In Vitro Electrophysiologic Effects of Morphine in Rabbit Ventricular Myocytes

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Background: Morphine is widely used in patients undergoing surgical operations and is also reported to mediate cardioprotection of preconditioning. The current study determined effects of morphine at therapeutic to pharmacologic concentrations on cardiac action potential, L-type Ca\(^{2+}\) current (I\(_{\text{Ca,L}}\)), delayed rectifier K\(^{+}\) current (I\(_{\text{Kd}}\)), and inward rectifier K\(^{+}\) current (I\(_{\text{K1}}\)) in isolated rabbit ventricular myocytes.

Methods: Ventricular myocytes were enzymatically isolated from rabbit hearts. Action potential and membrane currents were recorded in current and voltage clamp modes.

Results: Morphine at concentrations from 0.01 to 1 \(\mu\)M significantly prolonged action potential, and at 0.1 and 1 \(\mu\)M slightly but significantly hyperpolarized the resting membrane potential. In addition, morphine at 0.1 \(\mu\)M significantly augmented I\(_{\text{Kd}}\) (at +10 mV) from 5.9 ± 1.9 to 7.3 ± 1.7 pA/pF (by 23%; \(P < 0.05\) vs. control) and increased I\(_{\text{K1}}\) (at −60 mV) from 2.8 ± 1.0 to 3.5 ± 0.9 pA/pF (by 27%; \(P < 0.05\) vs. control). Five \(\mu\)M naltrindole (a selective \(\delta\)-opioid receptor antagonist) or 5 \(\mu\)M nornalbinaltorphimine (a selective \(\kappa\)-opioid receptor antagonist) prevented the increase in I\(_{\text{Kd}}\) induced by morphine, but 5 \(\mu\)M CTOP (a selective \(\mu\)-opioid receptor antagonist) did not. The three types of opioid antagonists did not affect the augmentation of I\(_{\text{K1}}\) by morphine. Morphine had no effect on I\(_{\text{K1}}\).

Conclusions: These results indicate that morphine prolongs action potential duration by increasing I\(_{\text{Kd}}\), an effect mediated by \(\delta\)- and \(\kappa\)-opioid receptors. It also hyperpolarizes cardiac resting membrane potential by increasing I\(_{\text{K1}}\), which is not mediated by opioid receptors.

MORPHINE is still widely used in postoperative and preoperative care\(^1\text{-}^5\) and sedation in critically ill patients.\(^6\) The drug is also effective in relieving the chest pain associated with acute myocardial infarction.\(^1\text{-}^6\) Morphine has been shown to mediate cardioprotection of preconditioning,\(^7\text{-}^8\) and the effect of morphine results from direct action at the level of the cardiac myocytes \(\text{via} \ \delta\text{- and} \ \kappa\text{-opioid receptors.}\(^9\) In addition, morphine showed antiarrhythmic activity in ischemia-reperfusion-induced arrhythmias.\(^10\) Therefore, morphine is used in prognostic myocardial damage in cardiac surgery.\(^11\)

Electrophysiologic effects of morphine on cardiac myocytes are not well understood. In multicellular preparations, morphine at higher therapeutic concentrations decreases the maximal upstroke velocity of action potential depolarization and increases the action potential duration (APD).\(^12\text{-}^13\) At the cellular level, the compound inhibits Na\(^{+}\) current in rat and human cardiac myocytes and has no effect on L-type Ca\(^{2+}\) current (I\(_{\text{Ca,L}}\)), transient outward K\(^{+}\) current, and inwardly rectifying K\(^{+}\) current (I\(_{\text{K1}}\)).\(^14\) A recent study in ischemia-reperfused guinea pig myocardium showed that morphine at clinically relevant concentrations decreases ischemia-induced conduction blocks and reperfusion-induced ventricular arrhythmias, which is believed to be mainly due to partial reverse of ischemia-induced membrane depolarization and decrease in action potential amplitude and the maximal upstroke velocity of action potential depolarization.\(^15\) However, the ionic mechanisms involved in the effects of morphine remain to be clarified. The current study was therefore designed to determine the effects of morphine at clinically relevant concentrations on the action potential and ionic currents in isolated rabbit ventricular myocytes using a whole cell patch clamp technique.

