Isoform-Specific Modulation of Voltage-Gated Na⁺ Channels by Calmodulin

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**Abstract**—Calmodulin (CaM) is a calcium-sensing protein that binds to Na⁺ channels, with unknown functional consequences. Wild-type CaM produced a hyperpolarizing shift in the steady-state availability of expressed skeletal muscle (μ1) but not cardiac (hH1) Na⁺ channels. Mutant CaM1234 did not alter the voltage dependence or the kinetics of gating of either μ1 or hH1. Mutation of the highly conserved IQ motif in the carboxyl terminus of both isoforms (IQ/AA) slowed the kinetics of current decay and abolished the effect of wild-type CaM of μ1, but did not alter hH1 currents. The IQ/AA mutation eliminated CaM binding to the carboxyl terminus of both μ1 and hH1 channels. Inhibition of Ca²⁺/CaM kinase (CaM-K) slowed the current decay, the rate of entry into inactivation, and shifted the voltage dependence of hH1 in the depolarizing direction independent of CaM overexpression with no effect on μ1 Na⁺ channels. CaM signaling modulates Na⁺ currents in an isoform-specific manner, via direct interaction with skeletal muscle Na⁺ channels and through CaM-K in the case of the cardiac isoform. The full text of this article is available at http://www.circresaha.org. (Circ Res. 2002;90:000–000.)

**Key Words:** sodium channels ■ calmodulin cardiac ■ skeletal muscle ■ Ca²⁺/calmodulin-dependent kinase

Voltage-gated Na⁺ channels are essential for the generation of action potentials and cell excitability.¹ Na⁺ channels are responsible for the upstroke of the action potential in excitable cells and are the target of local anesthetic drugs. Na⁺ channels are composed of a pore-forming α-subunit and smaller β-subunits that have been implicated in assembly, trafficking, and posttranslational modulation of the α-subunit.² A number of interacting signaling pathways modulate the Na⁺ channel. The function of neuronal and cardiac Na⁺ channels is altered by cAMP-dependent protein kinase (PKA) phosphorylation of residues in the linker between domains I and II. PKA-dependent phosphorylation of the neuronal channel reduces current density,³ ⁴ but directionally opposite effects are seen with cardiac Na⁺ channels.⁵ The α-subunit of the skeletal muscle channel is not affected by PKA despite the presence of consensus phosphorylation sites.⁶ ⁷ In contrast to PKA, protein kinase C (PKC) alters the function of all mammalian sodium channel isoforms.⁸ ⁹–¹³ PKC reduces channel conductance and alters gating in an isoform-specific manner; an effect largely attributed to phosphorylation of a highly conserved serine residue in the linker between domains III to IV of the channel. There is also evidence that neuronal sodium channel gating is modulated by a G-protein–coupled pathway acting through the carboxyl terminus.¹⁴

Calmodulin (CaM) is a ubiquitous, small (16.7 kDa) calcium-binding protein that acts as a Ca²⁺ sensor translating changes in cytoplasmic Ca²⁺ into cellular responses by interacting with a diverse group of signaling molecules.¹⁵ A group of kinases, Ca²⁺/CaM-dependent kinases (CaM-K) are activated by CaM and phosphorylate a number of functionally diverse effectors from ion channels and receptors to transcriptional activators. Ion channels are prominent targets of CaM; for example, CaM is bound to L-type voltage–dependent Ca²⁺ channels and mediates Ca²⁺–dependent inactivation.¹⁶ ¹⁹ The possibility that CaM modulates the Na⁺ current was suggested by yeast 2-hybrid experiments demonstrating the interaction of voltage-dependent sodium channels and CaM through an IQ-like motif in the carboxyl terminus of the α-subunit.²⁰

The functional consequences of CaM binding to Na⁺ channels are unknown. We demonstrate that coexpression of CaM with Na⁺ channels alters the function of the skeletal muscle (μ1) channels but not the cardiac (hH1) isoform. Further, mutation of the IQ motif in the carboxyl terminus of the μ1 skeletal muscle Na⁺ channel alters inactivation gating and eliminates the effect of CaM on the expressed current. Inhibition of CaM-K by KN-93, but not the CaM-KII–specific inhibitor autocamtide-2 peptide (AIP), slowed cardiac Na⁺ current decay, shifted the availability curve to more...
depolarized potentials, and slowed entry into inactivated states. Mutating the IQ motif eliminated CaM binding to carboxyl terminal peptides of both isoforms.

