The Role of the Putative Inactivation Lid in Sodium Channel Gating Current Immobilization

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Abstract We investigated the contribution of the putative inactivation lid in voltage-gated sodium channels to gating charge immobilization (i.e., the slow return of gating charge during repolarization) by studying a lid-modified mutant of the human heart sodium channel (hH1a) that had the phenylalanine at position 1485 in the isoleucine, phenylalanine, and methionine (IFM) region of the domain III–IV linker mutated to a cysteine (ICM-hH1a). Residual fast inactivation of I_Cm-hH1a in fused tsA201 cells was abolished by intracellular perfusion with 2.5 mM 2-(trimethylammonium)ethyl methanethiosulfonate (MTSET). The time constants of gating current relaxations in response to step depolarizations and gating charge–voltage relationships were not different between wild-type hH1a and ICM-hH1a. The time constant of the development of charge immobilization assayed at -180 mV after depolarization to 0 mV was similar to the time constant of inactivation of I_Na at 0 mV for hH1a. By 44 ms, 53% of the gating charge during repolarization returned slowly, i.e., became immobilized. In I_CM-hH1a, immobilization occurred with a similar time course, although only 31% of gating charge upon repolarization (OFF charge) immobilized. After modification of hH1a and ICM-hH1a with Anthopleurin-A toxin, a site-3 peptide toxin that inhibits movement of the domain IV-S4, charge immobilization did not occur for conditioning durations up to 44 ms. OFF charge for both hH1a and ICM-hH1a modified with Anthopleurin-A toxin were similar in time course and in magnitude to the fast component of OFF charge in ICM-hH1a in control. We conclude that movement of domain IV-S4 is the rate-limiting step during repolarization, and it contributes to charge immobilization regardless of whether the inactivation lid is bound. Taken together with previous reports, these data also suggest that S4 in domain III contributes to charge immobilization only after binding of the inactivation lid.

Key words: sodium channel • gating charge • inactivation • site-3 toxin • immobilization

Introduction The primary process by which voltage-gated sodium channels become nonconductive after opening in response to a strong step depolarization is called inactivation. Armstrong and Bezanilla (1977) were the first to demonstrate the relationship between fast inactivation of sodium ionic current (I Na) and measurements of sodium channel gating currents (I g) small asymmetrical currents that result from the movement of charged portions of the channel in response to changes in the electrical field. They showed that the time course of development of a slow component in I g recorded during repolarization at very negative potentials correlated with the time course of I Na inactivation. When the membrane potential was repolarized to less negative potentials, the slow component became too small and too slow to be accurately measured, and they described the gating charge as becoming “immobilized.” Nearly 60% of the total sodium channel gating charge could become immobilized in squid giant axon, and similar values have been reported in other preparations (Meves and Vogel, 1977; Nunner, 1980; Starkus et al., 1981; Greff et al., 1982).

Since the first cloning of a voltage-gated sodium channel by Noda et al. (1984), specific portions of the channel’s sequence have become associated with specialized channel functions. The voltage sensors have been shown to reside, in large part, in the fourth transmembrane spanning segment (S4) in each of four domains that form the α subunit. Part of the fast inactivation process was localized to the intracellular region formed by the linker between domains III and IV by Vassilev et al. (1988), who used antibodies directed to this region and by Stühmer et al. (1989), who noted a prolongation of I Na decay when the linker was cut and channels expressed in two pieces. This intracellular linker has been called the “inactivation lid” after mutation of the three adjacent amino acids, isoleucine, phenylalanine, and methionine (IFM),1 to QQQ

1Abbreviations used in this paper: Ap-A, Anthopleurin-A; hH1a, human heart sodium channel; ICM-hH1a, human heart sodium channel with F1485C mutation; IFM, isoleucine, phenylalanine, and methionine; MTSET, 2-(trimethylammonium)ethyl methanethiosulfonate; OFF charge, gating charge upon repolarization; ON charge, gating charge upon depolarization.
removed fast inactivation (see Fig. 1) in rat brain IIa (West et al., 1992) and in human heart (hH1a) (Hartmann et al., 1994). Additional studies have shown that the voltage sensor formed by domain IV–S4 has a unique role in channel inactivation (Chahine et al., 1994; Yang and Horn, 1995; Chen et al., 1996; Yang et al., 1996; Kontis et al., 1997; Kuhn and Greeff, 1999). In our previous studies, using a ste-3 peptide toxin that binds to the outside of sodium channels (Rogers et al., 1996; Benzinger et al., 1998), we identified a component of sodium channel Iq that is associated with inactivation from the open state (Hanck and Sheets, 1995; Sheets and Hanck, 1995), and we showed that the gating current component resulted from movement of the S4 in domain IV (Sheets et al., 1999). Recently, Cha et al. (1999), using site-directed fluorescent labeling of human skeletal muscle sodium channels, demonstrated that the S4 segments in domains III and IV, but not those in domains I and II, contributed to charge immobilization.

