Mechanism of Arachidonic Acid Modulation of the T-type Ca$^{2+}$ Channel α$_{1G}$

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ABSTRACT Arachidonic acid (AA) modulates T-type Ca$^{2+}$ channels and is therefore a potential regulator of diverse cell functions, including neuronal and cardiac excitability. Here we analyze the effects of AA on the T-type Ca$^{2+}$ channel α$_{1G}$ heterologously expressed in HEK-293 cells. AA inhibited α$_{1G}$ currents within a few minutes, regardless of preceding exposure to inhibitors of AA metabolism (ETYA and 17-ODYA). Current inhibition was also observed in cell-free inside-out patches, indicating a membrane-delimited interaction of AA with the channel. AA action was consistent with a decrease of the open probability without changes in the size of unitary currents. AA shifted the inactivation curve to more negative potentials, increased the speed of macroscopic inactivation, and decreased the extent of recovery from inactivation at −80 mV but not at −110 mV. AA induced a slight increase of activation near the threshold and did not significantly change the deactivation kinetics or the rectification pattern. We observed a tonic current inhibition, regardless of whether the channels were held in resting or inactivated states during AA perfusion, suggesting a state-independent interaction with the channel. Model simulations indicate that AA inhibits T-type currents by switching the channels into a nonavailable conformation and by affecting transitions between inactivated states, which results in the negative shift of the inactivation curve. Slow-inactivating α$_{1G}$ mutants showed an increased affinity for AA with respect to the wild type, indicating that the structural determinants of fast inactivation are involved in the AA–channel interaction.

KEY WORDS: Low voltage–activated calcium channel • fatty acid • kinetic model • inactivation • mutant

INTRODUCTION

T-type Ca$^{2+}$ channels belong to the family of voltage-dependent Ca$^{2+}$ channels, within which they are mainly distinguished by a relatively low threshold of activation and inactivation, fast deactivation, and a small single channel conductance. T-type channels are widely expressed and are involved in the regulation of multiple cellular functions, including excitability, development, excitation–contraction and excitation–secretion couplings, and acrosome reaction (Perez-Reyes, 2003). The activity of T-type channels may be affected by multiple neurotransmitters and hormones, extracellular pH, redox agents, and anti hypertensive, anesthetic, antiarrhythmic, and antiepileptic drugs (Vassort and Alvarez, 1994; Huguenard, 1996; Todorovic et al., 2001; Perez-Reyes, 2003).

Remarkably, it has been shown that two related endogenous compounds, arachidonic acid (AA) (Chesnay-Marchais and Fritsch, 1994; Schmitt and Meves, 1995; Zhang et al., 2000) and the endocannabinoid anandamide (N-arachidonoyl ethanolamine [AEA]) (Chemin et al., 2001) modulate T-type channels. Both decrease the time constant of macroscopic inactivation and shift the steady-state inactivation curve to more negative potentials, without striking changes in the activation properties. Based on these data, Zhang et al. (2000) proposed that AA inhibits the T-type channel α$_{1H}$ by acting mainly on a voltage-dependent transition between closed states. However, the support of this hypothesis is quite weak for two reasons. First, in the framework of recent models for T-type channel gating (Serrano et al., 1999; Burgess et al., 2002), the putative effects of AA on voltage-dependent transitions between closed states have to be very pronounced to account for the large decrease in current amplitude, but these would modify the activation curve to a much larger extent than observed experimentally. Second, the characterization of the effects of AA on kinetic properties is still too incomplete to propose a proper model for modulation.

In the present study we examined the mechanism of inhibition of the T-type Ca$^{2+}$ channel subunit α$_{1G}$ by AA in HEK-293 cells. We investigated whether AA effects were dependent on AA metabolism and performed a detailed characterization of changes induced in the gating kinetics of the channel. In addition, structural determinants of modulation by AA were probed by comparing the effects of AA on slow-inactivating mutants with those on the wild-type channel. Experimental data and model simulations suggest that current inhibition in physiological conditions results from the combination

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ABBREVIATIONS USED IN THIS PAPER: AA, arachidonic acid; AEA, N-arachidonoyl ethanolamine; ETYA, 5,8,11,14-eicosatetraenoic acid; FAAH, fatty acid amide hydrolase.
of two factors: the switch of the channels into a non-
available conformation and the shift of the voltage
dependence of the steady-state inactivation, which
results from the alteration of transitions between in-
activated states.

MATERIALS AND METHODS

Solutions

After mounting in the patch-clamp setup, the cells were allowed
to stabilize in Krebs solution, containing (in mM) 150 NaCl, 6
KCl, 1 MgCl₂, 1.5 CaCl₂, 10 glucose, 10 HEPES, titrated to pH 7.4
with 1 N NaOH. The effects of AA on the gating properties of α_g
were investigated with whole-cell recordings using an extracellular
solution containing (in mM) 2 CaCl₂, 150 NaCl, 5 CsCl, 5 glucose,
1 MgCl₂, and 10 HEPES and titrated to 7.4 with HCl. For
the comparison of the effects on α_g and slow inactivating mu-
tants and the test for tonic inhibition by AA we used 20 mM
CaCl₂ and 120 mM NMDG⁺ instead of NaCl. The intracellular so-
lution contained 162 mM CsCl, 10 mM HEPES, 5 mM MgCl₂, 5
mM Na₂ATP, 10 mM TEA-Cl, 10 mM EGTA, titrated to pH 7.4
with 1 N G0H. For inside-out experiments, the pipette solution
contained (in mM) 110 CaCl₂, 10 HEPES, pH 7.4, and the bath
solution 150 CsCl, 1 MgCl₂, 1 Na₂ATP, pH 7.2. AA, used in its Na-
salt form, was dissolved in water. 5,8,11,14-Eicosatetraenoic acid
(ETYA) and 17-octadecanoic acid (17-ODYA) were dissolved in
DMSO. All chemicals were purchased from Sigma-Aldrich.

