Propofol Increases Phosphorylation of Troponin I and Myosin Light Chain 2 via Protein Kinase C Activation in Cardiomyocytes

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Background: Troponin I (TnI) and myosin light chain 2 (MLC2) are important myofilibrillar proteins involved in the regulation of myofilament calcium (Ca^{2+}) sensitivity and cardiac inotropy. The objectives of this study were to determine the role of protein kinase C (PKC) in mediating propofol-induced changes in actomyosin adenosine triphosphatase activity in cardiac myofibrils and to examine the extent to which propofol alters the phosphorylation of TnI and MLC2 in cardiomyocytes.

Methods: Freshly isolated adult rat ventricular myocytes were used for the study. Cardiac myofibrils were extracted for assessment of actomyosin adenosine triphosphatase activity and phosphorylation of TnI and MLC2. Western blot analysis for PKC-α was performed on cardiomyocyte subcellular fractions. Simultaneous measurement of intracellular free Ca^{2+} concentration ([Ca^{2+}]_i) and myocyte shortening was assessed using fura-2 and video edge detection, respectively.

Results: Propofol (30 μM) reduced the Ca^{2+} concentration required for activation of actomyosin adenosine triphosphatase activity, and this effect was abolished by bisindolylmaleimide I. In addition, propofol stimulated dose-dependent phosphorylation of TnI and MLC2. PKC activation with phorbol myristic acetate also stimulated an increase in phosphorylation of TnI and MLC2. The actions of propofol and phorbol myristic acetate together on phosphorylation of TnI and MLC2 were not additive. PKC inhibition with bisindolylmaleimide I attenuated phorbol myristic acetate– and propofol-induced phosphorylation of TnI and MLC2. Propofol stimulated translocation of PKC-α from cytosolic to membrane fraction. Propofol caused a shift in the extracellular Ca^{2+}–shortening relationship, and this effect was abolished by bisindolylmaleimide I.

Conclusions: These results suggest that propofol increases myofilament Ca^{2+} sensitivity via a PKC-dependent pathway involving the phosphorylation of MLC2.

ALTERATIONS in cardiac inotropy and lusitropy are mediated by changes in the availability of intracellular free calcium (Ca^{2+}) concentration ([Ca^{2+}]_i) and/or myofilament Ca^{2+} sensitivity. The sensitivity of the cardiac myofibrils to [Ca^{2+}]_i is primarily regulated by the phosphorylation state of troponin I (TnI) and myosin light chain 2 (MLC2). However, changes in intracellular pH are also known to modulate myofibrillar responsiveness to Ca^{2+}. Previous studies have demonstrated that activation of protein kinase C (PKC) in rat cardiomyocytes results in phosphorylation of several myofilibrillar proteins and an increase in myofilament Ca^{2+} sensitivity. An increase in intracellular pH is also observed in response to PKC activation. Therefore, PKC activation can trigger several cellular mechanisms that can increase myofilament Ca^{2+} sensitivity, resulting in changes in cardiac inotropy and lusitropy.

We previously demonstrated that propofol causes a negative inotropic effect in rat ventricular myocytes under baseline conditions as well as during activation of sympathetic β adrenergic receptors. However, several recent studies from our laboratory and others have also shown that propofol can increase myofilament Ca^{2+} sensitivity in cardiac muscle, suggesting that this propofol-induced increase in myofilament Ca^{2+} sensitivity acts to offset the negative inotropic action of propofol. The propofol-induced increase in myofilament Ca^{2+} sensitivity in rat cardiomyocytes was associated, in part, with intracellular alkalinization mediated via PKC-dependent activation of sodium ion–hydrogen ion (Na^{+}–H^{+}) exchange. The propofol-induced increase in myofilament Ca^{2+} sensitivity is only partially attenuated by inhibition of Na^{+}–H^{+} exchange, suggesting that additional mechanisms could be involved in the propofol-induced increase in myofilament Ca^{2+} sensitivity. One possibility is that propofol alters PKC-dependent phosphorylation of the cardiomyocyte contractile proteins, TnI and/or MLC2.

The goals of the current study were to assess the effects of PKC inhibition on propofol-induced alterations in myofilament Ca^{2+} sensitivity and to correlate this effect with the phosphorylation state of cardiomyocyte myofilibrillar proteins. We tested the hypothesis that propofol alters the phosphorylation state of TnI and MLC2 via a PKC-dependent pathway.

Materials and Methods

All experimental procedures were approved by the Institutional Animal Care and Use Committee (Cleveland, Ohio).