Materials and Methods

The New Zealand white rabbits used in the current study were cared for in accordance with the Guide for the Care and Use of Laboratory Animals,\(^16\) and the experimental protocol was approved by the Ethics Committee on the Use of Animals in Teaching and Research, The University of Hong Kong (Pokfulam, Hong Kong SAR, China).

Ventricular Myocytes Preparation

Ventricular myocytes were isolated from the hearts of rabbits with a procedure previously described.\(^17\) Briefly, New Zealand white rabbits of either sex (1.5–2.5 kg) were anesthetized with pentobarbital (30 mg/kg, intravenous injection), and their hearts were quickly removed and placed in oxygenated Tyrode solution. Hearts were mounted on a Langendorff system and perfused for approximately 5 min with normal Tyrode solution and for an additional 10–12 min with Ca\(^{2+}\)-free Tyrode solution. Then, perfusion solution was switched to the Ca\(^{2+}\)-free Tyrode solution containing 0.5 mg/ml collagenase (CLS II; Worthington Biochemical, Freehold, NJ) and 1 mg/ml bovine serum albumin. The myocytes isolated from the softened heart were stored in high-K\(^{+}\)...
storage solution. Myocytes were placed in the recording chamber (0.3 ml) mounted on the stage of an inverted microscope and superfused at approximately 2 ml/min with external solution. Only quiescent, rod-shaped cells showing clear striations were selected for experiments. The experiments were performed at 36°C for recording action potentials and delayed rectifier K⁺ current (I_{K₁}) or room temperature (21°C–22°C) for recording I_{Ca,L} and I_{K₁}.

**Solutions and Drugs**

The high-K⁺ storage solution contained 10 mM KCl, 10 mM KH₂PO₄, 20 mM glucose, 120 mM KGluatamate, 10 mM taurine, 0.5 mM EGTA, 10 mM HEPES, and 1.8 mM MgSO₄ (pH adjusted to 7.2 with KOH). The Tyrode solution contained 140 mM NaCl, 5.4 mM KCl, 1.0 mM MgCl₂, 1.8 mM CaCl₂, 0.33 mM NaH₂PO₄, 10 mM glucose, and 10 mM HEPES (pH adjusted to 7.4 with NaOH). When Tyrode solution was used to record K⁺ currents, 200 μM Cd²⁺ and 3 mM 4-aminopyridine were added to respectively block I_{Ca,L} and transient outward K⁺ current (I_{To}). The pipette solution for K⁺ current recordings contained 20 mM KCl, 110 mM potassium aspartate, 1.0 mM MgCl₂, 10 mM HEPES, 5 mM EGTA, 0.1 mM GTP, 5 mM Mg₂ATP, and 5 mM sodium phosphocreatine (pH adjusted to 7.2 with KOH). An N-methyl-D-glucamine Tyrode solution, containing 140 mM N-methyl-D-glucamine, 5.4 mM CsCl, 1.0 mM MgCl₂, 1.8 mM CaCl₂, 0.33 mM KH₂PO₄, 10 mM glucose, and 10 mM HEPES, was used when I_{Ca,L} was measured (pH adjusted to 7.4 with CsOH). The pipette solution for I_{Ca,L} recording contained 20 mM CsCl, 110 mM cesium aspartate, 1.0 mM MgCl₂, 10 mM HEPES, 5 mM EGTA, 0.1 mM GTP, 5 mM Mg₂ATP, and 5 mM sodium phosphocreatine (pH adjusted to 7.2 with CsOH). Morphine (sulfate salt) was obtained 20 mM CsCl, 110 mM cesium aspartate, 1.0 mM MgCl₂, 10 mM HEPES, 5 mM NaCl, 0.5 mM EGTA, 120 mM K-glutamate, 10 mM glucose, and 10 mM HEPES, was used when I_{Ca,L} was measured (pH adjusted to 7.4 with NaOH).