Electrophysiology and Data Analysis

Human embryonic kidney cells (HEK-293) were grown in Dul-
becco’s modified Eagles medium containing 10% (vol/vol) hu-
manserum, 2 mM l-glutamine, 2 U/ml penicillin, and 2 mg/ml streptomycin at 37°C in a humidity controlled incubator with
10% CO₂. Transient transfection with the wild-type α_g or differ-
ent constructs (Marksteiner et al., 2001; Staes et al., 2001) was
performed using Trans-IT-293 reagents (Mirus). Currents were
recorded using an EPC-7 (List Electronics) patch-clamp ampli-
fier and filtered with an eight-pole Bessel-filter (Kemo). For con-
rol of voltage-clamp protocols and data acquisition, we used an
IBM-compatible PC with TL-1 DMA or Digidata 1322A inter-
faces (Axon Instruments) and pClAMP-software (Axon Instru-
mements). Patch pipettes (1–2.5 MΩ) were pulled from Vitrex cap-
illary tubes (Modulohm) using a DMZ-Universal puller (Zeitz
Instruments). Series resistance was compensated to the max-
imum extent possible (40–60%). An Ag-AgCl wire was used as
reference electrode. Membrane capacitive transients were elec-
tronically compensated and the linear background components
were digitally subtracted when possible before data analysis. In
the case of tail current measurements, linear background com-
ponents and capacitive transients were subtracted by the ap-
lication of a −P/4 protocol. Current traces were filtered at 2–5
kHz and digitized at 5–10 kHz. All experiments were performed
at 22–25°C.

The activation curve was determined for each cell and experi-
mental condition by dividing the I/V curve by a function I_{act} = I(V) that describes the open pore conduction (see below). Steady-state inactivation curves were fit by

\[ k_{ii}(V) = \frac{1}{1 + \exp((V - V_{\text{act}})/s_{\text{act}})}, \]

where \( V_{\text{act}} \) is the potential of half-maximal inactivation and \( s_{\text{act}} \) the slope factor. Steady-state current inhibition was described by a Hill function of the form

\[ \%\text{INH} = \frac{100}{1 + (EC_{50}/[AA])^n}, \]

where \( EC_{50} \) is the effective concentration for 50% current inhibition and \( N \) is the Hill coefficient. The voltage dependence of the amplitude of tail currents was described in the range from +80 to 90 mV by a cube eighth function of the form

\[ I_{\text{tail}}(V) = G(V - V_{i})/(V_0 + b - V + c), \]

where \( G \) is a scaling factor, \( V_i \) is the residual potential and \( b \) and \( c \) are parameters describing the rectification pattern of the open pore conduction (Talavera et al., 2003a,b).

In whole-cell recordings all voltage protocols, the holding po-
tential was −110 mV except when stated otherwise. The stimula-
tion frequency was adjusted for each particular protocol as to en-
sure at least 5 s of recovery at −110 mV. In inside-out experi-
ments, the holding potential was −80 mV and the stimulation frequency 0.5 Hz.

The data were analyzed using WinASCD (G. Droogmans, KU
For all measurements, pooled data are given as mean ± SEM. We
used Student’s t test, taking \( P < 0.05 \) or \( P < 0.01 \) as level of signif-
ificance. We used MATLAB (MathWorks) to solve and fit a Markov
model for the gating of α_g, in control and in the presence of 3
μM AA (Fig. 10). Parameter optimization and numerical solu-
tion of the differential equations were performed with the built-
in functions \( \text{fmin} \) and \( \text{exp} \), respectively. Voltage-dependent rate
constants were written in the form

\[ k_{ii} = K_0 \exp\left( \frac{\delta_i q_i}{V} \right) \]

and

\[ k_{ji} = K_0 \exp\left( \frac{(1-\delta_j) q_j}{V} \right), \]

where \( ij \) and \( ji \) represent the transitions between each pair of ad-
jaent states in the forward (activation) and the backward (deac-
tivation) directions, respectively. \( q_i \) is the gating charge associated with the \( i \)-th box of the kinetic scheme and \( \delta \), account for the coupling between the local electric potential sensed by \( q_i \) and the membrane potential \( V \). \( T = 25.4 \) mV is the thermal energy in electron volts.

RESULTS

Extracellular application of 3 μM AA inhibited α_g currents
evoked by depolarizations from −110 to −20 mV to
54 ± 4% \(( n = 6) \) of the control value and decreased the
time constant of inactivation within a few minutes
(Fig. 1 A). Inhibition of α_g current was dose depend-
ent, with an effective concentration \( (EC_{50}) \) of 3.9 ± 0.3
μM and a Hill coefficient \( (N) \) of 1.6 ± 0.2 (Fig. 1 B).

