>9</td>
<td>435 ± 54</td>
<td>82 ± 16</td>
<td>47 ± 10</td>
</tr>
<tr>
<td>IPC</td>
<td>9</td>
<td>428 ± 70</td>
<td>82 ± 14</td>
<td>44 ± 9</td>
</tr>
<tr>
<td>RPC (0.2 μg·kg⁻¹·min⁻¹)</td>
<td>5</td>
<td>383 ± 62</td>
<td>77 ± 10</td>
<td>38 ± 17</td>
</tr>
<tr>
<td>RPC (0.6 μg·kg⁻¹·min⁻¹)</td>
<td>6</td>
<td>436 ± 69</td>
<td>77 ± 15</td>
<td>41 ± 10</td>
</tr>
<tr>
<td>RPC (2 μg·kg⁻¹·min⁻¹)</td>
<td>8</td>
<td>460 ± 60</td>
<td>73 ± 7</td>
<td>45 ± 8</td>
</tr>
<tr>
<td>RPC (6 μg·kg⁻¹·min⁻¹)</td>
<td>7</td>
<td>414 ± 28</td>
<td>70 ± 10</td>
<td>40 ± 4</td>
</tr>
<tr>
<td>RPC (20 μg·kg⁻¹·min⁻¹)</td>
<td>6</td>
<td>439 ± 33</td>
<td>80 ± 10</td>
<td>47 ± 6</td>
</tr>
</tbody>
</table>

Baseline = 15 min after surgery; Treatment = after remifentanil preconditioning (RPC) or ischemic preconditioning (IPC); 30-min occlusion = 30 min after regional ischemia; 2-h reperfusion = 2 hours after reperfusion; HR = heart rate (beats/min); MBP = mean arterial blood pressure (mm Hg); RPP = rate-pressure product (mm Hg/min per 1000).

RPC hearts were subject to three cycles of 5 min infusion periods of remifentanil (0.2, 0.6, 2, 6 or 20 μg·kg⁻¹·min⁻¹) interspersed with drug-free periods. *P < 0.05 versus control group; †P < 0.05; ‡P < 0.01 versus baseline.
Effects of Remifentanil or Ischemic PC on Myocardial Infarct after Ischemia and Reperfusion with Blockade of Opioid Receptors

There were no differences in hemodynamic parameters between control and treatment groups (data not shown). Nor was there any difference in AAR, which ranged from 0.329 ± 0.015 to 0.499 ± 0.092 cm³. IPC and RPC (6 µg·kg⁻¹·min⁻¹) markedly reduced IS/AAR from 52.7 ± 5.5% (n = 9) to 12.9 ± 3.4% (n = 9, P < 0.01 versus control) and 16.2 ± 6.4% (n = 7, P < 0.01 versus control), respectively. 1 mg/kg CTOP, a selective µ-OR antagonist, or 5 mg/kg NTD, a selective δ-OR antagonist, administered 10 min before RPC completely abolished the cardioprotective effect of RPC (IS/AAR: CTOP + RPC 58.5 ± 4.6%, n = 5; NTD + RPC 47.4 ± 8.5%, n = 5, P > 0.05 versus control). 5 mg/kg nor-BNI, a selective κ-OR antagonist, administered 15 min before RPC attenuated the cardioprotective effect of RPC (IS/AAR: 33.1 ± 7.7%, n = 6, P < 0.01 versus control and RPC) (fig. 4). In the IPC group, blockade of the δ-OR abolished, whereas blockade of the κ-OR attenuated, the protection (IS/AAR: NTD + IPC 47.6 ± 8.3%, n = 5, P > 0.05 versus control; nor-BNI + IPC 31.9 ± 5.7%, n = 6, P < 0.01 versus control and IPC) (fig. 5). Blockade of the µ-OR did not alter the cardioprotective effect of IPC (IS/AAR: 18.4 ± 3.2%, n = 5, P > 0.05 versus control and IPC, respectively). The three antagonists did not change IS/AAR when either agent was administered to non-PC hearts (IS/AAR: NTD 51.6 ± 4.7%, n = 5, nor-BNI 50.3 ± 8.3%, n = 6, and CTOP 47.2 ± 5.3%, n = 6, P > 0.05 versus control, respectively) (fig. 5).

Fig. 3. Curve illustrating the relationship between IS/AAR and the dose of remifentanil. Infarct size (IS) expressed as a percentage of the area-at-risk (AAR). ED₅₀ is 2.7 µg·kg⁻¹·min⁻¹; sigmoid equation \( Y = 15.18 + 17.76/[1 + 10^{(0.162 - 0.898)}], r = -0.898 \). IPC = ischemic preconditioning; RPC = remifentanil preconditioning. Values are means ± SD. *P < 0.01 versus control.

Fig. 4. The effect of opioid antagonists on remifentanil preconditioning. Infarct size (IS) expressed as a percentage of the area-at-risk (AAR). Infarct sizes in rat hearts subjected to control, remifentanil preconditioning (RPC, remifentanil 6 µg·kg⁻¹·min⁻¹×3), naltrindole (5 mg/kg, intravenous; NTD + RPC) given 10 min before the RPC, nor-binaltorphimine (5 mg/kg, intravenous; nor-BNI + RPC) given 15 min before the RPC, or CTOP (1 mg/kg, intravenous; CTOP + RPC) given 10 min before the RPC. Values are means ± SD. *P < 0.01 versus control; †P < 0.01 versus RPC.