To investigate the role of the inactivation lid in charge immobilization, we studied the human cardiac sodium channel that had the phenylalanine at amino acid position 1485 in the IFM motif mutated to a cysteine (ICM-hH1a). The mutant sodium channel was transiently expressed in fused mammalian cells (Sheets et al., 1996), and the cysteine was modified by intracellular application of 2-(trimethylammonium)ethyl methanethiosulfonate (MTSET) to remove residual fast inactivation (ICM-hH1aMTSET) (Kellenberger et al., 1996; Chahine et al., 1997; Vedantham and Cannon, 1998). Our results showed that the gating charge–voltage (Q–V) relationship and the dominant time constants of Iq relaxations recorded during step depolarizations were unaltered regardless of whether the inactivation lid could bind to its receptor. In the absence of a functioning inactivation lid, charge immobilization still occurred in ICM-hH1aMTSET with a time course similar to that in wild-type hH1a, but only 31% of gating charge upon repolarization (OFF charge) became immobilized, compared with 53% in hH1a. Experiments with Anthopleurin-A (Ap-A) toxin, a ste-3 toxin that inhibits movement of the S4 in domain IV, abolished charge immobilization for both hH1a and ICM-hH1aMTSET. These data indicate that movement of the S4 in domain IV is the rate-limiting step in repolarization, and contributes to charge immobilization regardless of whether the inactivation lid is bound. Taken together with previous reports (Cha et al., 1999), these data also suggest that the S4 in domain III contributes to charge immobilization only after binding of the inactivation lid.

M E T H O D S

cDNA Clones

In hH1a (kindly provided by H. Hartmann and A. Brown (see Hartmann et al., 1994) the phenylalanine in the IFM motif at amino acid position 1485 (Fig. 1) was mutated to a cysteine by four-primer PCR (Higuchi et al., 1988; Ho et al., 1989). The insert containing the mutated site was confirmed by sequencing. Because anecdotal evidence suggested that cell survival of inactivation-impaired mutants could be increased by blocking sodium channels during culturing, we increased the sensitivity of the ICM-hH1a channel to block by tetrodotoxin by mutating the cysteine at position 373 to a tyrosine (C373Y) (Sabin et al., 1994; Chen et al., 1996). For expression of both hH1a and ICM-hH1a in mammalian cells, the cDNAs were subcloned directionally into the mammalian expression vector pRcCMV (Invitrogen Corp.).

Cell Preparation

Multiple tsA201 cells (SV40-transformed HEK293 cells) or multiple HEK293 cells were fused together using polyethylene glycol, as previously described (Sheets et al., 1996). After fusion, the cells were placed in cell culture for several days to allow for membrane remodeling, and then they were transiently transfected using a calcium phosphate precipitation method (GIBCO BRL). For some experiments with wild-type hH1a, HEK293 cells that stably expressed hH1a were fused before transient transfection with cdNA coding for hH1a. ICM-hH1a expression appeared to be increased by the addition of 300 nM tetrodotoxin to the culture media 1 d after transfection. 3–6 d after transfection, fused cells were detached from culture dishes with trypsin-EDTA solution (GIBCO BRL) and studied electrophysiologically.

Recording Technique, Solutions, and Experimental Protocols

Recordings were made using a large bore, double-barreled glass suction pipette for both voltage clamp and internal perfusion, as previously described (Hanck et al., 1990; Sheets et al., 1996). Iq was measured with a virtual ground amplifier (OPA-101; Burr-Brown) using a 2.5 Μ MΩ feedback resistor. Voltage protocols were imposed from a 16-bit DA converter (Masscomp 5450; Concurrent Computer) over a 30/1 voltage divider. Data were filtered by the inherent response of the voltage-clamp circuit (corner frequency near 125 kHz) and recorded with a 16-bit AD converter on a Masscomp 5450 at 200 kHz. A fraction of the current was fed back to compensate for series resistance. Temperature was controlled using a Sensortek thermoelectric stage (TS-4; Physiotemp Instruments, Inc.) mounted beneath the bath chambers and it typically varied —0.5°C during an experimental set. Cells were usually studied at 12–13°C.

A cell was placed in the aperture of the pipette and, after a high resistance seal formed, the cell membrane inside the pipette was disrupted with a manipulator-controlled platinum wire. Voltage control was assessed by evaluating the time course of the capacitive current and the steepness of the negative slope region of the peak current–voltage relationship as per criteria previously established (Hanck and Sheets, 1992). To allow for full sodium channel availability, the holding membrane potential was set to −150 mV. Iq protocols typically contained four repetitions at each test voltage that were one fourth of a 60 Hz cycle out of phase to maximize rejection of this frequency and to improve the signal-to-noise ratio.