Membrane-delimited Interaction of Arachidonic Acid with α_g

Fig. 2 A shows that extracellular application of 10 μM
ETYA, a nonmetabolizable analogue and inhibitor of
AA metabolism, decreased the amplitude of the cur-
rent to 73 ± 6% of its control value. However, it did not
modify the extent of AA-induced inhibition \( (49 ± 3%) \; n = 6 \).
Application of 17-ODYA (10 μM), an inhibi-
tor of the AA metabolism through the cytochrome
P450 pathway into epoxycosatrienoic acids and 19/20
HETE, did not alter the α_g current \( (99 ± 1 \) of the con-
trol value; \( n = 5 \)) or the inhibition by AA \( (2 \) μM; \( 21 ±

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4% in control \( n = 3 \) and 21 ± 5% in the presence of 17-ODYA \( [n = 5]; \) Fig. 2 B).

AA was able to inhibit the activity of \( \alpha_{1G} \) in cell-free inside-out patches with similar potency and time course to those observed in whole-cell experiments. Fig. 3 A shows an example of the AA-induced inhibition of currents evoked by voltage ramps from −80 to +20 mV in an inside-out patch. AA effect was rapidly reversed upon washout using BSA (Fig. 3, A and B). In average, application of 3 μM AA induced a 52 ± 4% peak current inhibition \( (n = 5) \). Fig. 3 C exemplifies the inhibitory effect of AA on currents evoked by depolarizing pulses from −80 to −10 mV. AA decreased the open probability and promotes the occurrence of null sweeps. Current inhibition can be confirmed by the comparison of the average of current traces recorded in control and in the presence of AA (Fig. 3 D). Notably, both the extent of current inhibition and the acceleration of the macroscopic inactivation were similar to those observed in whole-cell experiments (see Fig. 1 and Fig. 4, B and E). In summary, these results indicate that the inhibition of \( \alpha_{1G} \) by AA is not mediated by any of its metabolites and occurs in a membrane-delimited manner.

Both high channel overexpression and clustering made it impossible to observe single channel-containing patches. The size of unitary currents was therefore estimated by the fit of amplitude histograms built with single openings and the zero current level. As shown in Fig. 3 (C and E), the estimated unitary current was not changed by AA \( (-0.38 \pm 0.05 \) pA in control vs. \( -0.39 \pm 0.03 \) pA in AA). These results were confirmed by the analysis of histograms built with full current traces containing multiple channel openings (unpublished data).

**Arachidonic Acid Effects on the Gating of \( \alpha_{1G} \)**

To study the effects of AA on the gating properties of \( \alpha_{1G} \) we compared whole-cell data obtained in control conditions with those collected at the steady-state level of inhibition after a 3–4-min perfusion with 3 μM extracellular AA.
Activation and Inactivation

In order to study the effects of AA on activation properties of α_{IG}, current–voltage relationships (I/V curves) were determined from the peak amplitude of currents elicited by 200 ms–lasting voltage steps from a holding potential of −110 mV to potentials varying from −80 to 60 mV (Fig. 4 B, inset). Fig. 3 A exemplifies the effects of AA on the current traces elicited by steps to −80, −60, −45, −30, or 0 mV. As can be observed in the I/V curves (Fig. 4 B), AA induced a significant decrease of the current amplitude at potentials positive to −55 mV.

Fig. 4 C shows that AA did not significantly modify the activation curve at potentials positive to −55 mV and caused a small but significant increase of activation near the threshold (inset in the right). Steady-state inactivation curves h_{∞}(V) were determined from normalized peak amplitudes of currents recorded at −20 mV after 5 s–lasting prepulses to potentials from −110 to −55 mV (Fig. 4 C, left inset). AA shifted the inactivation curve to more negative potentials, with a voltage for half-maximal inactivation V_{inac} = −87.3 ± 1.0 mV compared with −74.2 ± 0.8 mV in control (Fig. 4 C). However, it did not affect the voltage sensitivity of steady-state inactivation (s_{inac} = 4.3 ± 0.2 mV in control and s_{inac} = 4.35 ± 0.09 mV in the presence of AA).

We have assessed the effects of AA on the kinetics of activation and inactivation from the voltage dependence of the time-to-peak (t_{p}) and the time constant of inactivation (τ_{inac}). AA significantly decreased t_{p} at potentials negative to −55 mV, but did not significantly alter the values at depolarized potentials (Fig. 4 D). On the other hand, τ_{inac} was significantly reduced at all voltages (Fig. 4 E).

Kinetics of Inactivation from Closed States

The results described above indicate that AA speeds up the transition from the open to the inactivated state, but give no clues about the possible effect of AA on the rate of inactivation from closed states. We therefore studied the effects of AA on the time course of the on-
set of inactivation at potentials below the threshold of channel activation. This was achieved by measuring the amplitude of the currents elicited by pulses to −20 mV, applied after steps of variable duration to −85 and −75 mV (Fig. 5 C, inset). These amplitudes were normalized to that of the current elicited with a pulse to −20 mV from a holding potential of −110 mV. The data were then subtracted from 1 and plotted as a function of the time of sojourn at −85 or −75 mV. Fig. 5 shows that AA increased the steady-state level of inactivation at both −85 and −75 mV, in accordance with the hyperpolarizing shift of the inactivation curve. However, AA only slightly increased the rate of inactivation from closed states, as shown by the comparison of normalized data (Fig. 5 D).

