G-protein–gated TRP-like Cationic Channel Activated by Muscarinic Receptors: Effect of Potential on Single-channel Gating

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ABSTRACT There is little information about the mechanisms by which G-protein–coupled receptors gate ion channels although many ionotropic receptors are well studied. We have investigated gating of the muscarinic cationic channel, which mediates the excitatory effect of acetylcholine in smooth muscles, and proposed a scheme consisting of four pairs of closed and open states. Channel kinetics appeared to be the same in cell-attached or outside-out patches whether the channel was activated by carbachol application or by intracellular dialysis with GTPyS. Since in the latter case G-proteins are permanently active, it is concluded that the cationic channel is the major determinant of its own gating, similarly to the K_{Ca} channel (Ivanova-Nikolova, T.T., and G.E. Breitwieser, 1997, J. Gen. Physiol. 109:245–253). Analysis of adjacent-state dwell times revealed connections between the states that showed features conserved among many other ligand-gated ion channels (e.g., nAChR, BK_{Ca} channel). Open probability (P_{o}) of the cationic channel was increased by membrane depolarization consistent with the prominent U-shaped I-V relationship of the muscarinic whole-cell current at negative potentials. Membrane potential affected transitions within each closed-open state pair but had little effect on transitions between pairs; thus, the latter are likely to be caused by interactions of the channel with its ligands, e.g., Ca^{2+} and Goα-GTP. Channel activity was highly heterogeneous, as was evident from the prominent cycling behavior when P_{o} was measured over 5-s intervals. This was related to the variable frequency of openings (as in the K_{Ca} channel) and, especially, to the number of long openings between consecutive long shuttings. Analysis of the underlying Markov chain in terms of probabilities allowed us to evaluate the contribution of each open state to the integral current (from shortest to longest open state: 0.1, 3, 24, and 73%) as P_{o} increased 525-fold in three stages.

KEY WORDS: Markov chain • channel kinetics • G-protein • carbachol • smooth muscle

INTRODUCTION

Many cell-surface receptors perform their intracellular communication functions by changing the activity, either opening or closing, of various ion channels. Mechanisms of gating of some ionotropic receptors in which agonist binding site(s) and ion channel pore are located within the same protein complex are now well understood, particularly in the case of the skeletal muscle nicotinic acetylcholine receptor (nAChR) (Edmonds et al., 1995). Appropriate models have been developed as an extension of an early scheme of del Castillo and Katz (1957) that now provide a physically realistic picture of how ligand binding could change receptor-conducting conformation (Colquhoun and Sakmann, 1998). These reaction mechanisms, also often referred to as kinetic models of ion channels, allow a physically meaningful interpretation of single-channel activity and a useful explanation of the whole-cell current behavior and physiological function (Pallotta, 1997).

The much larger and diverse superfamily of seven transmembrane spanning receptors produce signals to a variety of effectors, e.g., enzymes and ion channels, via G-proteins (for reviews see Gilman, 1987; Wickman and Clapham, 1995). However, much less is known about the interactions and mechanisms which lead to channel opening in these complex multi-component signaling systems.

One level of complexity arises due to the multisignaling nature of G-protein–coupled receptors (GPCRs), since both Goα-GTP and Gβγ subunits may have separate, sometimes opposite, functions (Hamm, 1998). An added level of complexity arises as multiple receptor subtypes for the same agonist are often coexpressed in the same tissue. These can converge to activate the

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Abbreviations used in this paper: ACh, acetylcholine; GPCR, G-protein–coupled receptor; mAChR, muscarinic receptor; nAChR, nicotinic acetylcholine receptor; TRP, transient receptor potential.
same channel in a subtype-specific manner depending on which type of G-protein is involved.

The muscarinic receptor–operated cationic channel, the subject of our present study, exemplifies such complexity of GPCR signal transduction. This cationic channel is widely expressed in various smooth muscle tissues such as the gastrointestinal tract and airways, where it mediates the excitatory action of acetylcholine (ACH). Two muscarinic receptor (mAChR) subtypes, M2 and M3, are colocalized in the same tissues (Eglen et al., 1996). We found that although M2 receptor activation primarily causes activation of the channel, the M3 subtype plays an important “permissive” role (Bolton and Zholos, 1997; Zholos and Bolton, 1997). Thus, both receptor subtypes control the channel opening. Further studies have shown that, consistent with early reports of the inhibitory action of Pertussis toxin treatment on the mAChR cationic current (mI_{CAT}) (Inoue and Isenberg, 1990a; Komori and Bolton, 1990), the channel is coupled to the muscarinic receptor via Gαo protein (presumably an M2 effect) (Yan et al., 2003), whereas PLC inhibition also abolishes mI_{CAT} (presumably an M3 effect) (Zholos et al., 2004).