The control extracellular solution for Iq, measurements contained (mM): 15 Na+, 185 TMA+, 2 Ca2+, 200 MES, and 10 HEPES, pH 7.2; and the intracellular solution contained: 200 TMA+, 200 F−, 10 EGTA, and 10 HEPES, pH 7.2. For measurement of Iq, the intracellular solution contained (mM): 200 TMA+, 50 mM F−, 150 mM MES, 1 mM BAPTA (1,2-bis 2-aminophenoxoethane-N,N,N′,N′-tetraacetic acid; Sigma Chemical Co.), 10 HEPES, and 10 EGTA, pH 7.2, 10 μM saxitoxin (Calbiochem Corp.), and the extracellular solution had Na+ replaced with TMA+. Reduction of intracellular F− and inclusion of BAPTA re-

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distribution as follows:

was a compromise between extrapolation of the data back to the
point used for fitting until the total charge from the fitted curve
equaled the total OFF charge for that voltage step. This method
was calculated during step repolarizations, and then extrapolated to the gating charge in hH1a and 15% of the total gating charge. For hH1a, two exponentials fit better 77% of the time. When there was a

The phenylalanine at position 1485 in the IFM region of the linker between domains III and IV was mutated to a cysteine.

produced the magnitude of endogenous ionic currents that occasionally
interfered with recordings. Anthopleurin A toxin (Sigma
Chemical Co.) was used at a concentration of 1 μM, which is
three orders of magnitude greater than the Kᵦ (Hanck and
Sheets, 1995; Khera et al., 1995). For experiments in which cells
were perfused internally with MTSET (Toronto Research Chemicals), it was dissolved in intracellular solutions ~1 min before use.

Data Analysis

Leak resistance was calculated as the reciprocal of the linear conductance between -190 and -110 mV, and cell capacitance was measured from the integral of the current responses to voltage steps between -150 and -190 mV. Peak Iₙa was taken as the mean of four data samples clustered around the maximal value of data digitally filtered at 5 kHz and leak corrected by the amount of the calculated time-independent linear leak. Data were capacity corrected using 4.16 scaled current responses recorded from voltage steps between -150 and -190 mV. All Iₙg were leak corrected by the mean of 2-4 ms of data, beginning at least 8 ms after the change in potential. For ON-Iₙg, this was typically at 8 ms, and 10 ms for OFF-Iₙg.

To determine time constants of Iₙ decay, current traces were trimmed until the decay phase was clearly apparent, and then fit by a sum of exponentials with DISCRETE (Provencher, 1976), a program that provides a modified F statistic to evaluate the number of exponential components that best describe the data. To fractionate the gating charge associated with each of the exponential components, it was necessary take into account the fact that the voltage clamp was not instantaneous. We first calculated the total OFF charge during each repolarization step, and then extrapolated the exponential curve backwards from the first point used for fitting until the total charge from the fitted curve equaled the total OFF charge for that voltage step. This method was a compromise between extrapolation of the data back to the start of the repolarization step, which would have resulted in over estimation of the contribution of the fast-time constant, and no extrapolation at all, which would have over estimated the contribution of the slow-time constant.

Charge-voltage relationships were fit with a simple Boltzmann distribution as follows:

\[
Q = \frac{Q_{\text{max}}}{1 + e^{V_s - V_{1/2}}}
\]

where Q is the charge during depolarizing step, Q_{\text{max}} is the maximum charge, V_s is the test potential, V_{1/2} is the half point of the relationship, and s is the slope factor in millivolts. For comparison between cells, fractional Q was calculated as Q/Q_{\text{max}} for each cell.

Data were analyzed and graphed on a SUN Sparcstation using SAS (Statistical Analysis System). Unless otherwise specified, summary statistics are expressed as means ± 1 SD. Regression parameters are reported as the estimate and the standard error of the estimate (S.E.E.), and figures show means ± SEM.

RESULTS

Intracellular MTSET Modification of ICM-hH1a

Similar to previous reports (Kellenberger et al., 1996; Chahine et al., 1997; Vedantham and Cannon, 1998), mutation of the phenylalanine to cysteine in the IFM motif in the linker between domains III and IV caused decay of Iₙa to be moderately slowed compared with wild-type hH1a, but perfusion with intracellular MTSET caused the decay to be almost completely inhibited (Fig. 2). We perfused cells expressing ICM-hH1a internally with 2.5 mM MTSET until additional slowing of the decay phase of Iₙa in response to step depolarizations was detectable (typically within 4 min), at which time the internal solution was changed back to control. Over the next 6 min, further modification occurred before decay of Iₙa stabilized with minimal inactivation over 50 ms (Fig. 2 C). As reported for other mammalian sodium channels (Yang and Horn, 1995; Kellenberger et al., 1996; Chahine et al., 1997), although not for squid giant axon (Khodakhah et al., 1998), internal perfusion with MTSET had no effect on Iₙa in wild-type hH1a (n = 2, data not shown). In the following experiments, we compared Iₙa and Iₙ measurements of ICM-hH1a_MTSET to wild-type hH1a.

ON-Gating Current Studies

If the putative inactivation lid were outside the voltage field and all voltage sensors had completed their translocation before the binding of the inactivation lid to its receptor, then Iₙ measured during step depolarizations should be insensitive to whether the inactivation lid can become bound to its receptor. Fig. 3 shows capacity and leak-corrected Iₙg traces and their corresponding integrals for typical cells expressing hH1a and ICM-hH1a_MTSET. Iₙg decays were fit by a sum of up to two exponentials, and a two-time-constant fit was accepted when it produced a statistically significant F statistic (Provencher, 1976). The dominant time constant was assigned as the one making the larger contribution to total gating charge. For hH1a, two exponentials fit better 53% of the time, while for ICM-hH1a_MTSET two exponentials fit better 77% of the time. When there was a second exponential, it contributed only 9% ± 8% (n = 5) to the gating charge in hH1a and 15% ± 11% (n = 4) to the charge in ICM-hH1a_MTSET channels. There was no difference between the dominant time constants for the two channels at any of the test potentials (Fig. 3 C). In addition, the Q-V relationships were nearly identical between hH1a and ICM-hH1a_MTSET.
(Fig. 3 D). These data indicate that an intact putative inactivation lid did not directly contribute to gating charge upon depolarization (ON charge).