Materials and Methods

Transfections of HEK293 and C2C12 Cell Lines

Human embryonic kidney cells (HEK293) were used to express the cloned sodium channels µ1 and hH1 in presence of wild-type or mutant CaM1234.17 C2C12 cells are a subclone derived from a mouse myoblast cell line expressing characteristic muscle proteins.21 Cells were grown in DMEM high glucose supplemented with FBS 10%, 1-glutamine (2 mM/L), penicillin (100 U/mL), and streptomycin (10 mg/mL) in a humidified 5% CO2 atmosphere. Transfections of the cells were performed using lipofectamine according to the manufacturer’s instructions. Cells were patch-clamped or stained 1 to 2 days after transfection.

Patch-Clamp Methods

Macroscopic Na+ currents from transfected cells were recorded using the whole-cell configuration of patch-clamp technique.22 Cells with currents no larger than 6 nA were clamped with Axopatch 200 patch-clamp amplifier using low-resistance electrodes and typical series resistance compensation of patch-clamp amplifier using low-resistance electrodes and typical series resistance compensation of >80% that minimized voltage-clamp errors. Membrane currents were filtered at 5 kHz and digitized with 12-bit resolution. In all experiments, recording was begun 10 minutes after whole-cell access was attained with the exception of the CaM-K inhibitor experiments where recording was begun 15 minutes after patch rupture to ensure stabilization of the time-dependent shift in gating.

Solutions and Reagents

The patch pipette (in mM/L) 35 NaCl, 105 CsCl, and 10 Cs-HEPES (pH 7.3) with no Ca2+ buffering. All of the experiments were initially performed using 105 mM/L CsF in the pipette; however, due to possible confounding effects on phosphorylation reactions and Ca2+ buffering, the experiments were repeated with the CsCl-containing intracellular solution. No differences in the response to CaM overexpression were observed with the different pipette solutions. All of the data reported in the text and in the tables were obtained using CsCl with the exception of experiments in C2C12 cells, where CsF data are reported.

For the experiments with 504 nmol/L free Ca2+, 5 mM/L BAPTA and 3.7 mM/L CaCl2 were added to the patch pipette. For the experiments with no free Ca2+, 10 mM/L BAPTA was added to the pipette solution and 0.1 mM/L EGTA was added to the bath solution. The bath solution contained (in mM/L) 150 NaCl, 2 KCl, 2 MgCl2, 10 glucose, and 10 Na-HEPES (pH 7.4). For the experiments with Ba2+, 1 mM/L BaCl2 was used in place of CaCl2. The CaM-K inhibitor KN-93 (Calbiochem) and the inactive analog, KN-92, were added to the patch pipette at concentrations of 10 µmol/L. KN-92 and KN-93 were dissolved in DMSO (10 mM/L stock solution); the final concentration of DMSO was 0.1%, which had no significant effect on the currents (data not shown). The CaM-KII-specific inhibitor, AIP (Calbiochem) was added to the pipette solution at 100 mM/L. Experiments were performed at room temperature, 22°C to 23°C.