Furthermore, intracellular Ca^{2+} was shown to have both a permissive and a potentiating effect on channel opening (Inoue and Isenberg, 1990c; Wang et al., 1997); hence, a rise in [Ca^{2+}] is necessary but not sufficient to activate mI_{CAT}. This results in a close, almost mirror, correlation between [Ca^{2+}], level and whole-cell current amplitude (Pacaud and Bolton, 1991; Komori et al., 1993; Gordienko et al., 1999).

Moreover, the current shows an intrinsic voltage-dependent behavior (Benham et al., 1985; Inoue and Isenberg, 1990b), such that in the presence of the agonist membrane hyperpolarization can strongly attenuate the current, but in its absence even strong depolarization does not produce any detectable channel activation. A close and intriguing relationship exists between G-protein control and intrinsic voltage dependence of this channel. Thus, increasing the agonist concentration shifts the activation curve up to 40 mV negatively (Zholos and Bolton, 1994), whereas desensitization has an opposite effect (Zholos and Bolton, 1996). Membrane depolarization, in turn, has a strong sensitizing effect on channel opening (e.g., shifting the membrane potential from −50 to 50 mV reduces the carbachol EC_{50} value 20-fold), reduces latency of the response from 380 to 160 ms, and accelerates on-rate and decelerates off-rate during fast agonist application and removal (Bolton and Zholos, 2003).

These various observations at present are hard to reconcile within a general mechanism. The major obstacle is the lack of information on single-channel gating. In earlier reports, this cationic channel proved to be difficult to investigate in excised membrane patches. Therefore, channel activity was resolved in the so-called “magnified whole-cell mode” (Inoue et al., 1987; Kang et al., 2001), which provided initial valuable information on channel conductance, selectivity, and voltage dependence of its open probability (P_o), but channel kinetic states still needed to be studied at higher resolution. At present only a simplified two-state model is available (Inoue et al., 1987; Inoue and Isenberg, 1990b).

Here, we sought to answer—by studying single cationic channel kinetics—the many questions that arise due to the complex nature of whole-cell mI_{CAT}. This analysis was significantly facilitated by the possibility of obtaining outside-out patches in which only one channel was present. Our analysis revealed that channel activity was much more complex than previously thought, e.g., at least four open and four closed states exist with additional flicker and inactivated states. The molecular structure of this cationic channel remains incompletely defined but it may be a homo- or a heteromultimer of transient receptor potential (TRP) proteins (Walker et al., 2001; Lee et al., 2003). For this novel family of channel proteins the gating stimuli and mechanisms remain largely unknown (Clapham, 2003). We found that cationic channel activity consists of bursts of short, intermediate, and long openings with strong correlations between adjacent states. Based on this, we also tested some predictions for the whole-cell mI_{CAT} behavior.

**MATERIALS AND METHODS**

**Cell Preparation and Current Recording**

Adult male guinea-pigs, weighing 300–400 g, were killed by dislocation of the neck followed by immediate exsanguination according to Schedule one of the UK Animals (Scientific Procedures) Act (1986). Single smooth muscle myocytes from the longitudinal muscle layer of the ileum were obtained after collagenase treatment as previously described (Zholos and Bolton, 1994, 1997).

Whole-cell and single-channel currents were recorded at room temperature using borosilicate patch pipettes of 1–3 and 3–5 MΩ, respectively, and an Axopatch 200B (Axon Instruments, Inc.) voltage-clamp amplifier. For single-channel recordings pipettes were coated with Dow Corning R-6101 elastomer. Current noise was <0.25 pA (rms, 5 kHz bandwidth). Voltage-clamp pulses were generated and data were captured using a Digidata 1322A interfaced to a computer running the pClamp 8 program (Axon Instruments, Inc.). Currents were filtered using the 4-pole low pass Bessel filter of the patch-clamp amplifier at 1 or 2 kHz in whole-cell and single-channel recordings, respectively, and sampled at 48 kHz for storage on a digital tape recorder (DTR-1204; Biologic Science Instruments). In whole-cell experiments series resistance was compensated by 80%. For illustrations, single-channel recordings were digitally filtered (200 Hz lowpass Gaussian filter) and sampled at 500 Hz. Extended portions of the traces that illustrate brief events are shown at the original resolution.

mI_{CAT} was activated by applying carbachol at 50 μM (submaximal concentration, compare with the EC_{50} value of 7.6 μM; Zho-
Los and Bolton, 1997) or by intracellular application of GTP$\gamma$S at 200 μM by adding it to the pipette solution in order to activate G-proteins directly, bypassing muscarinic receptors.

**Solutions and Chemicals**

The external solution in which cationic current was recorded consisted of (in mM): CsCl 120, glucose 12, HEPES 10, pH adjusted to 7.4 with CsOH (total Cs$^+$ 124 mM). Pipettes were filled with the following solution (in mM): CsCl 80, adenosine 5’-triphosphate magnesium salt (ATP) 1, creatine 5, guanosine 5’-phosphate lithium salt (GTP) 1, D-glucose 5, HEPES 10, BAPTA 10, CaCl$_2$ 4.6 ([Ca$^{2+}$], clamped at 100 mM), pH adjusted to 7.4 with CsOH (total Cs$^+$ 124 mM). GTP was omitted when guanosine 5’-O-(3-thiotriphosphate) (GTP$\gamma$S) was added to the pipette solution to activate mICAT directly. The Cs$^+$ solutions were used to block currents through potassium channels.