Development of Ionic Current Inactivation of hH1a-ICM Sodium Channels after Intracellular MTSET

A standard two-step development of inactivation protocol was used to assess the time course of fast inactivation of $I_{Na}$ (Fig. 4). Fig. 4 A (insert) illustrates the voltage-clamp protocol, which included a short voltage clamp-back step to $-120$ for 2 ms, which allowed any open sodium channels to close, but did not allow for recovery of inactivated channels. Over the 44-ms conditioning time, wild-type hH1a almost completely inactivated, while ICM-hH1aMTSET demonstrated little inactivation. Data for development times up to 1 s were fitted with the sum of two exponentials:

\[
\text{Fractional Availability} = A_1 e^{-t_1} + A_2 e^{-t_2} + k, \quad (2)
\]

where the parameters determined by the fit were: $t_1$, the faster time constant; $A_1$, the amplitude contribution of $t_1$, $t_2$, the slower time constant; $A_2$, the amplitude contribution of $t_2$, and $k (1 - A_1 - A_2)$, the noninactivating fraction, which was set to 0 for hH1a. Table I shows the values from fits to data from wild-type hH1a, ICM-hH1aMTSET, and unmodified ICM-hH1a. For wild-type hH1a, the faster time constant was short ($2.1 \pm 0.3$ ms) and accounted for most of the inactivation ($83 \pm 2\%$). In contrast, inactivation was almost completely abolished for ICM-hH1aMTSET, with only $18\% \pm 2\%$ ($n = 4$) of the current inactivated by 44 ms, and the faster time constant ($6.9 \pm 3.0$ ms) was more than three times longer than that for hH1a. Similar results were found when cells were perfused with 10 mM MTSET; only $16\% \pm 6\%$ ($n = 4$) of the current inactivated by 44 ms (data not shown). The residual “fast” inactivation in ICM-hH1aMTSET was unlikely to reflect residual ICM-hH1a unmodified by MTSET, because the fast time constant of unmodified ICM-hH1a was much shorter ($1.4 \pm 0.3$ ms). In addition, although a second time constant was present for each channel isoform, the slow time constant for ICM-hH1aMTSET would contribute little to the small reduction in $I_{Na}$ at 44 ms because it was nearly 80-fold longer than the fast time constant.

OFF-gating Current Studies

To investigate the contribution of the putative inactivation lid to gating charge immobilization (i.e., the slow return of gating charge during repolarization), $I_g$ was recorded during repolarization steps to $-180$ mV after conditioning to 0 mV for up to 44 ms in cells express-
ing wild-type hH1a and ICM-hH1a MTSET. The potential of \(-180\) mV was selected for recording of $I_{\text{g}}$ during repolarization (OFF-$I_{\text{g}}$) because the slow component became fast enough such that all of the OFF charge could be measured over 10–15 ms (i.e., the OFF charge measurement equaled the ON charge measurement), but it was still long enough that the slow and fast time constants of OFF-$I_{\text{g}}$ were different by about an order of magnitude and could be clearly separated using two exponential fits. Examples of OFF-$I_{\text{g}}$ and their integrals are shown for hH1a and ICM-hH1a MTSET in Fig. 5. The presence of a slow component is more apparent by inspection of the integrals of OFF-$I_{\text{g}}$ (bottom).

OFF-$I_{\text{g}}$ were fit by a sum of up to two exponentials, and the time constants sorted by speed. Fig. 6 shows the results of this analysis for both hH1a and ICM-hH1a MTSET. For this and subsequent experiments, results from five cells expressing hH1a were compared with those from four cells expressing ICM-hH1a MTSET. The values for both $\tau_f$ and $\tau_s$ were very similar for the two groups with a faster time constant of <0.4 ms and a slower time constant of ~2 ms. Note that no slow time constant was detectable until the duration of the conditioning step was at least 0.7 ms for either channel type.

Even though the time constants of relaxations of OFF-$I_{\text{g}}$ traces for hH1a and ICM-hH1a MTSET were similar, the contributions to OFF charge were very different between the two channels (Fig. 7). Data are graphed in a manner similar to those presented by Armstrong and Bezanilla (1977), who first showed that the time course in the reduction of the fast component in OFF charge was the same as the time course of development of $I_{\text{n}}$ inactivation. Because the sum of the charge in the fast- and slow-time constants equals unity, the time course of appearance of a slow component in OFF charge is equivalent to the time course of reduction in the contribution by the fast component. The fraction of OFF charge accounted for by the fast component calculated for each development duration compared with the total OFF charge measured for the same development duration for wild-type hH1a and ICM-hH1a MTSET is shown in Fig. 7. With the shortest conditioning duration of 0.3 ms, all of the OFF charge was accounted for in the fast component, but, as the conditioning duration was extended, the fast component accounted for a smaller fraction of the OFF charge.