**Reactivation**

Membrane repolarization returns T-type Ca^{2+} channels from inactivated to the resting state, a process known as
Reactivation or recovery from inactivation. Reactivation kinetics at −110 or −80 mV were determined using a standard double pulse protocol to −20 mV with interpulse potential of −110 or −80 mV (Fig. 6 A). Reactivation was calculated as a function of the interpulse duration by the ratio between the current amplitude in each pulse (I_{pulse2}/I_{pulse1}). AA did not affect recovery at −110 mV, but at −80 mV it significantly reduced the level of steady-state recovery (Fig. 6, B and C) and decreased the rate of reactivation, as clear from the comparison of the normalized data (Fig. 6 C, inset). We also examined the effect of AA on the voltage dependence of recovery for a fixed repolarization period (100 ms) (Fig. 6, D and E). The voltage dependence of channel recovery showed a biphasic behavior in control, with an increasing phase up to around −95 mV and a decreasing phase at less negative potentials. The data from −95 to −55 mV was described by the same type of Boltzmann function used for $k_m(V)$ with parameters $V_{max} = −76.9 ± 0.7$ mV and $s_{max} = 3.4 ± 0.2$ mV. AA shifted the voltage dependence of channel recovery to more negative potentials ($V_{max} = −89.3 ± 0.1$ mV) and decreased the voltage sensitivity ($s_{max} = 4.02 ± 0.09$ mV).

Deactivation and Macroscopic Conduction

When in the open conformation, T-type channels can close back to the nearest closed (noninactivated) state. This transition, known as deactivation, determines the mean open time and the bursting behavior. To study the possible effects of AA on the voltage dependence of the deactivation kinetics, tail currents were recorded during voltage steps between −120 and +110 mV following a 7.5 ms–lasting depolarization to −20 mV (Fig. 7 A, top left inset). We determined the amplitude ($I_{tail}$) and the time constant of current decay ($\tau_{deac}$) from a single-exponential fit of the time course of the tail currents. $\tau_{deac}$ corresponds to the time constant of deactivation ($\tau_{deac}$) at potentials negative to the activation threshold and to the time constant of the macroscopic inactivation ($\tau_{inac}$) at supra-threshold potentials. Fig. 7 A shows that AA does not affect the voltage dependency of the time constant of deactivation of $\alpha_{TG}$ ($\tau_{deac}$). On the other hand, AA decreased the time constant of tail current decay at potentials positive to the activation threshold, accordingly with the effects observed for the time constant of macroscopic inactivation (Fig. 4 E). Application of 3 μM AA decreased the amplitude of tail currents to ~50% without significant effects on the rectification pattern or the reversal potential of the channels (Fig. 7 B). This indicates that AA does not interact with the open state of the channel so as to affect its macroscopic conduction properties.

Two Components of AA Effect on the Gating of $\alpha_{TG}$

The observations that AA significantly inhibited the current at a holding potential of −110 mV, but did not
Figure 7. AA does not modify the deactivation or the macroscopic conduction properties of \( \alpha_{G} \). (A) Average time constant of the decay (\( \tau_{\text{decay}} \)) of tail currents through \( \alpha_{G} \) in control (filled squares) and in the presence of 3 mM AA (open circles) \( (n = 7) \). The inset in the upper left corner shows the voltage protocol used. The exponential phase at potentials negative to the activation threshold corresponds to the voltage dependence of the time constant of deactivation. The plateau phase at potentials positive to the activation threshold corresponds to the time constant of inactivation from the open state. The continuous lines represent the fit with the kinetic model described in Discussion. The inset in the bottom right corner shows examples of tail currents recorded at \(-80\) mV, fit by single-exponential functions, in control and in the presence of AA (*). (B) Amplitude of tail currents evoked in control (filled squares) or in the presence of AA (open circles). For each cell, the amplitudes were normalized to the values at \(-80\) mV. The triangles represent the amplitudes obtained in the presence of AA but normalized with respect to the values at \(-80\) mV in control. The inset zooms in on the range from \(-80\) to \(-90\) mV and shows the fit of the data with the function \( I_{\text{tail}} = I_{\text{tail}}(V) \) (see Materials and Methods). The parameters used to describe the rectification pattern and the reversal potential were not significantly different between control: \( b = -120 \pm 13\) mV, \( c = (7.2 \pm 0.9) \times 10^5\) mV, and \( V_r = 42 \pm 3\) mV; and in the presence of AA: \( b = -120 \pm 20\) mV, \( c = (0.0 \pm 1.2) \times 10^5\) mV, and \( V_r = 38 \pm 5\) mV.

Figure 8. The AA-induced changes in current amplitude and in the onset of inactivation have different time courses. (A) Time course of the amplitude of currents through \( \alpha_{G} \), evoked by pulses to \(-20\) mV that were applied alternatively from a holding potential of \(-110\) mV (I\(_1\), circles) or from a 120 ms–lasting pulse to \(-75\) mV (I\(_2\), squares) (see inset). To estimate the time course of the onset of inactivation, both datasets were homogenized in time by linear interpolation between each pair of consecutive points. For each cell, the values were normalized with respect to the maximal peak current amplitude in control condition. (B) Increase of the fraction of inactivated channels (Onset) by the application of AA. The inset plots the values of Onset versus the amplitude of currents evoked from the holding potential of \(-110\) mV (I\(_1\)), corresponding to the same time points. The changes of Onset do not strictly correlate with the changes in peak current amplitude. (C) Time course of the time constant of inactivation from the open state. The inset shows that the AA-induced changes in \( \tau_{\text{inac}} \) correlate with the changes in current amplitude. The continuous lines represent the fit of time courses of I\(_1\), Onset, and \( \tau_{\text{inac}} \) in the presence of AA by single exponential functions.