Pull-Down Assays

Fusion proteins of the µ1 and hH1 carboxyl termini containing the IQ motif and the mutated motif IQ/AA were constructed in pGEX using the glutathione S-transferase (GST) Gene Fusion System (Pharmacia). The Na+ channel-specific sequences of the fusion peptides were µ1 (residues 1689 to 1742): ALKQTMEEKF-MAANPSKVS YEPITTLKLQKVEQFAC1KIQRAYRRHLLRQS-VKQ and hH1 (residues 1870 to 1923): ALKIQMEEKFMAANPSKI- SYEPITTLRKKHEEVSMVQGRAFRHLRQLSKLH, where the underlined amino acids were changed to alanines in the IQ/AA mutants. Proteins were produced and purified according to the manufacturer’s instructions. Pull-down assays were performed by mixing 10 µg (1:1 molar ratio of NaQ:CaM) or 30 µg (3:1 molar ratio of NaQ:CaM) of each fusion protein with glutathione beads (70 µL). Binding of the beads to the GST-tagged fusion proteins was performed by incubating for 30 minutes at 4°C in solution A:25 mM/L Tris, pH 7.6, and 1 mM/L CaCl2. After a brief centrifugation, the supernatants were removed and the beads were mixed and incubated with solution A in the absence and presence of CaM for 2 hours at 4°C. The mixtures were washed and spun briefly. Then the proteins bound to the beads were eluted with SDS-PAGE 2X sample buffer (70 µL) and 30 µL of each sample was run on a 12.5% gel SDS-PAGE gel. After transfer to PVDF membranes CaM was detected by an anti-CaM monoclonal antibody (Upstate Biotechnology) and a horse radish peroxidase-linked secondary antibody.

Statistical Analysis

Data are expressed as mean±SEM. A 2-tailed Student’s t test was used to assess statistical significance when appropriate. Differences were considered to be significant at a value of P<0.05.

Results

Effects of CaM Coexpression With µ1 Skeletal Muscle Na+ Channels

To assess the effect of CaM binding on skeletal muscle sodium channels, we cotransfected HEK293 cells with µ1 and wild-type CaM or a mutant form of CaM with strongly impaired Ca2+ binding (CaM1234).17 In the absence of intracellular Ca2+ buffering, CaM overexpression did not significantly affect the whole-cell current (Figure 1A), current-voltage relationship (Figure 1B), voltage dependence of activation, time constants of inactivation (τi), recovery from inactivation, or the rate of entry into inactivation (Table 1). However, the steady-state availability relation was significantly shifted in the hyperpolarizing direction (Figure 1C). In contrast to wild-type CaM, coexpression of mutant CaM1234 with the µ1 Na+ channel produced no significant change in steady-state availability compared with the µ1 α-subunit expressed alone. The presence of the β3-subunit did not significantly alter the steady-state availability curve of the µ1 channel compared with the α-subunit alone, nor did it alter the hyperpolarizing shift produced by CaM. Table 1 summarizes the effects of wild-type and mutant CaM on the functional properties of the µ1 skeletal muscle Na+ channel expressed in the presence and absence of the β-subunit with CaM.

The action of CaM on effector molecules often requires Ca2+; therefore, we studied the effect of different free intracellular Ca2+ concentrations on the CaM modulation of µ1 sodium channels. Our standard recording conditions included no intracellular Ca2+ buffering and 2 mM/L external Ca2+. There was no significant difference in the effect of CaM on µ1 Na+ current when [Ca2+] was buffered to 504 mM/L compared with control recording conditions (data not shown). However, when extracellular Ca2+ was buffered with 0.1 mM/L EGTA and 10 mM/L BAPTA was added to the intracellular solution to ensure the removal of free Ca2+, the CaM-induced shift of the steady-state inactivation curve was no longer present (Figure 1D). Thus, the effect of CaM on gating of the skeletal muscle Na+ current is Ca2+-dependent (Table 1).

Effects of CaM Coexpression on the hH1 Cardiac Na+ Current

The carboxyl terminal IQ-like binding motif is conserved across all isoforms of the mammalian Na+ channel. There-
Therefore, we examined the effect of CaM on the function of the human heart sodium channel, hH1. When coexpressed with hH1, neither wild-type CaM nor mutant CaM\textsubscript{1234} significantly altered any whole-cell property of the current (Table 2). Expression of wild-type CaM and mutant CaM\textsubscript{1234} proteins was confirmed by immunofluorescence staining (see below). CaM coexpression had no effect on the hH1 Na\textsuperscript{+} current either in the absence or presence of the \(\beta\textsubscript{1}\)-subunit at any intracellular Ca\textsuperscript{2+} concentration. A cell line stably expressing hH1 was used for the \(\beta\textsubscript{1}\)-subunit coexpression experiments. An \(-10\) mV shift in the steady-state inactivation curve is observed in these cells compared with cells transiently transfected with hH1; however, CaM overexpression had no effect on the voltage dependence of inactivation. The rates of entry into and recovery from inactivation of the stably expressed channels was slower than transiently transfected hH1, but CaM overexpression had no significant effect on the kinetics of inactivation (Table 2).