For hH1a, the fraction of OFF charge contributed by the fast-time constant decreased with a time constant of $2.8 \pm 2.3$ ms, which was similar to the time course of the development of $I_{\text{n}}$ inactivation at 0 mV (2.1 ms, Table I). It reached a steady state value of $47 \pm 10\%$, where the slow component accounted for the remainder (53%) of the total OFF charge. Surprisingly, in the absence of a normally functioning inactivation gate (i.e.,

### Table I

<table>
<thead>
<tr>
<th>Na channel</th>
<th>n</th>
<th>Fast tau</th>
<th>Amplitude of fast tau</th>
<th>Slow tau</th>
<th>Amplitude of slow tau</th>
<th>Constant</th>
</tr>
</thead>
<tbody>
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<td>hH1a</td>
<td>7</td>
<td>2.1 ± 0.3</td>
<td>0.83 ± 0.02</td>
<td>21.7 ± 10.9</td>
<td>0.17 ± 0.02</td>
<td>0</td>
</tr>
<tr>
<td>ICM-hH1a MTSET</td>
<td>4</td>
<td>6.9 ± 3.0</td>
<td>0.12 ± 0.03</td>
<td>406 ± 158</td>
<td>0.43 ± 0.14</td>
<td>0.46 ± 0.14</td>
</tr>
<tr>
<td>ICM-hH1a</td>
<td>6</td>
<td>1.4 ± 0.3</td>
<td>0.50 ± 0.06</td>
<td>59 ± 22</td>
<td>0.24 ± 0.03</td>
<td>0.26 ± 0.04</td>
</tr>
</tbody>
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Figure 4. Two-pulse development of $I_{\text{n}}$ inactivation for wild-type hH1a (A) and ICM-hH1a MTSET (B). The inset illustrates the voltage-clamp protocol and an example of a capacity and leak-corrected $I_{\text{n}}$ trace from a cell expressing hH1a. Peak $I_{\text{n}}$ after various conditioning times to 0 mV were normalized to the peak $I_{\text{n}}$ in the absence of a conditioning step for each cell. The solid lines were calculated from the means of the parameters of the individual fits to Eq. 2. Fitted parameters are given in Table I.
in ICM-hH1αMTSET), there still remained two time constants in OFF-Ig. The time course of the decrease in the fraction of OFF charge accounted by the fast-time constant had a similar value (2.5 ± 1.4 ms) to that for hH1α, although the fraction of OFF charge that was accounted for by the slow component after longer conditioning durations was 69 ± 9%, while the fraction of OFF charge accounted for by the slow component decreased to 31% (P < 0.01 compared with wild-type hH1α by non-paired t test). Analysis of the time course of the appearance of the slow component in the OFF charge gave nearly equivalent values; time constants and amplitudes were 2.1 ± 1.9 ms and 52 ± 10% (wild-type hH1α) and 3.6 ± 3.0 ms and 33 ± 3% (ICM-hH1αMTSET). In one cell, we confirmed that wild-type hH1α perfused with intracellular MTSET showed no changes in OFF-Ig.

\[ \frac{Q_{\text{f}}}{Q_{\text{OFF}}} = (1 - A_f) e^{-t/\tau_f} + A_f \]  (3)

where fractional charge was calculated as the ratio of charge associated with the fast-time constant (Q_f) to the total OFF charge at each time, and the parameters determined by the fit were: \( \tau_f \), the time constant of the reduction in the contribution to OFF charge by the fast time constant, and \( A_f \), the steady state amplitude of OFF charge associated with the fast time constant while \( 1 - A_f \) represents the steady state amplitude of the OFF charge associated with the slow-time constant. The parameters from the best fits for hH1α (n = 5 cells) showed that \( \tau_f \) was 2.8 ± 2.3 ms, \( A_f \) the fraction of OFF charge in the fast tau, was 0.47 ± 0.10, and 1 - \( A_f \), the fraction of OFF charge in the slow tau, was 0.53 ± 0.10.* For ICM-hH1αMTSET (n = 4 cells), \( \tau_f \) was 2.5 ± 1.4 ms, \( A_f \) was 0.69 ± 0.09, and 1 - \( A_f \) was 0.30 ± 0.09.* *P < 0.01.
While it is possible that the slow-time constant in ICM-hH1a\textsubscript{MTSET} was related to residual inactivation of unmodified channels, this seems unlikely for the following reasons. First, the fast-time constant of $I_{\text{Na}}$ inactivation in ICM-hH1a\textsubscript{MTSET} was more than threefold longer than that in unmodified ICM-hH1a channels (6.9 vs. 1.4 ms, see Table I). Second, if inactivation of residual, non-MTSET-modified ICM-hH1a channels were responsible for the fast-time constant that remained in the OFF charge, then the amount of OFF charge accounting for the slow component should have been much smaller than the measured 31%. After all wild-type hH1a channels have been fast inactivated, ~47% of the OFF charge returned rapidly and 53% returned slowly. Applying a similar ratio to OFF charge of ICM-hH1a\textsubscript{MTSET}, where <20% of $I_{\text{Na}}$ became inactivated by 44 ms (Fig. 4), it would be expected that <10% of the charge should have become immobilized. Instead, >30% of the charge was contained in the slow-time constant. Lastly, the time constant of $I_{\text{Na}}$ inactivation at 0 mV for ICM-hH1a\textsubscript{MTSET} (6.9 ms) did not correspond to its time constant of development of immobilization (2.5 ms). Consequently, it is more likely that one or more of the four putative voltage sensors of ICM-hH1a\textsubscript{MTSET} return to their repolarized conformation with a slow-time constant even in the absence of an intact inactivation lid.