**Data Acquisition and Analysis**

Nonlinear curve fitting was performed using Sigmaplot (SPSS, Chicago, IL). Concentration–response effects of morphine were fit to the Hill equation: E = E_{max}/[1 + (EC_{50}/C)^b], where E is the effect at concentration C, E_{max} is the maximal effect, EC_{50} is the concentration for half-maximal effect, and b is the Hill coefficient. Curves for steady state activation (d) and inactivation (f) of I_{Ca,L} were fit to Boltzmann relations for activation and inactivation as follows: d (or f) = 1/[1 + exp((V_{1/2} - V)/K)], where V is the membrane potential, V_{1/2} is a midpoint of potential for activation or inactivation, and K is a slope factor.

Comparison of two means was performed using the paired and unpaired Student t tests, and comparison of several means was performed using analysis of variance, then with a Dunnett post hoc test for the comparison with control. Statistical differences were considered significant if the P value was less than 0.05. Results are presented as mean ± SD.

**Results**

**Effects of Morphine on Action Potentials in Isolated Rabbit Ventricular Myocytes**

Figure 1 shows representative action potentials recorded at 1 Hz in current clamp mode from a rabbit ventricular myocyte in the presence of 0.01, 0.1, and 1 μM morphine and after washout of the drug. The APD...
Fig. 1. Effect of morphine on action potentials. Action potentials were recorded from a representative rabbit ventricular myocyte, showing that action potential duration is prolonged and resting membrane potential is slightly hyperpolarized by the application of morphine at 0.01, 0.1, and 1 μM (6 min for each concentration). The effect was only partially reversed upon drug washout (10 min).

was substantially increased, and the resting membrane potential was slightly hyperpolarized by application of morphine. The effects were partially reversed by washout of the drug for 10 min. The effects on action potential variables in each experiment exposed to three concentrations of morphine are summarized in table 1.

**Effect of Morphine on I\textsubscript{Ca,L}**

Because I\textsubscript{Ca,L} is mainly responsible for the plateau of action potentials of the cardiac muscle, we determined the effect of morphine on the current. Figure 2A displays I\textsubscript{Ca,L} tracings recorded from a representative cell with 300-ms voltage steps to between −40 and +60 mV from −50 mV as shown in the inset. Morphine at 0.1 μM substantially increased I\textsubscript{Ca,L} after administration for 6 min. The effect was partially reversed upon washout for 10 min. Figure 2B shows current–voltage relations of mean values of I\textsubscript{Ca,L} density (n = 12) in the absence and presence of 0.1 μM morphine. The density of I\textsubscript{Ca,L} at +10 mV corresponding to peak current was significantly increased by 23 ± 8% (from 5.9 ± 1.9 to 7.3 ± 1.7 pA/pF; P < 0.05).

Figure 2C illustrates the concentration–response relation for the augmentation of I\textsubscript{Ca,L} by morphine. The mean data were fit to the Hill equation, and the EC\textsubscript{50} (at +10 mV) was 0.47 μM with a Hill coefficient of 0.31, and the E\textsubscript{max} was 47%.

Effects of morphine on steady state voltage dependence of I\textsubscript{Ca,L} activation and inactivation were evaluated in rabbit ventricular cells. Voltage-dependent activation of I\textsubscript{Ca,L} was determined, as described previously,