Ventricular Myocyte Preparation

Adult ventricular myocytes from rat hearts were isolated as previously described using established proce-
dires. In brief, the hearts were excised, cannulated via the aorta, attached to a modified Langendorff perfusion apparatus, and perfused with oxygenated (95% O₂, 5% CO₂) Krebs-Henseleit buffer (37°C) containing the following: 118 mM sodium chloride, 4.8 mM potassium chloride, 1.2 mM magnesium chloride (MgCl₂), 1.2 mM potassium phosphate (KH₂PO₄), 1.2 mM calcium chloride, 37.5 mM sodium bicarbonate, 16.5 mM dextrose; pH 7.35. Following a 5-min equilibration period, the perfusion buffer was changed to a Ca²⁺-free Henseleit buffer containing 40 mg collagenase type II (Worthington Biochemical Corp., Freehold, NJ; Lot No. 40P4421, 268 U/ml). Following collagenase digestion (20 min), the ventricles were minced and shaken in Henseleit buffer. The resulting cellular digest was washed, filtered using cheesecloth to trap any undigested cardiac tissue, and resuspended in phosphate-free HEPES-buffered saline (HBS) containing the following: 118 mM sodium chloride, 4.8 mM potassium chloride, 1.2 mM MgCl₂, 1.25 mM calcium chloride, 11 mM dextrose, 25 mM HEPES, 5 mM pyruvate; pH 7.35, and vigorously bubbled immediately before use with 100% O₂. Typically, 6–8 × 10⁶ cells per rat heart were obtained using this procedure. Viability, as assessed by the percentage of cells retaining a rod-shaped morphology, was routinely between 80 and 90%.

**Preparation of Cardiac Myofibrils**

Two-milliliter aliquots of the freshly isolated myocyte suspension were incubated in the presence or absence of propofol for 10 min at 37°C with gentle agitation. The myocytes were immediately washed twice in ice-cold HBS containing protease and phosphatase inhibitors and pelleted at 400g for 3 min, after which an equivalent volume of extraction buffer, 50 mM Tris(hydroxymethyl)aminomethane (pH 7.5) containing Triton X-100 (0.1%), sodium fluorescein (20 µM), dithiothreitol (0.5 mM), MgCl₂ (0.5 mM), EDTA (0.125 mM), antipain (5 µg/ml), leupeptin (10 µg/ml), pepstatin A (5 µg/ml), and para-methysulfonic acid (43 µg/ml) was added to the suspension. The cells were homogenized and kept on ice for 30 min. The Triton-extracted myofibrils were pelleted at 10,000g (5 min, 4°C). The detergent solubilized supernatant was set aside; the pellet was resuspended in an equivalent volume of extraction buffer and washed twice again. The resultant myofibrillar fraction was resuspended in Ca²⁺-free extraction buffer and stored at −20°C. Examination of the pellet under the microscope indicated that it was enriched in myofibrils.

**Actomyosin Adenosine Triphosphatase Activity**

The Ca²⁺-stimulated actomyosin adenosine triphosphatase (ATPase) activity of the myofibrillar fraction was measured from the rate of decrease of nicotinamide adenine dinucleotide absorbance (340 nm excitation wavelength) in a reaction coupled to the pyruvate kinase and lactate dehydrogenase reactions, as previously described by our laboratory. Triton X-100-extracted myofibrils were solubilized in a buffer containing the following: 25 mM N,N-bis-(2-hydroxyethyl)-2-aminoethanesulfonic acid (pH 7.4), 85 mM potassium methanol sulfonic acid, 3 mM MgCl₂, 2 mM EGTA, 10 mM sodium fluoride, 0.5 mM dithiothreitol, 0.5 mM leupeptin. The protein concentration of the extracted myofibrils was determined using the Lowry protein assay. The reaction mixture consisted of the following: 25 mM N,N-bis-(2-hydroxyethyl)-2-aminoethanesulfonic acid (pH 7.0), 2.7 mM MgCl₂, 2 mM EGTA, 10 mM sodium fluoride, 126 mM potassium methanol sulfonic acid, and varying free calcium chloride concentrations giving free Ca²⁺ concentrations from pCa 9 to 4. The reaction mixtures were prepared using an iterative computer program to determine the amount of calcium chloride required to achieve the appropriate concentrations. The reaction mixture also contained 200 mM phosphoenolpyruvate, 10 mM nicotinamide adenine dinucleotide, 0.5 mg/ml lactate dehydrogenase, 12.5 mg/ml pyruvate kinase, and 1 ml of one of the calcium buffers (pCa 4–9) containing myofibrillar fractions. The reaction was initiated by addition of 2 mM ATP and was allowed to continue for up to 10 min (37°C), although the reaction was usually complete within 5 min. Ca²⁺-stimulated actomyosin ATPase activity was monitored by the formation of ADP, coupled to the oxidation of nicotinamide adenine dinucleotide, and recorded by the change in absorption at 340 nm. The enzyme activity was determined from the rate of ATP hydrolysis and expressed as the percent of maximal actomyosin ATPase activity per milligram of protein.