Collagenase (type 1A), adenosine 5’-triphosphate (ATP, magnesium salt), guanosine 5’-triphosphate (GTP, lithium salt), guanosine 5’-O-(3-thiotriphosphate) (GTP$\gamma$S, tetralithium salt), creatine, N,2-hydroxyethylpiperazine-N’N’-2-ethanesulfonic acid (HEPES), 1,2-bis(2-aminophenoxy)-ethane-N,N,N’,N’-tetraacetic acid (BAPTA), N-methyl-d-glucamine (NMDG), and carbamoylcholine chloride (carbachol) were obtained from Sigma-Aldrich. All other chemicals were from BDH Laboratory Supplies (AnalaR grade).

**Data Analyses**

Data were analyzed and plotted using pClamp (Axon Instruments, Inc.) and MicroCal Origin software (MicroCal Software, Inc.). For kinetics analyses, the presence of one channel in the membrane patch could be confidently judged since $P_{O}$ was high (0.43 ± 0.06 in 11 patches selected for kinetics analysis) and no double openings were seen. Quantitatively, the probability of our runs of single openings if there were actually two channels present was estimated according to the equation given by Colquhoun and Hawkes (1995):

$$P(t \geq n_o) = \pi^{n_o-1},$$

where $\pi = (1 - P_O)/(1 - P_O/2)$, and $n_o$ is the number of single openings. In the above 11 patches the maximum probability of more than one channel present was of the order $10^{-20}$.

Single-channel events were identified on the basis of the half-amplitude threshold-crossing criteria. Transitions <0.16 ms (e.g., rise time for 2 kHz filter, see Fig. 3 A, c) were ignored. This was aimed mainly to ensure consistent time resolution for both openings and shuttins. Imposed resolution in principal makes allowance for missed events but this was not used. Thus, "open" and "closed" intervals were "apparent" intervals.

Histograms of open and closed durations were constructed conventionally as distributions of the logarithm of duration (in ms) (20 bins per decade) with exponential components fitted by the method of maximum likelihood (Colquhoun and Hawkes, 1995). The frequency density and fitted functions were plotted after a square root transformation. The number of probability density function components was determined using the automatic "compare models" routine of the pClamp software at the confidence level of 0.99. Current amplitude histograms were fitted with Gaussian functions. Although four closed states of the channel exist, no burst analysis was done since burst definition would be dubious (e.g., ~10 or more-fold difference in the mean closed times is required).

$P_O$ was determined from idealized traces as the ratio of the sum of all open durations to the total trace duration. All other analysis (correlations, durations of adjacent dwell times, opening frequency analysis, and analysis of channel activity over intervals of certain duration) was done using custom programs.

Cationic conductance activation curves, or $P_O$ values measured at different test potentials, were fitted by the Boltzmann equation in the following form:

$$A = \frac{A_{\text{max}}}{1 + \exp[(V - V_{1/2})/k]},$$

where $A$ is either cationic conductance (Siemens) or $P_O$ at potential $V$ (volts); $A_{\text{max}}$ is its maximal value; $V_{1/2}$ is the potential at which $A = 0.5A_{\text{max}}$; and $k$ is the slope factor (volts).

For each particular state the probability of being in that state, $P_j$, was calculated using the following equation:

$$P_j = P_{\text{class}} \cdot \frac{A_j \cdot \tau_j}{\sum_{j=1}^{A_j} \cdot \tau_j},$$

where $P_{\text{class}}$ refers either to $P_O$ for open states or to 1 − $P_O$ for closed states, $A_j$ is the relative area under the $j$th exponential component, and $\tau_j$ is its time constant (mean dwell time).

Values are given as the means ± SEM; $n$ represents the number of measurements. To determine the statistical significance of differences between the means an ANOVA or a t test were used. Differences were judged to be statistically significant when $P < 0.05$.

**RESULTS**

**General Observations: Three Types of Muscarinic Receptor–gated Cationic Channels in Ileal Myocytes**

Under conditions optimal for activation and isolation of whole-cell mICAT (symmetrical 125 mM Cs$^+$ solutions, external 50 μM carbachol or internal 0.2 mM GTP$\gamma$S present) three types of ion channels have been identified in cell-attached ($n = 89$) and outside-out patches ($n = 123$) based on the differences in their unitary conductances, kinetics, and voltage dependence. Their ion selectivity properties were not studied in detail (see Inoue et al., 1987; Kang et al., 2001), but it was verified that their unitary currents depended on the Cs$^+$ (NMDG$^+$ substitution experiments) but not the Cl$^-$ (methanesulfonate substitution) gradient. Also, unitary currents through the three types of channels reversed close to the caesium equilibrium potential, 0 mV. Using Cs$^+$ as the main charge carrier suppressed currents trough K$^+$ channels while various TRP channels are similarly permeable to Na$^+$, K$^+$, and Cs$^+$ (for review see Nilius, 2003).