The Effect of Inhibition of Movement of the Domain IV–S4 on Charge Immobilization

We have shown that Ap-A toxin slows inactivation of $I_{\text{Na}}$ by inhibiting movement of the voltage sensor formed by the S4 of domain IV (Hanck and Sheets, 1995; Sheets et al., 1999). We postulated, therefore, that this toxin could be used to probe the contribution of the S4 in domain IV to the slow component of OFF charge in the lid-modified mutant.

Because fast inactivation had already been modified in ICM-hH1a\textsubscript{MTSET} cells, the application of Ap-A toxin had little additional effect on $I_{\text{Na}}$ decay (data not shown). However, because Ap-A toxin also reduces $Q_{\text{max}}$ by about one-third (Sheets and Hanck, 1995, 1999), the Q-V relationship could be used to verify that channel modification by toxin had occurred. Fig. 8 shows that Ap-A toxin reduced $Q_{\text{max}}$ by about one-third in both wild-type hH1a and ICM-hH1a\textsubscript{MTSET}. Furthermore, the slope factors and half-points of the Q-V relationships for the two channels were comparable. The reduction in $Q_{\text{max}}$ by Ap-A toxin in ICM-hH1a\textsubscript{MTSET} confirmed that the toxin still modified ICM-hH1a\textsubscript{MTSET} ON charge similar to wild-type hH1a, even though inactivation of $I_{\text{Na}}$ had already been slowed.

The role of the domain IV–S4 in charge immobilization was then investigated by recording OFF-I\textsubscript{g} for both hH1a and ICM-hH1a\textsubscript{MTSET} after modification by Ap-A toxin. The same voltage protocol was used as previously; cells were depolarized to 0 mV for durations up to 44 ms before repolarization to −180 mV. OFF-I\textsubscript{g} were fit by a sum of up to two exponentials and sorted by speed. In contrast to the findings in control solutions (Fig. 6), OFF-I\textsubscript{g} for both hH1a and ICM-hH1a\textsubscript{MTSET} were best fit by a single exponential at all conditioning durations (Fig. 9). The time constants clustered around 0.3 ms, and they were similar to the fast-time constants recorded for both hH1a and ICM-hH1a\textsubscript{MTSET} cells in control solutions (Fig. 6 A). A decrease in the amount of charge immobilization has been previously reported in frog myelinated nerve after exposure to site-3 toxins (Neumcke et al., 1985).

To compare the magnitude of OFF charge for the two channels after toxin modification, the fraction of OFF charge in Ap-A toxin was normalized to the maximal OFF charge (i.e., $Q_{\text{max}}$) measured for each cell in the absence of toxin and plotted as a function of the duration of the conditioning pulse at 0 mV. These data are shown in Fig. 10 A for both wild-type hH1a and ICM-hH1a\textsubscript{MTSET}. The time course of the increase in OFF charge was nearly identical for both sodium channels with a time constant of ~0.7 ms. Note that the largest fraction of OFF charge was almost 70%, consistent with the reduction in gating charge by Ap-A toxin (Fig. 9). Both the absence of a slow component in the OFF
charge of ICM-hH1aMTSET after toxin modification and the \( \sim 30\% \) reduction in OFF charge suggest that the slow component of OFF charge for ICM-hH1aMTSET in control solutions (Fig. 7) may result from the slow return of charge associated with the S4 in domain IV.

If this were the case, then one would expect the OFF charge associated with the fast-time constant in ICM-hH1aMTSET to be similar to the OFF charge of both toxin-modified ICM-hH1aMTSET and toxin-modified wild-type hH1a. Fig. 10 B shows the time course of the appearance of OFF charge contributed by the fast time constant in control solutions for both wild-type hH1a and ICM-hH1aMTSET normalized to maximal OFF charge (i.e., \( Q_{\text{max}} \)). Note that the fraction and time course of OFF charge associated with the fast time constant for ICM-hH1aMTSET were comparable with those of both toxin-modified channels. The parameters from the best fits are given in Table II.