**Labeling of Myofibrils in Intact Ventricular Myocytes with [³²P]Orthophosphate**

Phosphorylation of myofibrils in rat ventricular myocytes by [³²P]orthophosphate (³²P) was performed as previously described by our laboratory. Freshly isolated ventricular myocytes were suspended in 12 ml phosphate-free HBS (5 × 10⁶ cells/ml) and incubated with 250 μCi ³²P for 2 h at room temperature. The cell suspension was gently agitated and maintained under an oxygen hood throughout the duration of the ³²P-labeling period. There was no significant loss in myocyte viability (rod-shaped cells) following the 2-h labeling period with ³²P. After labeling, the cells were centrifuged (400 rpm) and resuspended in phosphate-free Henseleit buffer, divided into 2-ml aliquots and placed in test tubes. To ensure that the cells remained viable and maximally oxygenated throughout the incubation, all tubes were purged with 100% O₂, then placed on their sides and gently agitated for 10 min at 37°C in a shaking water bath. Myocyte viability remained greater than 75% following the 10-min incubation at 37°C in the presence of the agonists and inhibitors. Following the incubation period, the reactions were terminated, and interventions...
were removed by rapidly washing the myocytes in saline (4°C, 5 ml) containing protease inhibitors (5 μg/ml pepstatin A, 10 μg/ml leupeptin, 43 μg/ml phenylmethylsulfonyl fluoride, 5 μg/ml antipain, and 5 mM EGTA) and a protein phosphatase inhibitor (0.1 μM sodium orthovanadate) immediately before suspending the pellet in 2 ml ice-cold “inhibiting buffer” (50 mM KH2PO4, 70 mM sodium fluoride, and 5 mM EDTA), as described by Holroyde et al.\textsuperscript{14} Myofibrils were isolated on ice for 1 h by adding 1% Triton X-100 plus the protease and phosphatase inhibitors listed above to the inhibiting buffer. Detergent-extracted myofibrils were centrifuged at 5,000g (5 min) using a microcentrifuge. The supernatant was discarded. Examination of the pellet under the light microscope indicated that it was enriched in myofibrils.

**Sodium Dodecyl Sulfate-Polyacrylamide Gel Electrophoresis**

Polyacrylamide gel electrophoresis of 32P-labeled cardiac myofibrils was performed on 12% slab gels, as described by Laemmli.\textsuperscript{15} The myofibrillar pellet was solubilized and denatured in a sample preparation buffer containing 4% sodium dodecyl sulfate (SDS), 0.25 M 2-mercaptoethanol, and 0.2 M Tris(hydroxymethyl)aminomethane hydrochloric acid (pH 6.5) at 100°C for 5 min. To standardize loading of the gels, protein determinations of the myofibrillar extracts were performed on each of the samples prior to loading the gel. Seventy-five micrograms protein was applied to each lane, and polyacrylamide gel electrophoresis was performed in the presence of 0.1% SDS at constant current (10 mAmp) overnight (16 h). Gels were dried the following day and subjected to phosphor screen autoradiography for quantitation of labeled proteins. A PhosphorImager (Molecular Dynamics, Piscataway, NJ) was used to quantify the amount of radioactivity in each band. The extent of 32P incorporation into protein bands was quantified using a commercial software package (Molecular Dynamics).

**Experimental Controls and Data Analysis**

Untreated controls were normalized to 100%. Increases in the phosphorylation of TnI and MLC2 in response to propofol, phorbol myristate acetate (PMA), or isoproterenol were calculated as percent increases in the phosphorylation of TnI and MLC2 in response to propofol, phorbol myristic acetate (PMA), or isoproterenol. Experimental treatments were adjusted to a protein concentration of 1–2 mg/ml in sample buffer, boiled for 5 min, and then kept at −20°C until use. Equal amounts of protein (50 μg) from each fraction were electrophoresed on 12% SDS-polyacrylamide gels and transferred to nitrocellulose membranes, as previously described by our laboratory.\textsuperscript{16} Blots were stained with 1% Ponceau S to visualize protein bands and confirm complete transfer of proteins to gels. Nonspecific binding was blocked with Tris buffered saline with Tween 20 (TBS-T) (0.1%, v/v) in 20 mM Tris(hydroxymethyl)aminomethane base, 137 mM sodium chloride adjusted to pH 7.6 with hydrochloric acid, containing 3% (w/v) bovine serum albumin for 1 h at room temperature. A monoclonal antibody against PKC-α was diluted 1:1,000 in TBS-T containing 1% bovine serum albumin for immunoblotting (2 h). After washing in TBS-T solution 3 times (10 min each), filters were incubated for 1 h at room temperature with horseradish-peroxidase–linked secondary antibody (ovine antimus; 1:5,000 dilution in TBS-T containing 1% bovine serum albumin). Filters were again washed and bound antibody detected by the enhanced chemiluminescence method.