### Table 1. Effects of Morphine on Action Potential Variables in Rabbit Ventricular Myocytes

<table>
<thead>
<tr>
<th>Condition</th>
<th>RMP (mV)</th>
<th>APA (mV)</th>
<th>APD\textsubscript{50} (ms)</th>
<th>APD\textsubscript{90} (ms)</th>
</tr>
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<tbody>
<tr>
<td>Control</td>
<td>−81.4 ± 1.3</td>
<td>122.5 ± 7.6</td>
<td>120.8 ± 29.7</td>
<td>130.8 ± 30.3</td>
</tr>
<tr>
<td>10 nM Morphine</td>
<td>−82.1 ± 1.0</td>
<td>123.1 ± 11</td>
<td>131.5 ± 48.5*</td>
<td>142.7 ± 54.1*</td>
</tr>
<tr>
<td>100 nM Morphine</td>
<td>−82.6 ± 1.0*</td>
<td>122.1 ± 9.6</td>
<td>139.0 ± 48.2*</td>
<td>148.4 ± 51.8*</td>
</tr>
<tr>
<td>1 μM Morphine</td>
<td>−83.0 ± 1.0</td>
<td>122.3 ± 10.2</td>
<td>142.9 ± 42.2*</td>
<td>154.7 ± 44.8*</td>
</tr>
<tr>
<td>Washout</td>
<td>−82.5 ± 1.0*</td>
<td>122.6 ± 8.3</td>
<td>135.5 ± 51.8*</td>
<td>146.2 ± 54.8*</td>
</tr>
</tbody>
</table>

*P < 0.05 vs. control.

APA = action potential amplitude; APD\textsubscript{50} and APD\textsubscript{90} = action potential duration at 50 and 90% of repolarization, respectively; RMP = resting membrane potential.

Fig. 2. Effect of morphine on L-type Ca\textsuperscript{2+} current (I\textsubscript{Ca,L}). (A) I\textsubscript{Ca,L} traces recorded in a representative myocyte using 300-ms steps to between −40 and +60 mV as shown in the inset during control, after the application of 0.1 μM morphine for 6 min, and after washout of the drug for 10 min. I\textsubscript{Ca,L} was increased by the application of 0.1 μM morphine and was partially reversed by drug washout. (B) Current–voltage relations of I\textsubscript{Ca,L} density (n = 12) in the absence (control; open circles) and presence of 0.1 μM morphine (filled circles). Data are expressed as mean ± SD. * P < 0.05 versus control. (C) Concentration–response relation of morphine effect on I\textsubscript{Ca,L}. Numbers within parentheses are number of experiments.
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Fig. 3. Absence of effect of morphine (0.1 µM) on voltage-dependent activation and inactivation of L-type Ca\(^{2+}\) current (I\(_{\text{Ca-L}}\)). (A) Representative current recordings used to determine voltage dependence of I\(_{\text{Ca-L}}\) inactivation. Cell was conditioned with 500-ms prepulses from holding potential of −80 mV to between −100 and 0 mV and back to −80 mV for 5 ms, then subjected to 300-ms test pulse to +10 mV. (B) Mean values of voltage-dependent activation and inactivation relations for I\(_{\text{Ca-L}}\). No significant differences of V\(_{0.5}\) and slope factor were observed for activation and inactivation of I\(_{\text{Ca-L}}\) before (control; open circles) and after application of 0.1 µM morphine (filled circles).

for inactivation averaged −20.1 ± 1.1 mV and −4.6 ± 0.9 mV for control and −20.4 ± 0.8 mV and −4.5 ± 0.7 mV for morphine (0.1 µM) treatment (n = 10), respectively. The steady state activation and inactivation of I\(_{\text{Ca-L}}\) were not affected by morphine. In addition, recovery of I\(_{\text{Ca-L}}\) from inactivation, determined with the procedure as previously described, was not influenced by 0.1 µM morphine, either (n = 7).

Figure 4 shows the effects of 0.1 µM morphine on I\(_{\text{Ca-L}}\) at +10 mV in the absence and presence of opioid receptor antagonists. These three types of opioid receptor antagonists themselves had no effect on I\(_{\text{Ca-L}}\); NTD or nor-BNI, but not CTOP, abolished the action of morphine on the current, suggesting that the enhancement of I\(_{\text{Ca-L}}\) by morphine is mediated by both δ- and κ-opioid receptors.

In addition, the prolongation of cardiac APD by morphine is related to the increase of I\(_{\text{Ca-L}}\) and mediated by δ- and κ-opioid receptors.