Effects of CaM Binding on Skeletal Muscle Na\textsuperscript{+} Currents Recorded From C2C12 Cells

In order to study the effect of CaM on native skeletal muscle Na\textsuperscript{+} channels, we transfected wild-type CaM and mutant CaM\textsubscript{1234} into C2C12 cells, a mouse myoblast cell line. C2C12 cells showed typical skeletal muscle sodium currents (Figure 2 and Table 1), as previously reported.\textsuperscript{21} The time constants of decay (\(\tau\textsubscript{c}\)) and recovery from inactivation are modestly but significantly slower in C2C12 cells compared with expressed \(\mu\textsubscript{1}\) currents recorded under identical conditions (Table 1). In the absence of exogenous CaM, the steady-state availability of C2C12 Na\textsuperscript{+} currents is shifted \(-20\) mV compared with expressed \(\mu\textsubscript{1}\) currents. Expression of wild-type CaM in C2C12 cells significantly shifts the steady-state availability of the Na\textsuperscript{+} currents in the hyperpolarizing direction (Figure 2C). However, coexpression of mutant CaM\textsubscript{1234} did not shift the voltage dependence of the steady-state availability relationship (Figure 2C). Neither wild-type nor mutant CaM\textsubscript{1234}
we abolished the CaM-induced shift of the steady-state (Figure 3C, Table 1). Interestingly, by mutating the IQ motif, L-type Ca\textsuperscript{2+} terminal region of Na\textsuperscript{+} channel IQ motif in CaM-induced shifts in availability relationship seen with coexpression of wild-type CaM and wild-type \(\mu_1\) (Figure 3C, Table 1).

### Mutation of CaM Binding Site

The isoleucine-glutamine (IQ) CaM binding domain is essential for CaM-mediated Ca\textsuperscript{2+}-dependent inactivation of the L-type Ca\textsuperscript{2+} current.\textsuperscript{17,18} Yeast 2-hybrid assays have established CaM binding to an IQ-like motif on the carboxyl terminal region of Na\textsuperscript{+} channels.\textsuperscript{20} In order to determine the role of the Na\textsuperscript{+} channel IQ motif in CaM-induced shifts in availability, we mutated IQ to alanines in both \(\mu_1\) (I1727A-Q1728A, \(\mu_1\)-IQ/AA) and hH1 (I1908A-Q1909A, hH1-IQ/AA) Na\textsuperscript{+} channels and then coexpressed these mutated channels with wild-type CaM and mutant CaM1234. The IQ/AA mutations in the \(\mu_1\) background significantly altered the whole-cell current compared with the wild-type current. The current decay became more obviously biexponential with the addition of a slow component of decay that resulted in a pedestal of current of \(\sim\)5% of the peak at 25 ms after the voltage step (Figure 3A). The peak IV relationship (Figure 3B) was not altered but the steady-state availability curve of \(\mu_1\)-IQ/AA was shifted \(\sim\)10 mV compared with \(\mu_1\)-WT (Figure 3C, Table 1). Interestingly, by mutating the IQ motif, we abolished the CaM-induced shift of the steady-state availability relationship seen with coexpression of wild-type CaM and wild-type \(\mu_1\) (Figure 3C, Table 1).

In contrast to \(\mu_1\)-IQ/AA, hH1-IQ/AA did not exhibit changes in whole-cell current decay compared with wild-type hH1. The wild-type hH1 current decay was best fitted with a biexponential function, and neither the time constants nor amplitudes of the components were altered by the IQ/AA mutations. Not surprisingly, coexpression of wild-type CaM with hH1-IQ/AA had no effect on any of the whole-cell properties of the current (Table 2).