**Measurement of [Ca2+]i and Shortening**

Simultaneous measurement of intracellular Ca2+ concentration ([Ca2+]i) and cell shortening was performed as previously described.\textsuperscript{18} Ventricular myocytes (0.5 × 106 cells/ml) were incubated in HBS containing 2 μM fura-2-acetoxy methylester at room temperature for 15 min. Fura-2-loaded ventricular myocytes were placed in a temperature-regulated (30°C) chamber (Biopotech,
In myofibrillar Actomyosin ATPase Activity. To determine whether propofol alters myofilament Ca\(^{2+}\) sensitivity, changes in actomyosin ATPase activity were measured in myofibrils isolated from control and propofol-treated (10 min) cardiomyocytes. The myocyte suspension was divided into separate aliquots, and each aliquot was treated with Bis (1 \(\mu\)M) alone, propofol (30 \(\mu\)M) alone, or pretreatment with Bis for 10 min before addition of propofol at 37\(^\circ\)C with gentle agitation. Neither propofol nor Bis had any effect on extracellular pH at the concentrations used in this study and did not appear to alter the assay conditions. Activity is expressed as a percentage of the maximum rate per milligram of protein.

**Protocol 2: Effects of Propofol on \(^{32}\)P, Incorporation into Cardiomyocyte Contractile Proteins.** To determine whether propofol alters myofibrillar protein phosphorylation, we examined the extent to which \(^{32}\)P, orthophosphate was incorporated into myofibrillar proteins isolated from control and propofol-treated cardiomyocytes. The \(^{32}\)P-labeled myocyte suspension was divided into separate aliquots, and each aliquot was pretreated with one concentration of propofol (1, 3, 10, 30, 60, and 100 \(\mu\)M) for 10 min with gentle agitation. Myofibrillar proteins were isolated, subjected to polyacrylamide gel electrophoresis and phosphor screen autoradiography for quantitation of the incorporated \(^{32}\)P, into contractile proteins. Data are expressed as percent increase in \(^{32}\)P, incorporation compared with control.

**Protocol 3: Effects of Bis on Propofol-, PMA-, and Isoproterenol-simulated Incorporation of \(^{32}\)P, Incorporation into Cardiomyocyte Contractile Proteins.** To determine whether the propofol-, PMA-, and isoproterenol-induced phosphorylation of contractile proteins in cardiomyocytes was mediated \(\textit{via}\) PKC activation, we examined the extent to which PKC inhibition with Bis altered phosphorylation of TnI and MLC2. Cardiomyocytes were pretreated with Bis (1 \(\mu\)M; 10 min) prior to a 10 min exposure to propofol (30 \(\mu\)M), PMA (1 \(\mu\)M), or isoproterenol (1 \(\mu\)M). Myofibrillar proteins were isolated and processed as described in protocol 2.

**Protocol 4: Effects of Propofol and Bis on PKC-\(\alpha\) Translocation.** To determine whether propofol causes translocation of PKC isoforms, we performed Western blot analysis on subcellular fractions of cardiomyocytes treated with PMA (1 \(\mu\)M), propofol alone (30 \(\mu\)M), or Bis (1 \(\mu\)M; 10 min pretreatment) plus propofol. Cytosolic and membrane fractions were prepared; proteins were separated and transferred to nitrocellulose for antibody labeling. Because our previous findings suggest a role for PKC-\(\alpha\) in the propofol-induced changes in \(\beta\)-adrenoreceptor signaling in cardiomyocytes,\(^7\) translocation of PKC-\(\alpha\) was examined in this study. Rat brain lysate was used as a positive control for PKC-\(\alpha\).