Mean single-channel conductances at potentials around −50 mV were 10.3 ± 0.2 pS ($n = 55$), 57.1 ± 7.0 pS ($n = 52$), and 131.8 ± 2.6 pS ($n = 51$). These three types of cationic channels were identified as channels gated by muscarinic receptor stimulation as Fig. 1 shows. They were also activated by G-proteins since intracellular GTP$\gamma$S (without agonist application) induced similar channel activation (e.g., Fig. 2).

Fig. 1 A illustrates an example of bath carbachol ap-
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Application on single-channel activity after a cell-attached patch was formed using 50 μM carbachol-containing patch pipette. As the bottom expanded trace segment in Fig. 1 A shows channel activity consisted of large and frequent but very brief transitions of 7 pA in maximal size produced by 130-pS channel openings (similar to that shown in Fig. 1 B); longer and hence better defined events of 3.1 pA in size (i.e., 62-pS conductance given the membrane potential of -50 mV) and small openings visible during a few periods of low activity as shown magnified in the inset. The latter were 0.7 pA in size (i.e., 14-pS channel conductance). In contrast, the activity of the 10- and 57-pS channels lasted tens of minutes after patch excision (Figs. 2, 3 A, 9, and 11 A) suggesting that freely diffusible second messengers are not so important for their gating. However, the 57-pS channel could rarely be activated in cell-attached patches (4 in 77) with carbachol in the pipette and/or in the bath (Fig. 1 A), or by carbachol when applied after an outside-out patch was formed (1 in 11). When a cell-attached patch was formed after cell dialysis with GTPγS (e.g., by using double-patch configuration, or by withdrawing a first patch pipette containing

In the experiment of Fig. 1 A the 130-pS channel activity lasted 17 min, but it was fairly quickly lost in outside-out patches (on average within 81 ± 19 s, n = 18; see top trace in Fig. 1 B showing two channels present initially which cease to open 164 s after carbachol application). This suggests the importance of some freely diffusible second messenger(s). 130-pS channel activity consisted of clear bursts of very brief openings as an expanded trace segment in Fig. 1 B shows, i.e., in this patch at -50 mV mean open times and relative proportions of two fitted exponential components were 0.75 ms (0.69) and 3.53 ms (0.31) resulting in a low P₀, typically <0.1. At positive potentials P₀ somewhat increased while single-channel conductance decreased (Fig. 1 B, bottom right), which resulted in average patch current being an almost linear function of voltage.

In contrast, the activity of the 10- and 57-pS channels lasted tens of minutes after patch excision (Figs. 2, 3 A, 9, and 11 A) suggesting that freely diffusible second messengers are not so important for their gating. However, the 57-pS channel could rarely be activated in cell-attached patches (4 in 77) with carbachol in the pipette and/or in the bath (Fig. 1 A), or by carbachol when applied after an outside-out patch was formed (1 in 11). When a cell-attached patch was formed after cell dialysis with GTPγS (e.g., by using double-patch configuration, or by withdrawing a first patch pipette containing
GTPγS and creating an on-cell patch on the same cell using another pipette) then the 57-pS channel activity was more likely (4 out of 12). A similar proportion was also observed when an outside-out patch was pulled after the whole-cell current had fully developed in response to 50 μM carbachol application (15 out of 50). Thus, it appears that important signaling links need to be established in the whole cell that then remain after patch excision. It is less clear why so few patches with channel activity were obtained in the conventional cell-attached configuration. Kang et al. (2001) noted the same difficulty (2 successful recordings out of 121 trials in their experiments).

In the present work the behavior of the 57-pS channel was analyzed in detail. We have found that this channel has properties that account for the major part of the whole-cell current in the negative range (see below); thus, from the standpoint of the physiological function of the muscarinic cationic conductance this channel type is the most important.

61% of outside-out patches formed after whole-cell mICAT activation were blank (33 out of 62 in case of GTPγS and 35 out of 50 in case of carbachol stimulation), 19.5% had one (12 out of 62 in case of GTPγS and 10 out of 50 in case of carbachol stimulation), and the remaining 19.5% had multiple active 57-pS channels (from 2 to 7; 17 patches out of 62 in the case of GTPγS and 5 patches out of 50 in the case of carbachol stimulation). In the latter case the probability of seeing 1,2,3...N channels simultaneously open followed a binomial distribution closely; thus, the channels gated independently of each other but at the same time they appeared to be clustered in the membrane.

Fig. 2 shows typical examples of single-channel currents activated by carbachol or GTPγS in outside-out and cell-attached patches, as indicated. The membrane potential of outside-out patches was held at −40 mV; the same value was assumed for the cell-attached patch since the holding potential was set at 40 mV and the cell was dialyzed and then kept in a high-Cs+ solution that would zero its resting potential.