Effect of Morphine on I\(_{K}\)

Figure 5 displays the effect of morphine on I\(_{K}\) (I\(_{Kr}\) and I\(_{Ks}\)) in a typical experiment. Morphine at 0.1 µM had no effect on I\(_{K}\). In a total of six ventricular myocytes, the tail current (measured at −30 mV from the peak tail to the completed deactivation level) of I\(_{K}\) was 2.2 ± 0.8 pA/pF in control and 2.2 ± 0.9 after application of 0.1 µM morphine (n = 6; not significant). No change in I\(_{K}\) tail...
Decreased by 11 $\pm$ 7, 25 $\pm$ 9, and 32 $\pm$ 11%; $P < 0.05$ for 0.1 and 1 $\mu M$ morphine).

Figure 6C summarizes the mean data of morphine effect on $I_{K1}$ at $-60$ mV in the absence and presence of opioid receptor antagonists. Pretreatment with 5 $\mu M$ NTD, 5 $\mu M$ nor-BNI, or 5 $\mu M$ CTOP did not affect the action of morphine on the current, indicating that the increase of $I_{K1}$ by morphine is not mediated by opioid receptors.

**Discussion**

In the current study, we demonstrated that morphine at 0.01–0.1 $\mu M$ prolonged APD and increased $I_{Ca,L}$ in isolated rabbit ventricular myocytes. The effects were prevented by blockade of $\delta$- or $\kappa$-opioid receptors. At 0.1–1 $\mu M$, morphine also hyperpolarizes the resting membrane potential and enhances $I_{K1}$, but this effect was not mediated by opioid receptors. Based on the pharmacokinetics of morphine in humans, i.e., a volume of distribution of 3.2 l/kg and 35% protein binding, the equilibrate plasma concentration is approximately 0.06 $\mu M$ after intravenous injection of 0.2 mg/kg morphine. Therefore, the concentrations at 0.01–0.1 $\mu M$ used in the current study are within therapeutic concentrations.

It is well known that prolongation of action potential is dependent on increase of inward current (e.g., $I_{Ca,L}$) or decrease of outward K currents ($I_{K}$ or $I_{K1}$). A previous report demonstrated that morphine prolonged cardiac APD in cardiac tissue,13 but the ionic mechanisms are not understood. In the current study, using a whole cell patch clamp technique, we provided evidence that morphine prolonged cardiac APD by increasing $I_{Ca,L}$, not by decreasing $I_{K}$ or $I_{K1}$. The increase of $I_{Ca,L}$ by morphine had an EC$_{50}$ of 0.5 $\mu M$ with a Hill coefficient of 0.31. The small Hill coefficient suggested a wide effective concentration range of morphine.

The current observation on the increase of cardiac $I_{Ca,L}$ by morphine was supported by previous studies using $^{45}$Ca$^{2+}$ or spectrophotometry, in which morphine was found to induce transmembrane Ca$^{2+}$ influx in cardiac myocytes.9,22 In contrast to the current finding, stimulation of opioid receptor with 0.01 $\mu M$ leucine-enkephalin, a $\delta$-opioid receptor agonist, was shown to reduce $I_{Ca,L}$ in rat ventricular myocytes.23 This discrepancy may be due to the use of different opioid receptor agonists in the two studies: morphine in the current study and leucine-enkephalin in the previous study.23 Actually, the opposing effects of opioids on voltage-dependent Ca$^{2+}$ channels ($I_{Ca,L}$) were documented in nerve cells. Most of the studies indicated inhibitory effects of opioids on $I_{Ca,L}$,24–26 but stimulation was also observed.27 It was reported that morphine at 50 $\mu M$ did not affect $I_{Ca,L}$ in rat ventricular myocytes.14 The discrepancies...
between these findings might be related to drug concentration, species, experimental procedures, opioid receptor subtypes involved, or other unknown factors. In the heart, L-type calcium channels play an important role in generating electrical activity and excitation–contraction coupling. It is well established that increases in \( I_{\text{Ca,L}} \) produce positive inotropic effects and induce triggered arrhythmias, which is highly undesirable in patients with acute myocardial infarction. However, increases in \( I_{\text{Ca,L}} \) by Bay Y5959, a \( Ca^{2+} \) promoter, have recently been shown to prevent the initiation of reentrant ventricular tachycardia in the epicardial border of healing infarcted canine heart, indicating antiarrhythmic actions of an increase in \( I_{\text{Ca,L}} \).