**Protocol 5: Effects of Propofol and Bis on the Extracellular Ca\(^{2+}\)–Shortening Relationship.** To determine whether propofol alters myofilament Ca\(^{2+}\) sensitivity at the functional level (myocyte contractility) \(\textit{via}\) a PKC-dependent pathway, we examined the dose-response curve to extracellular Ca\(^{2+}\) ([Ca\(^{2+}\)]\(_i\)) in the presence or absence of propofol and Bis. Baseline parameters were collected from individual myocytes for

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1.5 min. Dose-response curves to \([\text{Ca}^{2+}]_o\) were performed by exchanging the buffer in the dish with a new buffer containing the desired \([\text{Ca}^{2+}]_o\). Data were acquired for 1.5 min following establishment of a new steady state. Dose-response curves to \([\text{Ca}^{2+}]_o\) were then performed in the presence of propofol (30 \(\mu M\)). Cells were allowed to stabilize for 5 min following each intervention. The relative contribution of PKC in mediating changes in the \([\text{Ca}^{2+}]_o\)-shortening relationship was assessed by pretreating the cells (10 min) with Bis (1 \(\mu M\)).

**Materials**

Collagenase type II was obtained from Worthington Biochemicals (Freehold, NJ). Propofol was acquired from Research Biochemicals International (Natick, MA) and solubilized in dimethylsulfoxide to appropriate stock concentrations. PMA, Bis, and isoproterenol were purchased from Sigma Chemical Co. (St. Louis, MO). Triton X-100, proteogel (30%, w/v) acrylamide, 0.8% (w/v) bisacrylamide stock solution, and 10X electrophoresis tank buffer (0.25 M Tris(hydroxymethyl) -aminomethane-1.92 M glycine–1% SDS) were purchased from National Diagnostics (Atlanta, GA). TEMED (N,N,N,N-tetramethyl-ethylenediamine), protein G, 2-mercaptoethanol, ammonium persulfate, and prestained high- and low-molecular-weight markers were obtained from Biorad Laboratories, Inc. (Melville, NY). A monoclonal antibody against PKC-\(\alpha\) was obtained from Upstate Biotechnology (Lake Placid, NY). Fura-2/AM was obtained from Texas Fluorescence Labs (Austin, TX).

**Statistical Analysis**

Each experimental protocol was performed on multiple myocytes from the same heart and repeated in at least four hearts. Results obtained from myocytes in each heart were averaged so that all hearts were weighted equally. Results of all trials for each experimental condition were averaged, and comparisons between groups were made by two-way analysis of variance and Bonferroni–Dunn post hoc test. Differences were considered statistically significant at \(P < 0.05\). Results from each experimental condition were normalized to unstimulated controls, which were taken as 100%. Results are expressed as mean ± SEM.

**Results**

**Effects of Propofol and Bis on Actomyosin ATPase Activity**

To directly test the hypothesis that propofol increases myofilament \(\text{Ca}^{2+}\) sensitivity via a PKC-dependent pathway, we assessed the effects of propofol (30 \(\mu M\)) alone and following pretreatment with Bis (1 \(\mu M\)), on myofilibrillar actomyosin ATPase activity. As previously demonstrated,\(^7\) propofol alone caused a leftward shift in the actomyosin ATPase activation curve (fig. 1). Propofol increased the \(EC_{50}\) (pCa) value (i.e., decreased the \(\text{Ca}^{2+}\) requirement) from 5.7 ± 0.1 to 6.3 ± 0.2 (\(P < 0.05\)). Propofol (30 \(\mu M\)) reduced (\(P < 0.05\)) the maximal activation of actomyosin ATPase \((V_{\text{max}})\) by 15 ± 7%, from a control value of 186 ± 11 nmol · min\(^{-1}\) · mg\(^{-1}\). Pretreatment with Bis (1 \(\mu M\)) attenuated the propofol-induced leftward shift (\(EC_{50}\) value = 5.8 ± 0.1) and reduction in \(V_{\text{max}}\) (181 ± 16 nmol · min\(^{-1}\) · mg\(^{-1}\)). Bis alone had no effect on actomyosin ATPase activity.

**Effect of Propofol on \(^{32}\text{P}\) Incorporation into Cardiomyocyte Contractile Proteins**

Following a 2h prelabeling period of endogenous pools of ATP with \(^{32}\text{P}\), myocytes were washed and subsequently incubated with propofol for 10 min at 37°C. Autoradiography of SDS gels of myofibrils from untreated (CON) myocytes demonstrated the presence of \(^{32}\text{P}\) incorporation in several myofibrillar proteins, including troponin T (TnT), tropomyosin, Tnl, and MLC2 (fig. 2, lane I). Propofol caused a dose-dependent increase in the labeling of Tnl and MLC2, with peak phosphorylation levels occurring at about 60 \(\mu M\) for both myofibrillar proteins. Propofol (10 \(\mu M\)) caused a 74 ± 13% increase in the phosphorylation of Tnl above baseline, whereas MLC2 phosphorylation was increased by 167 ± 15%.