Affect the steady-state inactivation (Fig. 4 C) or the recovery (Fig. 6) at this potential, indicate that the modified gating properties are not the main cause of channel inhibition at \(-110\) mV and may suggest that both effects of AA are unrelated. In a way to test this hypothesis we determined whether the current inhibition was temporally correlated with the modification of the inac-
Arachidonic Acid Modulation of Cav3.1 Activation Kinetics. Fig. 8A shows the time course of the amplitude of currents evoked by depolarizing pulses to −20 mV that were applied every 5 s, alternatively from a holding potential of −110 mV (I1) or from a preceding 120 ms–lasting pulse to −75 mV (I2). The data points represent interpolated current amplitudes normalized to the maximal current evoked from −110 mV under control condition in each cell. The depolarization to −75 mV, which inactivates a fraction of closed channels, accelerates the time course of AA current inhibition. If we calculate the fraction of inactivated channels at the end of the −75-mV prepulse, which we quantify as Onset(t) = 1 − I2/I1, it becomes clear that this fraction increases during exposure to AA. This increase occurred with a time constant \( \tau_{onset} = 14 ± 2 \) s, which is smaller than that for the inhibition of the current evoked from −110 mV (\( \tau_{inh} = 57 ± 2 \) s), indicating that the changes of current amplitude and of the rate of inactivation from closed states are temporally distinct (see inset). In contrast, the time course of the rate of inactivation from the open state (\( \tau_{inac} = 37 ± 2 \) ms; Fig. 8C) correlates well with that of the reduction in current amplitude.

AA Interacts with Both Resting and Inactivated States of α1G

To test if the interaction of AA with α1G is state dependent, we used the following protocol. First, current amplitude was monitored in control by repetitive depolarizations from −100 to 0 mV. Stimulation was then stopped and cells were incubated with 3 μM AA for 3 min, during which the membrane potential was clamped at either −100 or 0 mV ([Ca^{2+}]_{ext} = 20 mM). Stimulation was then resumed with the same protocol.
used in control. Tonic inhibition was estimated from the comparison of the peak current in control and the peak current in the first pulse after resuming stimulation. We observed a tonic inhibition of 32 ± 5% (n = 5) and 39 ± 4% (n = 3) for perfusion periods at −100 and 0 mV, respectively, and no further significant decrease of current amplitude. The values of tonic inhibition were not significantly different to the level of steady-state inhibition by AA during repetitive stimulations (37 ± 5%; n = 8).

Molecular Determinants of Macroscopic Inactivation of \( \alpha_{1G} \) Modulate the Inhibition by Arachidonic Acid

The results described above indicate that AA modifies the inactivation of \( \alpha_{1G} \). This suggested to us that \( \alpha_{1G} \) mutants that show slowed macroscopic inactivation (Marksteiner et al., 2001; Staes et al., 2001) might display different sensitivity to AA. Fig. 9 A shows a representation of the structure of \( \alpha_{1G} \) and the mutants investigated. GC1G is a chimera in which the last 409 amino acids of \( \alpha_{1G} \) are replaced by the amino acids 1540–2166 of \( \alpha_{1C} \). This chimera conserves the first 23 amino acids of the COOH terminus we have previously reported to be necessary for fast inactivation of \( \alpha_{1G} \) (Staes et al., 2001). In GC1G and GC1C, the first 23 amino acids of the COOH terminus of \( \alpha_{1G} \) were substituted by the corresponding stretch of \( \alpha_{1C} \) or deleted, respectively. Marksteiner et al. (2001) described what they called a “hot spot” of determinants of fast inactivation in the S6 segment of the third domain of \( \alpha_{1G} \). To diversify the structural determinants of fast inactivation to be tested for AA sensitivity, we also studied the mutant M1510I, which shows an ~10-fold decrease in the rate of macroscopic inactivation with respect to \( \alpha_{1G} \).

Fig. 9 B shows examples of the inhibition of currents through \( \alpha_{1G} \) and the slow-inactivating mutants GC1G, GC1C, and M1510I by 3 μM AA. All these mutants were inhibited faster and to a larger extent than \( \alpha_{1G} \) (Fig. 9, C and E). The higher sensitivity of slow-inactivated mutants was confirmed by the comparison of the dose–response curves (Fig. 9 D). The values of \( EC_{50} \) and Hill coefficient (N) for GC1G, GC1C, and M1510I were significantly lower than for the wild type (Fig. 9 F). Notably, the GC1C mutant, which inactivates as fast as \( \alpha_{1G} \) (Staes et al., 2001), showed a nearly identical sensitivity to that of the wild type. Taken together, these data suggest that the AA sensitivity is modulated by the structural determinants of fast inactivation of \( \alpha_{1G} \).

A typical feature of the modulation of T-type channels is the decrease of the time constant of inactivation. Remarkably, \( \alpha_{1G} \) and the GC1C4 mutant showed similar reduction of this parameter with increasing doses of AA (Fig. 9 G). The effective concentration and the Hill coefficient describing the pooled data of both channels were 2.4 ± 1.2 μM and 1.5 ± 0.8, respectively. In contrast, AA did not affect the time constant of inactivation of any of the slow-inactivating mutants (Fig. 9 G), indicating that the increase of the rate of inactivation from the open state is not a determinant for AA-induced inhibition.

Discussion

In the present study we investigated the mechanism of modulation of \( \alpha_{1G} \) by arachidonic acid as an essential step in understanding its influence on the physiology of T-type channels. To our knowledge, this is the first study applying model simulations to provide for a mechanism of AA modulation of the gating of a voltage-dependent channel and to address directly the structural determinants of AA interaction with voltage-dependent Ca2+ channels. We demonstrate that AA can inhibit \( \alpha_{1G} \) currents directly, by exerting two independent effects, (a) reducing channel availability and (b) shifting the voltage dependence of the steady-state inactivation to more negative potentials. We also show that AA interacts with \( \alpha_{1G} \) in both resting and inactivated states and that structural determinants of inactivation modulate the affinity for AA.