\[ \text{fractional } Q = A \left(1 - e^{-t/\tau}\right) \quad (4) \]

where the parameters of the fit were the time constant \( \tau \) of the appearance of OFF charge and \( A \), the fractional amplitude returned. (A) Fractional \( Q \) was calculated as the ratio of OFF charge at the times indicated in Ap-A toxin to the maximal OFF charge in control solutions for hH1a (>). (B) Fractional \( Q \) was calculated as the ratio of OFF charge at the times indicated in control solutions (see Fig. 7) to the maximal OFF charge in control for hH1a (>) and ICM-hH1aMTSET (>). Note that both the amplitude and time course of OFF charge associated with the fast time constant for ICM-hH1aMTSET were comparable with those of both toxin-modified channels.

| Parameters from Fits to Eq. 4 for Fraction of OFF Charge Normalized to Maximal OFF Charge in Control |
|----------------------------------|----------------|
| Na channel isoform               | n | Toxin present | \( A \) (fractional amplitude) | \( \tau \) (ms) |
| hH1a                             | 5 | yes          | 0.69 ± 0.08                  | 0.74 ± 0.15 |
| ICM-hH1aMTSET                    | 4 | yes          | 0.69 ± 0.06                  | 0.98 ± 0.17 |
| Fast component in ICM-hH1aMTSET  | 4 | no           | 0.71 ± 0.09                  | 0.74 ± 0.24 |
| Fast component in hH1a           | 5 | no           | 0.54 ± 0.07                  | 0.42 ± 0.10 |

There was no significant difference \( P < 0.05 \) between the amplitudes and \( \tau \)s of OFF charge for ICM-hH1aMTSET in toxin and either wild-type hH1a in toxin or OFF charge associated with the fast time constant of ICM-hH1aMTSET in control solution.
though fast inactivation had been modified in this preparation, inactivation over hundreds of milliseconds can still occur in sodium channels with mutations in the IFM motif (Featherstone et al., 1996). Such slow inactivation was not addressed in the studies reported here.

We found that the Q-V relationships of wild-type hH1a and hICM-hH1aMTSET were similar, as were the time courses of ON relaxation, demonstrating that an intact inactivation lid had little effect on movement of the channel’s voltage sensors during step depolarizations. However, comparison of the OFF-charge measurements between the two sodium channels showed that 53% of the charge became immobilized in wild-type hH1a, while only 31% of the charge became immobilized in hICM-hH1aMTSET. After the application of Ap-A toxin, a site-3 peptide toxin that has been shown to modify inactivation of INa by inhibiting movement of the S4 segment of domain IV (Sheets et al., 1999), the OFF charge was similar in both magnitude and time course for both wild-type hH1a and hICM-hH1aMTSET.

The Role of the Inactivation Lid in Charge Immobilization

Armsmstrong and Bezanilla (1977) found that the OFF charge of inactivated sodium channels in squid giant axon contained two components, a fast and a slow component, with the slow component (immobilizable fraction) accounting for nearly 60% of the total charge. Furthermore, the time course of the reduction in the fast component in OFF charge (as well as the time course of the development of the slow component) paralleled the time course of development of INa inactivation. When the repolarization voltage was less negative, the slow component of the OFF charge was too small and too slow to be accurately measured. As a consequence, the magnitude of the OFF charge was reduced compared with ON charge, and the gating charge was said to become immobilized. We found a similar correlation between the time course of reduction in the fast component of OFF charge and the degree of inactivation of INa. In wild-type hH1a, the predominant time constant of INa inactivation at 0 mV was 2.1 ms, which was comparable with both the time course of reduction in the fast component (2.8 ms) and to the appearance of the slow component (2.1 ms) in OFF charge (Figs. 4 and 7). After longer conditioning durations, the slow component accounted for up to 53% of total OFF charge, similar to the nearly 60% found for sodium channels in squid giant axon (Armstrong and Bezanilla, 1977; Greeff et al., 1982) and to the 56% found for heterologously expressed rat brain IIa (Kuhn and Greeff, 1999).

Armsmstrong and Bezanilla (1977) also found that internal perfusion of the squid giant axon with the non-specific proteolytic enzyme, pronase, removed both fast inactivation and charge immobilization. Based on this finding, it seemed reasonable to expect that focal disruption of the putative inactivation lid of sodium channels might also eliminate charge immobilization. However, we found that was not the case; the amount of OFF charge in hICM-hH1aMTSET that could become immobilized was reduced but not eliminated (from 53% to 31%). In hICM-hH1aMTSET, charge immobilization still occurred with a time course of 2.5 ms (Fig. 7), which was similar to the time course in wild-type hH1a. Although fast inactivation was “removed” by either intracellular proteolytic enzymes or by mutagenesis, these results suggest that the two methods are not equivalent. Similarly, differences between the two methods has been shown for cardiac Na channels where modification of fast inactivation by proteolytic enzymes enhanced slow inactivation (Clarkson, 1990), whereas mutation of the inactivation lid had little effect on slow inactivation (Bennett et al., 1995). Because proteolytic enzymes are expected to cleave the Na channel protein at multiple sites, it is likely that intracellular proteolytic enzymes produce more complicated channel modifications than that achieved by channel mutagenesis. Consequently, differing effects on movement of the voltage sensors would not be unexpected.