**Effect of PKC Inhibition on Propofol-, PMA-, and Isoproterenol-induced Incorporation of \(^{32}\text{P}\) into Cardiomyocyte Contractile Proteins**

To test the hypothesis that PKC was responsible for the propofol-induced phosphorylation of Tnl and MLC2,
we pretreated the myocytes with Bis (1 µM) prior to stimulation with propofol. Pretreatment with Bis completely abolished the propofol-induced phosphorylation of TnI and MLC2 (fig. 3, lane 3). Similar to propofol (fig. 3, lane 2), PKC activation with PMA (1 µM) stimulated increases in the phosphorylation of TnI and MLC2 (fig. 3, lane 4), which were abolished by pretreatment with Bis (fig. 3, lane 5). Small, insignificant increases in phosphorylation of TnT and tropomyosin were occasionally observed in response to PMA and propofol. Addition of PMA and propofol together increased phosphorylation of TnI and MLC2 to the same extent as that observed with either PMA or propofol alone, (fig. 3, lane 6). Activation of the β-adrenergic signaling pathway with isoproterenol (1 µM) also stimulated an increase in phosphorylation of TnI slightly greater than that observed with propofol or PMA, whereas MLC2 phosphorylation was only 50% of that observed with PMA or propofol (fig. 3, lane 7). In contrast to propofol and PMA, pretreatment with Bis had no significant effect on isoproterenol-stimulated phosphorylation of TnI or MLC2 (fig. 3, lane 8).

Effects of Propofol and Bis on PKC-α Translocation

Western blot analysis of cardiomyocyte cytosolic and membrane fractions revealed that approximately 80% of the immuno-labeled PKC-α resides in the cytosolic compartment, whereas approximately 20% is associated with the membrane fraction (fig. 4, lane 3 and 4). Pretreatment with propofol (30 µM) caused a dramatic translocation of PKC-α from cytosolic to membrane fraction (fig. 4, lanes 3 and 4). Pretreatment with Bis (1 µM) prevented the propofol-induced translocation from cytosolic to membrane fraction (fig. 4, lanes 5 and 6). PMA (1 µM) also stimulated translocation of PKC-α from the cytosolic to membrane fraction (fig. 4, lanes 7 and 8). Rat brain lysate (B) was used as a positive control for antibody binding and molecular weight determination (fig. 4, lane 9).
Effect of Bis on the Propofol-induced Shift in the Dose–Response Curve to [Ca\(^{2+}\)]\(_r\)

Confirming our previous results, the propofol-induced increase in myofilament Ca\(^{2+}\) sensitivity is manifested as an upward shift in the [Ca\(^{2+}\)]\(_r\)-shortening relationship (fig. 5). To test the hypothesis that this effect is due to PKC activation, we assessed the effect of Bis (1 μM) on the propofol-induced change in the [Ca\(^{2+}\)]\(_r\)-shortening relationship. Bis abolished the propofol-induced shift in the [Ca\(^{2+}\)]\(_r\)-shortening relationship (fig. 5).

Discussion

This is the first study to both directly assess the role of PKC in mediating propofol-induced alterations in myofilament Ca\(^{2+}\) sensitivity and identify the extent to which propofol alters the phosphorylation state of the myofibrillar contractile proteins, TnI and MLC2. We previously demonstrated that propofol increases myofilament Ca\(^{2+}\) sensitivity and intracellular pH (pHi) via activation of Na\(^+\)-H\(^+\) exchange in rat ventricular myocytes. The increase in pHi was attributed to a propofol-induced activation of PKC. We also demonstrated that propofol alters the phosphorylation state of the contractile proteins, TnI and MLC2, via a PKC-dependent pathway. Propofol also stimulates translocation of PKC-α from the cytosolic to membrane fraction. The phosphorylation of MLC2 by the PKC signaling pathway, in addition to a previously observed PKC-dependent increase in pHi, likely explains the propofol-induced increase in myofilament Ca\(^{2+}\) sensitivity in rat ventricular myocytes.