We show that AA effects on \( \alpha_{1G} \) are ~10-fold faster and more potent than those reported for \( \alpha_{1M} \) (Zhang et al., 2000). This difference is probably due to an \( \alpha_{1} \) subunit specificity of AA effects. Schmitt and Meves (1995) reported that in the NG108-15 cell line, which mainly expresses \( \alpha_{1M} \) (Chemin et al., 2002), AA produced a continuous and slow decrease of T-type current amplitude with a similar range of potency (25–100 μM) to that observed by Zhang et al. (2000). In contrast, Chesnay-Marchais and Fritsch (1994) showed that the effects of 2–10 μM AA on the T-type currents of rat osteoblastic cells, which mainly express \( \alpha_{1C} \) (Gu et al., 1999), developed within a few minutes, more like the results presented here.

AA Interacts with \( \alpha_{1G} \) in a Membrane-delimited Fashion

To fully understand the mechanism of AA inhibition it is important to know whether AA and/or some of its metabolites or PKC activation are responsible for this effect. Zhang et al. (2000) showed that the inhibition of the T-type channel subunit \( \alpha_{1M} \) is partially antagonized by the preincubation with the epoxygenase inhibitor 17-ODYA or by the intracellular perfusion of a PKC inhibitor. However, Park et al. (2003) reported the absence of inhibitory effects of PKC in the three T-type isoforms when expressed in HEK-293 cells. We confirmed this result for \( \alpha_{1G} \) (unpublished data). Our data indicate that AA is directly responsible for the decrease of the \( \alpha_{1G} \) current, as the application of 17-ODYA and ETYA, a nonmetabolizable analogue and inhibitor of the AA metabolism, did not influence the inhibition by...
Kinetic Modeling

Currently available information on the effects of AA on the gating properties of T-type channels is scarce and does not provide solid support to previous hypotheses on the mechanism of modulation (see Introduction). We therefore studied the effect of AA on the voltage dependencies of activation and steady-state inactivation, the rate of inactivation from open and closed states, the recovery from inactivation, the deactivation, and on the macroscopic conduction properties of the T-type channel \( \alpha_{1G} \). To analyze these data in a compact and consistent way we used a Markov model that describes the gating properties of \( \alpha_{1G} \) (Fig. 10), following a similar approach to that previously used to study the effects of extracellular pH and Ca\(^{2+} \) concentration (Talavera et al., 2003a) and mutations in the selectivity filter (Talavera et al., 2003b) on the gating properties of \( \alpha_{1G} \). Table I lists the optimal values of model parameters that describe the data in control and in the presence of 3 \( \mu \)M AA.

AA (see also Schmitt and Meves, 1995). It could be also speculated that AA acts through its conversion to anandamide via the reverse mode of fatty acid amide hydrolase (FAAH). However, this hypothesis can be rejected as AA has stronger effects on \( \alpha_{1G} \) than anandamide (Chemin et al., 2001; see below). Furthermore, AA was able to inhibit \( \alpha_{1G} \) in cell-free inside-out patches with similar potency and time course to those observed in whole-cell experiments. In addition, FAAH is not expected to produce anandamide from AA in inside-out patches given the lack of ethanolamine in the bath solutions (Arreaza et al., 1997). In summary, we demonstrated that AA inhibits \( \alpha_{1G} \) channels in a membrane-delimited manner, though it remains to be elucidated whether this action is exerted by binding to the protein itself or, indirectly, by modifying the lipid environment.

Modulation of \( \alpha_{1G} \) Gating by AA: Mechanistic Insights from Kinetic Modeling

Currently available information on the effects of AA on the gating properties of T-type channels is scarce and does not provide solid support to previous hypotheses on the mechanism of modulation (see Introduction). We therefore studied the effect of AA on the voltage dependencies of activation and steady-state inactivation, the rate of inactivation from open and closed states, the recovery from inactivation, the deactivation, and on the macroscopic conduction properties of the T-type channel \( \alpha_{1G} \). To analyze these data in a compact and consistent way we used a Markov model that describes the gating properties of \( \alpha_{1G} \) (Fig. 10), following a similar approach to that previously used to study the effects of extracellular pH and Ca\(^{2+} \) concentration (Talavera et al., 2003a) and mutations in the selectivity filter (Talavera et al., 2003b) on the gating properties of \( \alpha_{1G} \). Table I lists the optimal values of model parameters that describe the data in control and in the presence of 3 \( \mu \)M AA.