One feature of channel activity was its quite remarkable “mirror” symmetry. For example, although channel openings produce downward deflections in the top and middle pairs of traces and upward deflections in the bottom pair of traces, visually it is hard to tell the difference between them. In other words, channel activity consisted of prolonged bursts of long openings interrupted by brief shuttings, prolonged long closed states interrupted mainly by brief openings, and a series of alternating medium durations opening and closings. Much of the analysis that follows was done to quantify these visual features. Some of this analysis (e.g., PO change in intervals or sequences of long openings and shuttings) was semiquantitative since a more precise burst analysis would be compromised by a poor separation of the mean closed times (see Table I).

Number of States and Connections Between Them (Markov Chain)

For detailed analyses of channel kinetics we selected one of the longest available records, which is shown in Fig. 3 A, a (326 s; outside-out patch was excised into 50 μM carbachol-containing solution after whole-cell carbachol-evoked mICAT had fully developed; holding potential was −50 mV). Afterwards, the conclusions were verified and overall mean dwell times and probabilities were calculated by analyzing ten more records in the same manner (mean record duration was 209 s).

In the record shown in Fig. 3, mean PO was 0.44. Before the channel became unavailable (desensitization at the single-channel level developed abruptly; not depicted) 9,012 transitions occurred, which was sufficient for a rigorous analysis of the channel kinetics. An all-point amplitude histogram (Fig. 3 B) reveals one major peak at −3.12 pA and additional peaks near the baseline level (−0.4 pA) and near the major open level.
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(-3.53 pA) as shown by the dotted lines. Thus, two types of cationic channels are present with conductances of 62 and 8 pS (horizontal bar above the record shows when the latter was particularly active). In fact, there were at least two 8-pS channels in this patch as judged from occasional double openings; the NPO value was 0.16. This example well illustrates the fact that the 10-pS channel, because of its much lower PO and unitary current amplitude, makes only a trivial contribution to mICAT (estimated at 4.84 ± 0.01% [n = 12] in the negative range of potentials). Fig. 3 A, b and c, shows short segments of recordings at a higher time resolution. The 190 ms shutting which was just above one rise time (160 ms) is well resolved. The expanded trace in Fig. 3 A, b, also illustrates that typically one or a few brief openings occurred before and immediately after the channel entered a period of gating characterized by long openings and brief closings.

### Table I

<table>
<thead>
<tr>
<th>State</th>
<th>Mean dwell time (ms)</th>
<th>Area of component relative to total shut or open time</th>
<th>Relative probability (P_J) of state</th>
<th>Contribution to integral current</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>471 ± 124</td>
<td>0.151 ± 0.023</td>
<td>0.431 ± 0.058</td>
<td>0.023</td>
</tr>
<tr>
<td>C2</td>
<td>58.7 ± 12.4</td>
<td>0.229 ± 0.008</td>
<td>0.119 ± 0.023</td>
<td>0.001</td>
</tr>
<tr>
<td>C3</td>
<td>4.66 ± 0.75</td>
<td>0.324 ± 0.022</td>
<td>0.015 ± 0.003</td>
<td>0.000</td>
</tr>
<tr>
<td>C4</td>
<td>0.66 ± 0.13</td>
<td>0.290 ± 0.021</td>
<td>0.002 ± 0.0004</td>
<td>0.001</td>
</tr>
<tr>
<td>O1</td>
<td>0.54 ± 0.10</td>
<td>0.136 ± 0.020</td>
<td>0.0006 ± 0.0001</td>
<td>0.1%</td>
</tr>
<tr>
<td>O2</td>
<td>5.43 ± 1.25</td>
<td>0.315 ± 0.023</td>
<td>0.013 ± 0.003</td>
<td>3.0%</td>
</tr>
<tr>
<td>O3</td>
<td>46.6 ± 15.6</td>
<td>0.289 ± 0.035</td>
<td>0.104 ± 0.037</td>
<td>24.1%</td>
</tr>
<tr>
<td>O4</td>
<td>190 ± 43</td>
<td>0.257 ± 0.034</td>
<td>0.315 ± 0.043</td>
<td>72.8%</td>
</tr>
</tbody>
</table>

Mean values for each state are the average of 11 measurements from outside-out (n = 9) and cell-attached (n = 2) patches expressing one channel activated either by carbachol (n = 3) or by direct G-protein activation with GTPyS (n = 8). Mean PO was 0.432 ± 0.057 (n = 11). Mean probabilities of channel being in each of its states (P_J) were calculated using Eq. 3. Contribution of each open state to the whole-cell mICAT was calculated based on these values. Probabilities and time constants of separate shut and open states were not significantly different for carbachol- and GTPyS-induced channel activities (two-tailed P values ranged from 0.15 to 0.96).