Effects of Propofol and PKC Inhibition on Actomyosin ATPase Activity

The molecular basis for myocardial contractility involves an increase in [Ca\(^{2+}\)]\(_c\), which in turn triggers activation of the intrinsic actomyosin ATPase associated with the cardiac myofibrils. The sensitivity of the contractile machinery to Ca\(^{2+}\) is regulated primarily by the troponin complex associated with the thin filament. It is well established that alterations in pHc can modulate myofilament Ca\(^{2+}\) sensitivity. In addition, phosphorylation of the contractile proteins TnI, TnT, and MLC2 play a role in modulating myofilament Ca\(^{2+}\) sensitivity. We also observed that propofol did not directly alter actomyosin ATPase activity in isolated myofibrils, indicating a requirement for a cytosolic mediator for the actions of propofol on actomyosin ATPase activity. In the current study, we observed that pretreatment of the cardiomyocytes with the PKC inhibitor, Bis, abolished the propofol-induced leftward shift in the actomyosin ATPase activity curve. These data suggest that a PKC isof orm(s) likely represents the cytosolic mediator involved in the propofol-induced increase in myofilament Ca\(^{2+}\) sensitivity. These current data are consistent with other studies demonstrating that propofol and halothane stimulate purified brain PKC activity and that PKC activation increases myofilament Ca\(^{2+}\) sensitivity in cardiac myocytes.

Effect of Propofol on Phosphorylation of Contractile Proteins

Phosphorylation of contractile proteins in response to myocardial receptor activation is known to result in changes in cardiac inotropy and lusitropy mediated by alterations in myofilament responsiveness to Ca\(^{2+}\). This is the first study to demonstrate a propofol-induced phosphorylation of TnI and MLC2 at clinically relevant concentrations. Although no stoichiometry was performed, propofol stimulated a much greater increase in MLC2 phosphorylation than that observed for TnI phosphorylation. Phosphorylation of TnI can occur via activation of the PKA and/or PKC signaling pathways. In contrast, phosphorylation of MLC2 can occur via activation of myosin light chain kinase, PKC, as well as activation of PKA. Phosphorylation of TnI is associated with a decrease in myofilament Ca\(^{2+}\) sensitivity manifested as a rightward shift in the actomyosin ATPase activity curve. The overall net effect of TnI and MLC2 phosphorylation on actomyosin ATPase activity, and hence myocardial performance, will be the sum.
of the individual components. Because the propofol-induced phosphorylation of MLC2 was much greater than that observed for TnI, we propose that phosphorylation of MLC2, together with the increase in pH, observed in our earlier study,7 plays a primary role in contributing to the propofol-induced increase in myofilament Ca2+ sensitivity. Our next goal was to determine whether propofol-induced activation of PKC mediates the phosphorylation of contractile proteins in cardiomyocytes.

Effect of PKC Inhibition with Bis on Propofol-Induced Phosphorylation of Contractile Proteins

Previous studies have demonstrated that TnI and MLC2 are substrates for PKCα, PKA, and MLCK-dependent phosphorylation in myocardial cells.2,4,5 We hypothesized that PKC activation by propofol would result in the phosphorylation of myofilibrillar contractile proteins. PKC activation with PMA stimulates the phosphorylation of TnI and MLC2, as previously demonstrated by our laboratory and others.2,4,13 In addition, PKC inhibition with Bis attenuates both the propofol-induced and PMA-induced phosphorylation of TnI and MLC2, providing further support for a propofol-induced activation of PKC as the mediator of the phosphorylation of TnI and MLC2. Finally, addition of propofol and PMA together did not result in an additive effect on the phosphorylation of TnI or MLC2, indicating that both compounds are working through a common pathway involving activation of PKC. The current study also provides data demonstrating the quantitative differences in PKA-dependent phosphorylation of TnI and MLC2 compared with PKC-dependent phosphorylation. Compared with PMA- and propofol-stimulated phosphorylation of TnI and MLC2, β-adreno-receptor activation with isoproterenol stimulated increases in TnI phosphorylation that were greater than those observed with propofol or PMA alone. In contrast to PMA and propofol, isoproterenol stimulated little increase in MLC2 phosphorylation. It should be noted that phosphorylation of TnI by PKC or PKA occurs at different sites on TnI, which may serve to fine-tune effects on actomyosin ATPase activity.5 Specifically, PKA-mediated phosphorylation of TnI occurs on serine 23/24, leading to desensitization of the myofilbrils to Ca2+, whereas PKC-dependent phosphorylation of TnI occurs on serine 43/45 and/or threonine 144, resulting in an increase in the sensitivity of the myofilbrils to Ca2+. Therefore, PKA and PKC-dependent phosphorylation of TnI can result in opposing effects on myofilament Ca2+ sensitization. Because pretreatment with Bis had no effect on β-adreno-receptor-dependent phosphorylation but inhibited propofol- and PMA-induced phosphorylation, our results suggest that Bis is a specific inhibitor of PKC-dependent phosphorylation events in cardiac myocytes. Therefore, we suspect that propofol- and PMA-induced phosphorylation of MLC2 plays a more important role than TnI phosphorylation in determining the overall net effect of PKC activation on actomyosin ATPase activity and myocyte contractile function.