In the absence of binding of the inactivation lid, what is the origin of the gating charge that can become immobilized in hICM-hH1aMTSET? Fig. 10 suggests that the S4 in domain IV is responsible for charge immobilization in hICM-hH1aMTSET. Previous studies have shown that site-3 toxins such as Ap-A toxin bind extracellularly to regions in domain IV (Thomsen and Catterall, 1989; Rogers et al., 1996; Benzinger et al., 1997, 1998), and that site-3 toxins inhibit movement of the S4 of domain IV (Sheets and Hanck, 1995; Sheets et al., 1999). Consequently, sodium channels that are modified by Ap-A toxin allow only the S4s in domains I–III to contribute to gating charge. In Ap-A toxin, the time course and the magnitude of OFF charge for both wild-type hH1a and hICM-hH1aMTSET were the same (Fig. 10 A). Comparison of these data to the OFF charge associated with only the fast-time constant in hICM-hH1aMTSET in control solutions showed the time courses and magnitudes of the OFF charge to be analogous (Fig. 10 B), and suggests that the S4s in domains I–III in nontoxin-modified hICM-hH1aMTSET contributed to the fast component of OFF charge. Consequently, the S4 in domain IV appears to be responsible for the slow component of OFF charge in hICM-hH1aMTSET.

These data also suggest that charge movement from the S4 in domain IV occurs on a slower time scale than activation. In the presence of Ap-A toxin, all OFF charge is contained in the fast component with a time course of appearance of ~0.7 ms (Fig. 10), and represents the return of gating charge associated only with channel activation because fast inactivation has been inhibited.
by the toxin. Similarly, because the fast component of OFF charge in ICM-hH1aMTSET is nearly identical to the OFF charge in Ap-A toxin, it also is likely to represent gating charge associated with channel activation resulting from movement of the S4s in domains I–III. The time course of appearance of the slow component of OFF charge in ICM-hH1aMTSET is much longer (~2.5 vs. 0.7 ms), suggesting that the S4 in domain IV moved after the other S4s had moved. This conclusion is consistent with previous ON charge studies showing that the S4 in domain IV moved after sodium channel activation had occurred (Sheets and Hanck, 1995; Sheets et al., 1999) and that it moved more slowly than the other S4s in domains I–III (Cha et al., 1999).

As shown in Fig. 7, there was an additional 22% of OFF charge in control solutions that returned slowly in wild-type hH1a (53%) compared with the amount that returned slowly in ICM-hH1aMTSET (31%). The data with Ap-A toxin suggest that this voltage sensor is not the S4 in domain IV, but they do not directly address what additional voltage sensors may be responsible for the slow return of OFF charge in wild-type hH1a. Recently, Cha et al. (1999) showed that charge immobilization was the result of slow movement of the S4 in domain III and even slower movement of the S4 in domain IV, while the voltage sensors from domains I and II returned rapidly and accounted for the fast component of OFF charge that did not immobilize. Our results are consistent with these data and suggest that the S4 in domain III is the voltage sensor responsible for contributing an additional component to the OFF charge that returns slowly only when the inactivation lid has bound. Interestingly, residues in the S4–S5 linker in domain III have been implicated as forming part of the inactivation lid receptor site (Smith and Goldin, 1997).

Implications for a Structurally Based Model

The experiments reported here expand upon the model recently proposed by Cha et al. (1999). Our studies confirm that the S4 in domain IV is the last voltage sensor to move during repolarization after fast inactivation, and that it contributes ~30% to the total OFF charge. The results in this study demonstrate that the slow movement of the S4 in domain IV during repolarization is intrinsic to the voltage sensor, and not dependent on the binding of the inactivation lid. In the model proposed by Cha et al. (1999), the rate-limiting step during repolarization was proposed to be the unbinding of the inactivation lid. If that were the case, then one would expect either no slow component in the OFF charge of ICM-hH1aMTSET or a component that was intermediate between the fast and slow components of wild-type hH1a. But this was not what was found; the time course of the slow component in the OFF charge in ICM-hH1aMTSET had the same time course as that of $I_{Na}$ inactivation. This finding suggests that the rate-limiting step is not the unbinding of the inactivation lid, but the movement of the S4 in domain IV. However, binding of the inactivation lid did modulate the movement of an additional voltage sensor that contributed 22% to the OFF charge; i.e., the difference between the 53% of charge immobilized in wild-type hH1a and the 31% of charge immobilized in ICM-hH1aMTSET that could be attributed to the S4 in domain IV. Our data taken together with the data of Cha et al. (1999) suggest that a likely candidate for this is the S4 in domain III. When the inactivation lid is not bound to its receptor, either because the inactivation lid has been altered, as in ICM-hH1aMTSET, or because the receptor for the inactivation lid has been modified by inhibition of the movement of the domain IV–S4 by site-3 toxins in wild-type hH1a, the S4 in domain III moves rapidly and contributes to the fast component of OFF charge.

We thank WenQing Yu for her excellent technical assistance.

This research was supported by National Heart, Lung and Blood Institute grants HL-PO1-20592 (D.A. Hanck and J.W. Kyle) and HL-R01-44630 (M.F. Sheets).

Submitted: 29 November 1999
Revised: 7 March 2000
Accepted: 10 March 2000

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