### CaM Binding to the IQ Motif

The colocalization of CaM and the Na\textsuperscript{+} channel is further supported by protein binding experiments. GST-fusion proteins of carboxyl-terminal regions containing the wild-type IQ motifs and the IQ/AA mutants of the hH1 and \(\mu_1\)-Na\textsuperscript{+} channels were made. The carboxyl terminal \(\mu_1\) and hH1 fusion proteins with an intact IQ binding motif interact with CaM. In contrast, neither of the IQ/AA mutant proteins are able to pull-down CaM (Figure 4). Therefore, binding of CaM to the IQ motif appears to be necessary for the modulation of \(\mu_1\) channel gating but is not sufficient in that binding to the hH1 carboxyl terminus does not alter gating of the cardiac isoform.
TABLE 2. Functional Effects of CaM and Mutant CaM<sub>1234</sub> on hH1 Expressed in HEK293

<table>
<thead>
<tr>
<th>Biophysical Parameters</th>
<th>Steady-State Inactivation (V&lt;sub&gt;1/2&lt;/sub&gt; in mV)</th>
<th>Decay Time Constant (τ&lt;sub&gt;in&lt;/sub&gt; in ms at –30 mV)</th>
<th>Recovery From Inactivation (τ&lt;sub&gt;rec&lt;/sub&gt; in ms)</th>
<th>Entry Into Inactivation (Time Constant in ms)</th>
<th>Activation (V&lt;sub&gt;a&lt;/sub&gt; in mV)</th>
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n indicates number of cells.

*Significantly different from hH1+KN-92 (P<0.05); †significantly different from hH1+CaM+KN-92 (P<0.05).

Effect of CaM-K Inhibition on Na<sup>+</sup> Currents

The cellular effects of CaM often involve downstream signaling through CaM-K. The activity of Na<sup>+</sup> channels is known to be modulated through different phosphorylation pathways. Because CaM binds to an IQ-like motif located in the C-terminus of Na<sup>+</sup> channels, phosphorylation of the channel by CaM-K is possible. The isoform-specific differences in the response to CaM may result from differences in the 2 channels as substrates for phosphorylation by CaM-K. To assess this possibility, we used a nonselective CaM-K inhibitor, KN-93, and its inactive analog, KN-92. We applied KN-93 and KN-92 intracellularly at a concentration of 10 μmol/L to μl Na<sup>+</sup> channels expressed alone and in the presence of CaM.

KN-93 and the inactive analog KN-92 had no effect on the voltage dependence or kinetics of μl gating either in the presence or absence of CaM overexpression. Specifically, neither compound altered the rate of current decay (Figure 5B), rates of recovery from or entry into inactivated states (Table 1). Further, neither compound altered the CaM-induced hyperpolarizing shift of the steady-state availability relationship of μl Na<sup>+</sup> channels (Figure 5A) The CaM-KII–specific inhibitor AIP (100 nmol/L) was applied to expressed μl currents with results similar to the KN compounds. AIP did not alter the voltage dependence or kinetics of gating of μl channels and did not diminish the hyperpolarizing shift of the steady-state inactivation relationship induced by CaM overexpression (Table 1).

In contrast, KN-93 had robust effects on hH1 current, independent of CaM coexpression. KN-93 slowed the current decay with the most prominent effect on the fast time constant (Figure 6A, Table 2), shifted the steady-state inactivation relationship in depolarizing direction (Figure 6B), and slowed entry into inactivated states (Figure 6D, Table 2).

KN-92 also had effects on hH1, but not μl currents: it shifted the steady-state inactivation curve in the hyperpolarizing direction and produced an apparent slowing of recovery at −120 mV. However, the currents are not fully reprimed at this voltage in the presence of KN-92. KN-92, and to a lesser extent KN-93, retards recovery from inactivation compared with hH1 alone; therefore, KN-induced slowed recovery from inactivation cannot be considered a specific effect of CaM-K inhibition. The slowing of recovery by these compounds was not observed in expressed μl channels.
Figure 2. Biophysical properties of sodium currents recorded from C2C12 cells in presence of CaM or mutant CaM\(_{1234}\). A, Representative currents through C2C12 Na\(^+\) channels in the absence (solid line) or presence of overexpression of CaM (dashed line) or mutant CaM\(_{1234}\) (dotted line) were recorded as shown in Figure 1. B, Normalized IV relationships, similar to Figure 1B, show no change in C2C12 cells overexpressing CaM (circles) or mutant CaM\(_{1234}\) (triangles) compared with C2C12 Na\(^+\) currents alone (squares). C, Steady-state inactivation relationship is obtained as described in Figure 1 and exhibits a shift similar to that of expressed \(\mu\)1 currents in the presence of wild-type CaM.
In contrast, AIP, a selective CaM-KII inhibitor, had no effect on channel activity and did not block the depolarizing shift in the steady-state inactivation curve by the subsequent addition of KN-93 to the bath (data not shown). Thus, a CaM-K other than CaM-KII, possibly CaM-KIV, which is richly expressed in the heart, may modulate the shift in the voltage dependence of inactivation of cardiac Na\textsuperscript{+} channels.