Given the absence of any indication that AA might alter the size of the gating charges (\( q_{1} - q_{3} \)), these values were fixed to those obtained for control. Changes in the coupling between the local fields sensed by the gat-

![Figure 10](https://example.com/figure10.png)

**Figure 10.** Kinetic model used to describe the gating properties of \( \alpha_{1G} \) in control and in the presence of AA. At very negative potentials, the channels are in the resting state, in equilibrium between the closed state \( C_{1} \) and the inactivated state \( I_{1} \). Given a supra-threshold depolarization, T-type channels undergo a sequence of transitions between closed states (\( C_{1} - C_{3} \)) and eventually transit through an open state (\( O \)) before accumulating in a nearly absorbing inactivated state (\( I_{0} \)) (Droogmans and Nilius, 1989; Chen and Hess, 1990). The thick arrows represent the voltage-dependent transitions. The dashed arrows indicate the transitions for which the rate at 0 mV is significantly (approximately twofold) increased (\(+\)) or decreased (\(\sim\)) by AA, respectively. The decrease in the rate of the transition \( C_{3} \rightarrow C_{2} \) predicts the slight increase in activation near the threshold (Fig. 4 C). The increase of \( k_{C1} \) and \( k_{CB} \) results in the decrease in current amplitude (Fig. 4 B) due to a reduction in channel availability. Modifications of the transitions between inactivated states in the forward (activation) direction explain the shift of the inactivation curve to more negative potentials (Fig. 4 G) and the modifications in the rates of inactivation from closed states (Fig. 5) and of recovery from inactivation (Fig. 6). Changes in the rates \( k_{DC} \) at \( k_{Ca} \) and \( k_{O} \) resulted from the constraint of the model with the principle microscopic reversibility applied for each box of the model.
ing charges and the membrane potential (\(\delta_1-\delta_3\)) did not improve the fit of the data obtained in AA. AA shifts the foot of the activation curve of \(\alpha_{1G}\) to more negative potentials (Fig. 4 C). This can be accounted for by varying the rate constant of the transitions between the closed states of the activation pathway, especially by decreasing \(K_{3G2}\) (Table I and Fig. 10). Interestingly, this result may also explain the observations of Zhang et al. (2000), who described the effects on the activation curve of the T-type channel \(\alpha_{1H}\) as an increase of the slope factor. More dramatic shifts in the activation curve of T-type channels were described previously (Chesnoy-Marchais and Fritsch, 1994; Schmitt and Meves, 1995), and also for high voltage–activated Ca\(^{2+}\) channels (Barrett et al., 2001; Liu et al., 2001) and Na\(^+\) channels (Lee et al., 2002). On the other hand, AA had no significant effect on the deactivation properties of \(\alpha_{1G}\) (Fig. 7), indicating that it does not affect the transition from the open to the nearest closed state (O \(\rightarrow\) C5; Fig. 10).

In contrast, AA profoundly modified the inactivation properties by shifting the voltage dependence of steady-state inactivation by \(\sim 13\) mV to more negative potentials (Fig. 4 C), an effect that was reflected in the voltage dependence of the recovery from inactivation (Fig. 6 E). However, AA only slightly increased the rate of inactivation from closed states (onset of inactivation) and decreased the rate of recovery from inactivation at \(-80\) mV (Fig. 5 D and inset of Fig. 6 C). These results can be explained by a slight increase of the rate of the transition I1 \(\rightarrow\) I2 and a more pronounced increase of the rate of transition I2 \(\rightarrow\) I3, which were partially balanced by a decrease of the rate of the transition I3 \(\rightarrow\) I6 (Table I and Fig. 10). We propose that the increase in the rate of transitions between inactivated states in the forward (activation) direction is the basis of the negative shift of the inactivation curve induced by AA and related compounds in voltage-dependent Na\(^+\) (Fraser et al., 1993; Xiao et al., 1995; Vreugdenhil et al., 1996; Bendahhou et al., 1997; Lee et al., 1999, 2002; Leifert et al., 1999) and Ca\(^{2+}\) channels (Chesnoy-Marchais and Fritsch, 1994; Schmitt and Meves, 1995; Petit-Jacques and Hartzell, 1996; Unno et al., 1996; Zhang et al., 2000; Chemin et al., 2001).

We also observed a decrease of the time constant of macroscopic inactivation (\(\tau_{\text{inact}}\)), but in contrast with Zhang et al. (2000), AA did not affect the voltage sensitivity of this parameter but induced a more uniform reduction over the whole voltage range. This is accounted for by an \(\sim 14\%\) increase in the rate of the transition between the open state and the nearest inactivated state (O \(\rightarrow\) I6; Table I).

One of the most important conclusions that can be derived from the experimental data and the kinetic modeling is that the decrease in current amplitudes for depolarizations from a holding potential of \(-110\) mV (Fig. 4 B) cannot be explained by any of the AA effects on macroscopic gating we observed. Our results demonstrate that this decrease does not result from the modification of the conduction properties of \(\alpha_{1G}\) since AA did not change the unitary current and did not significantly modify the rectification pattern of the open pore conduction or the reversal potential of \(\alpha_{1G}\). Notably, AA did not affect the unitary conductance of Ca\(^{2+}\) (Liu and Rittenhouse, 2000), Na\(^+\) (Xiao et al., 1995; Bendahhou et al., 1997), Cl\(^-\) (Anderson and Welsh, 1990; Hwang et al., 1990), K\(^+\) (Brinngmann et al., 1998; Devor and Frizzell, 1998), and NMDA receptor channels (Miller et al., 1992).

Single channel data from L-type Ca\(^{2+}\) channels of rat sympathetic neurons revealed that the AA-induced reduction of macroscopic current is due to an increased probability of null sweeps (Liu and Rittenhouse, 2000). Our results from inside-out patches are consistent with this mechanism (Fig. 3 B). Within this view, AA induces a fraction of channels to transit to a nonfunctional conformation or, alternatively, an increase in the rate of inactivation from closed states (Fig. 4 B and Table I). We denote, therefore, that AA exerts two different actions on the gating of \(\alpha_{1G}\): one on the transitions between inactivated states and another by which it decreases the fraction of channels that are available to open. The distinct time courses of the decrease of current amplitude and the increased inactivation from closed states (Fig. 8) provide further support for this contention. In addition, this observation indicates that the interaction of AA with the channel is in the range of several seconds, in contrast with the estimate of minutes obtained from the decrease of current amplitude.