Figure 3. Cationic channel activity recorded after patch excision into 50 μM carbachol-containing solution after whole-cell mICAT had fully developed. (A, a) 326-s continuous recording divided into nine consecutive traces. The horizontal bar indicates a period when the 8-pS channel was particularly active. A, b, shows an extended segment. The box is shown further expanded in A, c (some brief event durations are indicated). Note that the 190-μs closing can be reliably detected. Holding potential was -50 mV. All-point (B) and fitted-levels (C) amplitude histograms were fitted with Gaussian functions (superimposed lines). In the latter case, events shorter than twice the rise time (0.33 ms) were excluded from the amplitude analyses. Note that smaller peaks adjacent to the two major peaks are evident in the all-point amplitude histogram (B); these represent 8-pS channel activity (at least two small conductance channels were present in this patch). Also note, that full width at half-maximum (FWHM) is larger for the distribution of open level amplitudes indicating more current noise when the channel is open.

Figure 3. Cationic channel activity recorded after patch excision into 50 μM carbachol-containing solution after whole-cell mICAT had fully developed. (A, a) 326-s continuous recording divided into nine consecutive traces. The horizontal bar indicates a period when the 8-pS channel was particularly active. A, b, shows an extended segment. The box is shown further expanded in A, c (some brief event durations are indicated). Note that the 190-μs closing can be reliably detected. Holding potential was -50 mV. All-point (B) and fitted-levels (C) amplitude histograms were fitted with Gaussian functions (superimposed lines). In the latter case, events shorter than twice the rise time (0.33 ms) were excluded from the amplitude analyses. Note that smaller peaks adjacent to the two major peaks are evident in the all-point amplitude histogram (B); these represent 8-pS channel activity (at least two small conductance channels were present in this patch). Also note, that full width at half-maximum (FWHM) is larger for the distribution of open level amplitudes indicating more current noise when the channel is open.
Histograms of distributions of apparent closed and open times (20 bins per decade) measured in the experiment of Fig. 3 A are shown in Fig. 4 A. These were fitted with the sum of four exponential components (continuous line, the components are plotted separately). In this and other similar figures mean dwell times and relative areas, which are equivalent to frequency probabilities of being in a particular state, are indicated near each component. Thus, as long as different mean dwell times may be regarded as reporters of different conformations of the channel protein there are at least four open and four closed states of the channel. A model with four open and four closed states will be assumed and used as a basis for further analysis (Scheme I) while accepting that minor contribution by additional states may exist that cannot be detected due to limitations of frequency response of the recording system, and the fitting process/number of acquired events. The scheme is similar to the synergistic model of gating proposed for K<sub>ACh</sub> channel by Petit-Jacques et al. (1999), whereby ligands interacting with the channel increase its open probability in three stages. The overall structure of cationic channel Markov chain is similar to some other ion channels, such as nAChR (Scheme V given by Colquhoun [1998]), which includes spontaneous channel openings in the absence of agonist), BK<sub>Ca</sub> channel (Scheme II given by Cox et al. [1997]), or hyperpolarization-activated HCN channel (Altomare et al., 2001).

To reveal adjacent states in the model (Scheme I) durations of adjacent closed and open states were measured. Qualitatively, the plot of open intervals versus adjacent shut time in Fig. 4 B shows that with very few exceptions (6 out of 4,506) there is a strong inverse relationship between the duration of openings related to closed events. This is true for both next and previous open durations as illustrated in the insets. Quantitatively, these correlations were evaluated by measuring mean time of open events adjacent to closed durations in four ranges that corresponded to the time constants of four components of the closed time distribution (indicated by triangles in Fig. 5, the chosen range was ±5 bins around the corresponding mean closed time) as suggested by McManus et al. (1985). The differences between mean open times were statistically significant (note that different symbols show data calculated separately for previous, next and both adjacent open intervals). The histogram shown by the dotted line illus-
Fig. 5. Analyses of adjacent intervals. Histogram of distribution of closed durations is shown at the bottom for comparison (same as in Fig. 4 A, top) with the four ranges used for analysis indicated by the gray columns. Each range was centered (±5 bins) around a mean closed time (triangles). Thus, for τ1 = 0.68 ms the range was 0.382–1.21 ms; for τ2 = 5.19 ms: 2.92–9.25 ms; for τ3 = 64.8 ms: 36.4–115.2 ms; and for τ4 = 371 ms: 209–660 ms. The mean durations of previous (squares), next (diamonds), and both (circles) open intervals are plotted for each range. Since the intervals do not follow normal distribution, for assessment of the statistical significance of the differences a Kruskal-Wallis test (nonparametric ANOVA) was used which gave P < 0.0001. Dunn’s multiple comparisons test gave the P values as indicated. Dotted-line histogram shows the same relation over the whole range using groups of five bins.