A previous study reported that activation of opioid receptors would hyperpolarize cell membrane in neurons. In the current study, we showed that morphine at the therapeutic concentration of 0.1 \( \mu M \) increased \( I_{\text{K1}} \) in cardiac myocytes via an opioid receptor–independent pathway. There is evidence that a reduction in \( I_{\text{K1}} \) is associated with arrhythmias. Patients with Andersen syndrome, a rare inherited disease with a mutation in a major contributor of the \( I_{\text{K1}} \) channel, Kir2.1, which causes a reduction in \( I_{\text{K1}} \), exhibit complex ventricular ectopy and polymorphic ventricular tachycardia. Therefore, it is likely that an increase in \( I_{\text{K1}} \) hyperpolarizes the resting membrane potential, thus producing a membrane stabilizing effect.

It should be noted that the concentrations of morphine used in the previous study \( \text{were much higher than} \) those used in clinical practice. Recently, it was found that morphine at low concentrations produced preconditioning in brain Purkinje cells. Yvon et al. reported that morphine at clinically relevant concentrations did not modify action potential variables in guinea pig ventricle in normoxic conditions but significantly attenuated the ischemia-induced depolarization and increase in amplitude of action potential and \( v_{\text{max}} \) and therefore reduced the incidence of conduction block during ischemia and reperfusion-induced arrhythmias. Nevertheless, we observed that morphine at 0.1 and 1 \( \mu M \) hyperpolarized the resting membrane potential significantly and prolonged APD in single ventricular myocytes from rabbit hearts. Analyses of ionic currents showed that morphine increases both \( I_{\text{Ca,L}} \) and \( I_{\text{K1}} \). The increase in \( I_{\text{Ca,L}} \) and \( I_{\text{K1}} \) would prolong and shorten the cardiac APD, respectively, thus resulting in a moderate prolongation of the APD. The effects of morphine on these two types of currents would be responsible for decreased ischemia-reperfusion–induced arrhythmias as observed by Yvon et al. Together with its analgesic and cardioprotective action, morphine at the therapeutic concentrations may be very useful in the management of acute myocardial infarction.

The following limitations must be considered in the assessment of the relevance of our study. The species differences, in vitro study, healthy myocardium versus diseased myocardium, normal physiologic conditions versus abnormal conditions (e.g., hypoxia, ischemia), and interaction with other anesthetic agents should all be taken into consideration. In addition, no clear explanation was available for the observed slow reversibility of morphine effect (by washout). Possible explanations for this phenomenon would be the tight binding of morphine with cell membrane protein and the participation of intracellular events. It has been found that several signal pathways (e.g., protein kinase A, protein kinase C, protein kinase G) are involved in physiologic actions mediated by opioid receptors. The slow reversibility is likely related to the fact that the effects from these pathways may require a longer time to disappear after washout of the receptor ligand.

It is interesting to note that blockade of either \( \delta \) or \( \kappa \)-opioid receptors abolished the effect of morphine. A similar phenomenon has been reported previously by us. The infarct-sparing effect of preconditioning of remifentanil, an ultrarapid-acting opioid receptor agonist, is abolished by blockade of \( \kappa \) or \( \delta \)-opioid receptors.

Further study is required to determine whether this is related to interaction of \( \kappa \)-opioid receptors with \( \delta \)-opioid receptors. In conclusion, the current study has demonstrated that morphine at a clinically relevant concentration of 0.1 \( \mu M \) increases \( I_{\text{Ca,L}} \) and \( I_{\text{K1}} \) in isolated rabbit ventricular myocytes. Its action on \( I_{\text{Ca,L}} \) is mediated by \( \delta \)- and \( \kappa \)-opioid receptors, whereas its effect on \( I_{\text{K1}} \) is not mediated by opioid receptors.

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