Fig. 5. The effect of opioid antagonists on ischemic preconditioning. Infarct size (IS) expressed as a percentage of the area-at-risk (AAR). Infarct sizes in rat hearts subjected to control, NTD or NTD + IPC (naltrindole 5 mg/kg, intravenous; 10 min before ischemia or IPC), CTOP or CTOP + IPC (CTOP 1 mg/kg, intravenous; 10 min before ischemia or IPC), nor-BNI or nor-BNI + IPC (nor-binaltorphimine, 5 mg/kg, intravenous; 15 min before ischemia), ischemic preconditioning (IPC). Values are means ± SD. *P < 0.01 versus control; †P < 0.01 versus IPC.
Discussion

Remifentanil reduced IS dose-dependently in open chest anesthetized rats; this is the first time that a preconditioning effect has been demonstrated with remifentanil. More interestingly, the protective effect of RPC was abolished by all three OR antagonists CTOP, NTD, and nor-BNI, indicating that the effect of remifentanil is mediated via μ-, δ-, and κ-ORs.

A previous study has shown that a brief infusion of morphine can produce a preconditioning effect.\textsuperscript{10,14} Because the half-life of morphine is long, its effect may last beyond the preconditioning period. Therefore it is not clear whether the protective effect of morphine was a direct effect of morphine itself or the effect of preconditioning triggered by morphine. In the current study, we used an ultra-short acting μ-opioid agonist, remifentanil, and found that it also confers cardioprotection. However, in view of the extremely short half-life, it is likely that this drug mimics ischemic preconditioning.

Both δ-ORs and κ-ORs are present in the heart.\textsuperscript{21,22} This study, in accordance with previous studies, has shown that these two receptors in the heart mediate the cardioprotection of IPC.\textsuperscript{12,15,23,26} There is no evidence of μ-ORs in the rat heart from binding studies\textsuperscript{21,22,27} or physiologic studies,\textsuperscript{28,29} and in the current study we also found that blockade of the μ-opioid receptor with its antagonist, CTOP, did not alter the cardioprotective effect of ischemic preconditioning, suggesting that an intracardiac μ-opioid receptor is not involved in the cardioprotection of ischemic preconditioning. We found that blockade of any of the three opioid receptors by systemic administration of selective opioid receptor antagonists abolished or attenuated the protective effect of remifentanil in the anesthetized rat. Therefore, the action of remifentanil may be mediated, at least partly, via the cardiac δ-ORs and κ-ORs but not by a cardiac μ-OR. It is possible that a μ-OR that is located outside the myocardium may also mediate the effect of remifentanil. One possibility is the central nervous system. During myocardial ischemia, there is an accumulation of norepinephrine in the myocardium as a result of an increased nonexocytotic release from sympathetic nerve terminals, which induces injury.\textsuperscript{30–33} There is evidence that activation of the μ-OR by morphine administered intravenously reduces IS in a rat model of myocardial ischemia reperfusion injury\textsuperscript{34} and also depresses the somatocardiac reflex.\textsuperscript{35} It is possible that activation of the μ-OR in the central nervous system may inhibit the sympathetic influence on the heart, thus reducing the release of norepinephrine and injury during ischemia. This is supported by the clinical observation of decreased heart rates in patients receiving remifentanil-based anesthesia\textsuperscript{36} and could be an interesting area for further study.

Brief renal, mesenteric, or skeletal muscle ischemia of remote origin can effectively precondition the heart (‘remote preconditioning’).\textsuperscript{37} This concept is consistent with the fact that regional cardiac ischemia can initiate global protection and render remote myocardium resistant to infarction (‘preconditioning at a distance’).\textsuperscript{38,39} Therefore, another possibility is that remifentanil may have some effect on other organs that indirectly renders remote myocardium resistant to infarction.

A previous study showed that morphine, a predominantly μ-OR agonist, acts on the heart via κ-ORs and δ-ORs.\textsuperscript{25} It is, therefore, not surprising that remifentanil, also a μ-OR agonist, acts via κ-ORs and δ-ORs.

It is interesting that blockade of one of the three receptors abolished or markedly attenuated the effect of preconditioning. This is most likely attributable to the fact that activation of any one of the receptors leading to cardioprotection involves the same final common pathway, which may be cytosolic Ca\textsuperscript{2+} overload, believed to be a precipitating factor of injury. If activation of one of the receptors leads to a significant reduction of Ca\textsuperscript{2+} overload induced by ischemia, cardioprotection is achieved. Activation of another receptor in or outside the heart will not necessarily confer additional protection.

We also observed that remifentanil decreased heart rate, mean blood pressure, and rate pressure product in agreement with previous observations.\textsuperscript{36,39,40} However, other than a slight but significant reduction in mean blood pressure during ischemia in the groups preconditioned with 0.6 and 2.0 μg·kg\textsuperscript{-1}·min\textsuperscript{-1}, there were no differences in any of the hemodynamic parameters between the control and treatment groups during ischemia and reperfusion. This observation suggests that it is unlikely that the effect of preconditioning on myocardial infarct is related to alterations in hemodynamic parameters.

We found the effect of remifentanil on reducing infarct size was dose dependent. Given in clinically relevant larger doses to rats (from 0.2 to 20 μg·kg\textsuperscript{-1}·min\textsuperscript{-1}), remifentanil produces its maximum effect at a dose of 6 μg·kg\textsuperscript{-1}·min\textsuperscript{-1} with an ED\textsubscript{50} of 2.7 μg·kg\textsuperscript{-1}·min\textsuperscript{-1}, although it is difficult to extrapolate such doses from a small animal model to the human. Remifentanil is now being increasingly used in anesthesia because its unique pharmacokinetic profile allows it to be given in very high doses during surgery without fear of postoperative respiratory depression.\textsuperscript{18}

In summary, this study has provided evidence for the first time that RPC confers protection against injury induced by ischemia in the intact rat heart. All three subtypes of ORs, namely μ-ORs, δ-ORs, and κ-ORs, mediate the action of remifentanil, although the μ-OR effect is likely to be initiated extracardiac.

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