Fig. 6 shows the results of the analyses of channel activity recorded under these conditions (original trace segments obtained from this patch were shown in Fig. 2, bottom pair). Channel conductance was 59 pS as estimated from the unitary current amplitude of 2.36 pA at a holding potential of 40 mV (membrane potential −40 mV). 13,861 events observed during 775 s were subject to the same analysis as described above. Exponential components in open and closed time distributions as well as their relative areas were very similar to those observed for the carbachol-gated channel in an outside-out patch (compare Figs. 6 A and 4 A; statistical tests presented in the Table I legend). An important conclusion that follows from this observation is: although channel PO is increased through its interaction with the Gαo-GTP molecule (Yan et al., 2003), likely by increasing the probability of transition toward the O4 state (see below) the channel possesses an intrinsic gating mechanism that kinetically remains the same whether Gαo is bound to the hydrolyzable GTP or to the much more stable GTPγS (compare with similar observations in case of KAC, channel by Ivanova-Nikolova and Breitwieser, 1997). In other words, bursts of long openings that account for the major part of mICAT (see below), and hence likely arise due to the interaction with activated Gαo-GTP, are not terminated simply because GTP is hydrolyzed and inactive Gαo-GDP is formed.

Correlation analysis of adjacent closed and open states also produced a similar result (compare Figs. 6 B and 4 B). We did not calculate the dependence of mean adjacent open intervals over selected ranges of closed times as in Fig. 5 (symbols), since compiling the histogram over the whole range was more straightforward. These are shown in Fig. 6 C by columns for this patch and by circles for the average data from 11 patches. Maximum open time in each patch was normalized as 1.0 irrespective of where the maximum occurred (e.g., the second column in the histogram of Fig. 6 C). Absolute maximal values in different patches varied from 45 to 260 ms with a mean of 109 ± 23 ms (n = 11).

From these results we conclude that the states are connected as shown in Scheme I (mean values from 11 patches are shown in Table I).

Cycling Behavior within Markov Chain of Cationic Channel

Many novel features of KAC, channel in heart, such as four distinct modes of gating of the G-protein–gated KAC channel, were revealed by analysis of its PO and the frequency of openings after dividing a continuous record into consecutive segments of fixed duration (Ivanova-Nikolova et al., 1998). Thus, we have performed a similar analysis. Some of our results are consistent with the above study, but novel features were
also found. Notably, while it was found that the K_ACh channel P_O increases from mode 1 to mode 4 mainly because the channel opens progressively more frequently and for longer durations, cationic channel P_O is mostly determined by cycles within the Markov chain (e.g., the number of long open states, O₄, encountered before it enters a long shut state, C₄).

Fig. 7 shows P_O measured over 5-s intervals from the record in Fig. 3 A. Mean frequency of channel openings was 13.8 s⁻¹, thus on average 69 openings were included in each interval yet there was a significant scatter of P_O values in the range of 0.005–0.89. Since the O₄ state generates 73% of the integral current (Table I) its frequent occurrence could explain periods when P_O was high while frequent occurrence of the C₁ state might explain periods when P_O was very low. All occurrences of C₁ and O₄ states given the overlapping distributions are not possible to quantify but a phenomenon known as length-biased sampling is known (Colquhoun and Hawkes, 1995). This arises due to a positive skew of the exponential distribution; as a result above-average dwell times are fewer in number but make a greater functional contribution. Thus, we restricted our analysis to include only O₄ and C₄ states defined, respectively, as openings >79 ms and closings longer than 371 ms (based on distributions of Fig. 4 A). These are plotted at the top of Fig. 7. Their total contribution to the trace duration amounted to 24.3% for the C₄ state and 33.6% for the O₄ state. Considering the areas under exponential components, it can be calculated that 95.2% of C₄ belong to the C₁ state and 97.1% of O₄ belong to the O₄ state. Although such definitions include only 37% of C₁ and O₄ states because of the above-men-
tioned phenomenon C₄ and O₄ account for 74% of the total time occupied by C₁ and O₄ states, respectively.

It was also found, as with the K_ACh channel, that the frequency of openings increased as P_O increased (correlation coefficient R = 0.59; P < 0.0001). Thus, there is a possibility that several frequency modes exist for the cationic channel, but they are not as distinct as for the K_ACh channel (Ivanova-Nikolova et al., 1998). In contrast, as shown in Fig. 8 A (squares) there was a close relationship between P_O measured in 5 s sequential intervals and the number of visits to the O₄ state between consecutive visits to the C₄ state in the same intervals. The number varied from 0 (e.g., two C₄ states with no O₄ in between) to a maximum of 45 (i.e., 45 openings >79 ms occurred before a closing longer than 371 ms; 39 was the average value). The mean value of the number of O₄ openings after one C₄ was 5.5 ± 0.9 (n = 99).

The number of visits to the C₄ state between consecutive O₄ was much smaller, ranging from 0 to 5 with the average of 0.18 ± 0.02 (n = 546) (Fig. 8 A, circles). However, in this patch mean P_O was high and thus one could expect a converse at low mean P_O in which case the number of visits to C₄ state between consecutive visits to O₄ state could become an important factor in determining P_O (see below).