Effects of Propofol and Bis on PKC-α Translocation

Based on recent findings from our laboratory,9 we used a monoclonal antibody to PKC-α and probed subcellular fractions (cytosolic and membrane) of propofol- and PMA-treated cardiomyocytes. Translocation of PKC-α from the cytosol to membrane fraction in response to propofol was observed, and PKC inhibition with Bis prevented the translocation. These data are consistent with a propofol-induced activation of PKC-α in rat cardiomyocytes. However, to establish a linkage between PKC-α translocation and phosphorylation of contractile proteins, it will be necessary to identify translocation of the PKC isoform to a distinct intracellular site. Propofol may activate additional PKC isoforms in parallel with PKC-α, which could have specific and selective roles in mediating the functional effects of propofol on cardiomyocyte contractility. These effects could include activation of Na+/H+ exchange, phosphorylation of contractile proteins, and inhibition of L-type Ca2+ channel activity. Further studies are required to fully elucidate these possibilities.

Effect of Bis on the Propofol-induced Shift in the [Ca2+]o-Shortening Relationship

If PKC activation mediates the propofol-induced shift in the [Ca2+]o- shortening relationship, then this effect should be blocked by inhibiting PKC with Bis. Our results indicate that inhibition of PKC with Bis attenuates the propofol-induced increase in myofilament Ca2+ sensitivity by more than 90%. We previously demonstrated that inhibition of Na+/H+ exchange with ethylisopropyl amiloride attenuated the shift in the [Ca2+]o- shortening relationship by approximately 50%.7 Our current data are consistent with the idea that PKC activation results in phosphorylation of MLC2 and plays a role in mediating the propofol-induced shift in the [Ca2+]o- shortening relationship.

Clinical Implications

As always, extrapolation of results obtained from in vitro studies at the cellular level to the clinical setting can be difficult. However, it is known that PKC activation is a key mediator of ischemic and anesthetic preconditioning and cardiac protection. In addition, increases in myofilament Ca2+ sensitivity can partially offset the negative inotropic effects of certain agents, including propofol. Therefore, propofol may be beneficial in patients exhibiting end-stage heart failure (or other cardiomyopathies) in which Ca2+ overload is observed. In this patient population, propofol may increase cardiac function without further altering Ca2+ homeostasis, which could be beneficial to the patient.
**Limitations**

It is well known that propofol partitions in vivo between serum proteins, lipid microsomes, and into tissue. Therefore, difficulty arises in determining the precise concentration of free and active propofol at the tissue level. In the current study, we used isolated cells rather than intact tissue. Therefore, the effects of propofol may be enhanced because of reduced solute diffusion distances between the cytosol and extracellular medium. Also, this in vitro study only deals with intrinsic myocardial function, whereas changes in cardiac contractility in vivo following propofol administration also depend on a variety of other factors including venous return, afterload, and neurohumoral compensatory mechanisms. Additionally, the experimental conditions (temperature, stimulation frequency, unloaded cells) used in this study do not parallel in vivo conditions. However, the strength of this model is that we can directly assess the effects of propofol on cellular mechanisms that regulate contractile function.

**Summary**

Our results provide the first direct evidence that propofol increases the sensitivity of myofibrillar actomyosin ATPase to Ca$^{2+}$ (i.e., increases myofilament Ca$^{2+}$ sensitivity) via a PKC-dependent pathway. In addition, our results demonstrate that propofol stimulates phosphorylation of TnI and MLC2 and results in translocation of PKC-α from the cytosolic to the membrane fraction. It is likely that PKC-dependent myofibrillar protein phosphorylation contributes to the propofol-induced increase in myofilament Ca$^{2+}$ sensitivity in rat ventricular myocytes.

**References**

1. Fabiato A, Fabiato F. Effects of pH on the myofilaments and the sarcoplasmic reticulum of skinned cells from cardiac and skeletal muscles. J Physiol (Lond) 1978; 276:253–55
5. Venema RC, Kuo JF. Protein kinase C-mediated phosphorylation of troponin I and C-protein in isolated myocardial cells is associated with inhibition of myofibrillar actomyosin MgATPase. Biochem J 1995; 286:2705–11
8. Kanaya N, Murray PA, Damron DS. Propofol and ketamine only inhibit intracellular Ca$^{2+}$ transients and contraction in rat ventricular myocytes at suprachloraline concentrations. Anesthesiology 1998; 88:781–91
18. Wender PA, Kochler KF, Sharkey NA, Dell’Aquila ML, Blumberg PM. Analysis of phosphoribular enteropharmacophore on protein kinase C as a guide to the rational design of new classes of analogs. Proc Natl Acad Sci 1986; 83:4214–8

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