**Discussion**

CaM is the most ubiquitous Ca\textsuperscript{2+}-sensing protein in mammalian cells. The Ca\textsuperscript{2+}/CaM complex directly modulates the function of a number of proteins including a family of serine/threonine kinases (CaM-K), ion channels, and receptors. CaM that is constitutively tethered to L-type Ca\textsuperscript{2+}...
channels mediates Ca\(^{2+}\)-dependent inactivation and facilitation of the current.\(^{16-18}\) On Ca\(^{2+}\) binding, CaM associates with a conserved IQ motif\(^{23}\) in the carboxyl terminus of the channel. The presence of a highly conserved IQ-like motif in the carboxyl terminus of the Na\(^{+}\) channel suggested the possibility of CaM-mediated modulation of Na\(^{+}\) currents. Supportive evidence for such a mechanism included the demonstration of Ca\(^{2+}\)-dependent and Ca\(^{2+}\)-independent binding of CaM to a carboxyl terminal fragment of the Na\(^{+}\) channel containing the IQ motif.\(^{20}\) The functional consequences, if any, of CaM binding to the Na\(^{+}\) channel were previously unknown.

We demonstrate that CaM does indeed modify the function of the \(\mu_1\) skeletal muscle isoform of the Na\(^{+}\) channel, shifting the steady-state inactivation curve in the hyperpolarizing direction (Figure 1, Table 1). The CaM effect on gating requires intact Ca\(^{2+}\) binding because a mutant, CaM\(_{1234}\), with impaired Ca\(^{2+}\) binding does not alter the gating of the \(\mu_1\) Na\(^{+}\) channel. In addition, buffering of Ca\(^{2+}\) eliminates the wild-type CaM-mediated shift in steady-state availability (Figure 1D, Table 1). As expected, buffering Ca\(^{2+}\) produced a hyperpolarizing shift in channel gating, and we cannot exclude the possibility that this shift masks the CaM effect. CaM modulation of the skeletal muscle Na\(^{+}\) channel does not require the presence of the \(\beta_1\)-subunit, nor does \(\beta_1\) alter the effect of CaM on the expressed current (Table 1). The modulation of the expressed \(\mu_1\) current was recapitulated in C2C12 cells, a bona fide skeletal muscle cell line. These data suggest that native skeletal muscle channels, regardless of subunit composition, are targets for CaM.

Analogous to the Ca\(^{2+}\) channel, an IQ-like motif is a crucial component of the functional effects of CaM on skeletal

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**Figure 4.** NalQ/CaM interaction assays. \(\mu_1\) and hH1 GST-fusion proteins of the C-terminal domain containing either the wild-type (IQ) or the mutated IQ motifs (IQ/AA) were incubated with glutathione-linked beads followed by incubation in the absence of CaM, or a 1:1 molar ratio of NalQ/CaM or 3:1 molar ratio of NalQ/CaM (3\(\times\)). CaM (120 ng) was run as a control. The lanes labeled GST had no fusion proteins in the mixture and served as a control. CaM was detected using an anti-CaM monoclonal antibody. Increasing the molar ratio of NalQ enhanced the CaM pull-down. Mutating the IQ-motif for both \(\mu_1\) and hH1 eliminated CaM binding as shown by the absence of CaM pull-down.