We found that AA induced similar tonic inhibition after perfusion periods during which the membrane potential was held at \(-100\) or 0 mV. This proves that AA interacts indistinctively with both the resting and inactivated states of \(\alpha_{1G}\). The analysis of the data by model simulations indicates, however, that this interaction only alters certain gating transitions.

**Molecular Determinants of Macroscopic Inactivation**

Modulate AA Sensitivity

AA effects on the inactivation properties of \(\alpha_{1G}\) suggested us to test the effects of AA on several slow-inactivating mutants of \(\alpha_{1G}\) (Fig. 9 A) (Marksteiner et al., 2001; Staes et al., 2001). Remarkably, all of them showed an enhanced AA sensitivity with respect to \(\alpha_{1G}\). Furthermore, the GC\(\Delta C_4\) chimera, with a major modification in the COOH terminus but the same fast-inactivation pattern as the wild-type \(\alpha_{1G}\) (Staes et al., 2001), showed a similar sensitivity to that of \(\alpha_{1G}\). To explain these results, it could be envisaged that AA inhibits preferentially noninactivated channel conformations.
However, this is contradicted by the absence of inhibition of wild-type currents at potentials at which there is a relatively slow rate of inactivation (i.e., close to the activation threshold; Fig. 4 B) and by the tonic inhibition observed after AA was applied at 0 mV (channels in the inactivated state). The simplest explanation for these observations is that the mutations we studied induce an increase in the affinity of a putative AA–channel interaction, independently of the effects on the rate of macroscopic inactivation.}

Further analysis of the data obtained for the mutant channels allows us to extract some complementary conclusions. First, the AA–channel interaction is not determined by the specific sequence of the last 409 amino acids of the COOH terminus of α1G. Second, AA does not significantly inhibit α1G by acting on the open state, since it does not modify the rate of inactivation from the open state in the slow-inactivating mutants, in contrast to the case of α1G and the GCΔC4 chimera. And third, the faster inhibition observed for the slow-inactivating mutants (Fig. 9 C) indicates that channel conformation is an important determinant of the rate of inhibition, in contrast with the hypothesis of slow metabolism of AA to other active compounds as the only cause of the slow action of AA (Zhang et al., 2000).

Interestingly, the structural determinants of modulation by AA or analogue compounds have been also mapped in S6 transmembrane segments in the human cardiac Na+ channel hH1α (Xiao et al., 2001) and the intermediate conductance Ca2+-activated K+ channel hIK1 (Hamilton et al., 2003) or in intracellular domains, NH2 terminus of ROMK1 (Macica et al., 1998), and COOH terminus of TREC-2 (Kim et al., 2001), TREC-1 (Patel et al., 1998; Maingret et al., 2000), and Kir3.4 (Rogalski and Chavkin, 2001). Given the low sequence analogy among these channels, including T-type channel α1G, it is likely that fatty acid–channel interactions are determined by analogous tertiary structures rather than by the presence of conserved consensus binding motifs.

Functional Relevance of AA Modulation of T-type Channels

AA is a ubiquitous second messenger that modulates a wide range of cellular processes (Piomelli, 1993). We have shown that AA directly inhibits the opening of α1G, which limits the contribution of this channel to the early depolarization phase in excitable tissues. In addition, AA significantly shifts the inactivation curve to more negative potentials without dramatic effects on the activation curve. Consequently, AA is expected to decrease the window current, thereby limiting the Ca2+ influx through α1G at basal membrane potentials in both nonexcitable and excitable tissues. Therefore, α1G is a possible target for AA-induced cytoprotection and decrease of neuronal and cardiac excitability. Indeed, in parallel to the action of some antiepileptic drugs (Huguenard, 1996; Heady et al., 2001), the inhibition of T-type currents due to accumulation of free AA (Bazan, 1989; Van der Vusse et al., 1997) may underlie a mechanism of protection against neuronal and cardiac damage during epileptic and ischemic episodes. Analogously, the antiarrhythmic (Kang and Leaf, 2000), bradycardic (Mullane et al., 1979), and hypotensive (Damas and Troquet, 1978; Lee and Murthy, 1979; Mullane et al., 1979) effects of AA may be partially due to the inhibition of T-type channels, but further investigation is required to support these hypotheses.

Chemin et al. (2001) reported the inhibition of recombinant and native T-type channels by the endocannabinoid anandamide (AEA) and discussed the possible significance of this modulation in the mechanisms of slow-wave sleep, epilepsy, nociception, heart pacemaking, and cellular proliferation and development. These authors argued for a direct effect of AEA on T-type channels. However, we show here that the product of AEA hydrolysis via the action of FAAH, AA, also has an inhibitory effect on α1G. In fact, in addition to the negative shift of the inactivation curve, AA inhibits this channel at very negative holding potentials, in contrast to the observations with AEA. Chemin et al. (2001) showed that 3 μM AEA produces ~40% inhibition of α1G current amplitude at a holding potential of −80 mV, while we predict that, at the same concentration, AA induces a 90% inhibition at this holding potential. This indicates that after AEA hydrolysis, the effect on α1G is enhanced through the action of AA. In contrast, comparison with studies on α1H (Schmitt and Meves, 1995; Zhang et al., 2000) suggests that hydrolytic function of FAAH attenuates the effects of AEA, due to the relatively lower sensitivity of this channel to AA.

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