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**Figure 5.** Effect of CaM-K inhibition on \(\mu_1\). A, KN-93 (–CaM open squares, +CaM open circles) but not KN-92 (–CaM filled squares, +CaM filled circles) significantly shifts the steady-state inactivation curve of \(\mu_1\) Na\(^{+}\) currents in the depolarizing direction only in presence of CaM overexpression. B, Representative Na\(^{+}\) currents through \(\mu_1\) channels in the presence of the CaM-K inhibitor KN-93 (–CaM solid line, +CaM dashed line).
muscle Na\(^+\) channels. Mutation of the IQ motif eliminates CaM binding to (Figure 4) and modulation (Figure 3) of \(m_1\) skeletal muscle currents. Our data indicate that the IQ motif has important functional effects on skeletal muscle Na\(^+\) currents independent of CaM binding. Indeed, the \(m_1\)-IQ/AA mutation itself slows the decay of the whole-cell current and shifts the steady-state inactivation curve to hyperpolarized potentials relative to wild-type \(m_1\). In fact, the shift in the availability curve produced by mutating IQ to AA exceeds the shift produced by coexpression of CaM with wild-type \(m_1\). It is unlikely that the effect of the IQ to AA mutation is simply the result of a loss of CaM binding because the direction of the shift is opposite to what would be predicted by the elimination of CaM binding (Figure 3C). Instead, this suggests that the IQ region of the skeletal muscle Na\(^+\) channel is an important component of the channel’s inactivation machinery that is modulated by CaM-mediated signaling.

IQ-mediated binding of CaM to Na\(^+\) channels is a necessary but not sufficient condition for modulation of channel function. \(hH1\) and \(\mu_1\) Na\(^+\) channels have IQ motifs with similar CaM binding capacity (Figure 4), yet CaM coexpression does not alter the function of \(hH1\) channels. The difference in the functional effects of CaM on the Na\(^+\) channel isoforms may be the result of the conformation of CaM bound to the channel. It has been shown that CaM can bind to the IQ motif of the rat brain II Na\(^+\) channel in its Ca\(^{2+}\)-bound and Ca\(^{2+}\)-free (apo-CaM) states.\(^{20}\) Indeed, Ca\(^{2+}\) buffering eliminates CaM modulation of \(\mu_1\) channel gating (Figure 1D). However, the functional roles of the IQ motifs in skeletal muscle and cardiac Na\(^+\) channels appear to differ independent of CaM binding, as revealed by the IQ/AA mutant channels. Unlike the \(\mu_1\) mutant channel, \(hH1\)-IQ/AA does not alter gating (Tables 1 and 2).

Alternatively, binding of CaM to the Na\(^+\) channel may serve to facilitate phosphorylation of the channel complex by CaM-K. We do not have direct evidence for phosphorylation of either channel isoform; however, inhibition of CaM-K (possibly CaM-KIV) modifies cardiac Na\(^+\) channel inactivation, shifting the steady-state inactivation curve in the depolarizing direction, slowing entry into inactivated states, and
hastening recovery when compared with the inactive analog KN-92. KN-92 itself has effects on the cardiac Na\(^+\) channel (shifting the inactivation curve in the hyperpolarizing direction and slowing recovery) that cannot be ascribed to CaM-K inhibition. The differential effects of CaM-K inhibition on skeletal muscle and cardiac channels suggest the possibility of distinct functionally significant phosphorylation sites on each of the channel isoforms. However, the existence and precise identity of such sites remain to be demonstrated.

CaM signaling appears to fine-tune the function of voltage-dependent Na\(^+\) channels in isoform-specific ways. The physiologic significance of such modulation is uncertain, but recruitment of CaM signaling tends to stabilize inactivation of skeletal muscle and cardiac channels, albeit by distinct molecular mechanisms.

Interestingly, the C-terminal region of the cardiac Na\(^+\) channel is a hot spot for mutations that cause inherited cardiac arrhythmias, such as long-QT and Brugada syndromes. We have recently demonstrated that the C-terminus of the Na\(^+\) channel plays a role in fast inactivation. A common theme is that these disease-causing mutations alter gating and often disrupt inactivation of the Na\(^+\) channel. The mutations may directly alter Na\(^+\) channel function; however, it is possible that the effect of the mutation is through interruption of CaM/CaM-kinase signaling leading to destabilization of inactivation of the Na\(^+\) channel. In the heart under pathophysiological conditions associated with increased intracellular Ca\(^2+\), CaM-KII appears to enhance the arrhythmogenic transient inward current.

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References


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