The mean open and closed times were also measured over the same 5-s intervals and these values are plotted against P_O in Fig. 8 C, which further revealed that a decrease in the mean closed time (closed circles) makes a more significant contribution. Finally, the histogram of P_O measured in 5-s consecutive intervals (Fig. 8 B) revealed that (using the same terminology as for the K_ACh

![Figure 6](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC881222/figure/fig6.jpg)

**Figure 6.** Analysis of cationic channel activity that was induced by direct activation of G-proteins using GTPγS and recorded in the cell-attached configuration (see Fig. 2, two traces at the bottom). (A) Histograms of distributions of apparent closed and open durations. (B and C, histogram) Correlation analysis performed as in Figs. 4 B and 5, respectively. Circles in C show mean data (±SEM) from 11 observations.
channel) modal preferences of gating of the cationic channel exist that are not so much in the frequency domain but rather in the open probability domain (which in turn is related to the number of OL states between consecutive CL states). Thus, three modes of PO can be visualized with mean values and areas under Gaussian curves of 0.14 (16%), 0.45 (70%), and 0.72 (14%) (Fig. 8 B). This graph shows that channel gating is highly heterogeneous even if the trace is arbitrarily divided into consecutive 5-s segments (as mentioned, these include on average 69 openings in each interval). According to the mean parameters in Table I four modes should exist with characteristic PO values of 0.001, 0.085, 0.909, and 0.996 and fractional times of 0.43, 0.13, 0.12, and 0.32, respectively. However, these are not seen in Fig. 8 B because the channel changes its gating mode frequently (as evident from the occurrences of OL and CL in Fig. 7) and dividing the trace in a mode-specific segments has the same problem as burst analysis namely that channel state cannot be unequivocally identified from burst events (see MATERIALS AND METHODS).

It is interesting to note that if PO was measured over shorter intervals (e.g., 400 ms as for KAC channel) then two major peaks at PO = 0.03 and PO = 0.98 appeared while the peak at PO = 0.45 disappeared, suggesting a better discrimination between the modes. Constructing a moving average of these data points by symmetrical averaging of 15 adjacent points revealed a striking cycling behavior with a rather constant period between.

Figure 7. PO values measured over 5-s consecutive intervals from the record in Fig. 3 A. The horizontal dashed line indicates the mean PO value. The occurrence of CL (≥371 ms) and OL (≥79 ms) states is indicated at the top.

Figure 8. The number of visits to the OL state that occur between visits to the CL state is the major determinant of PO and cycling behavior of cationic channel activity. (A) The relationship between this number (squares) and PO measured in 5-s consecutive intervals. In each 5-s segment the average number was formed from: (a) the number of OL states which followed each CL state (if any) in that segment; (b) the number of OL states that followed the last CL state in the previous segment(s) before the first CL state in that segment; and (c) the number of OL states that followed the last CL state in that segment before first CL in the next segment(s). The average number of visits to the CL state that occur between visits to the OL state calculated by the same algorithm is also shown (circles). (B) Histogram of PO values measured in 5-s consecutive intervals fitted by three Gaussian components (the mean values and areas are indicated in the text). (C) Averaged open (open circles) and closed (closed circles) event durations measured in each 5-s segment plotted against PO of the same segment. (D) Regular cycles of PO change during the experiment (see text for more details). We verified that averaging data points over a moving window of twice the size did not change the number or position of these apparent PO peaks (compare top and bottom traces). Note, that we used symmetrical averaging that does not produce a time shift and that the moving average filter, due to its very slow roll-off, has little ability to separate one band of frequencies from another (Smith, 1997). Note that the same result can be obtained by measuring PO in a 6-s window sliding with a 400-ms increment. Also note that at lower mean PO, mixed gating produced less scatter of data points in 5-s segments and hence similar oscillations could be visualized more directly in raw data (see Fig. 9 B).
the peaks of ~20 s (Fig. 8 D, top trace). It can be noted that the moving average filter is optimal for random noise reduction (e.g., by a factor of 15 1/2 in Fig. 8 D; top trace) while keeping the sharpest step response and thus is ideal for analyzing signals in the time but not in the frequency domain (Smith, 1997). Two observations suggested that the oscillations of PO were not a data filtering artifact. First, averaging PO over a window of twice the size did not noticeably reduce their frequency (bottom trace in Fig. 8 D). Second, in some patches, particularly when the channel had a lower mean PO, the cycling behavior could be visualized in the raw data (e.g., Fig. 9 B). Peaks of PO arise from runs of long openings (see Fig. 8 A and Fig. 9 A, inset) that could be related to periodic channel interaction with G_o-GTP (or, less likely, other ligands), but this hypothesis needs further tests.

Similar analysis was done for a cell-attached patch as shown in Fig. 9, A and B. In this patch channel mean PO was much lower (0.18) and the histogram of a number of 5-s intervals versus PO revealed one expected major peak at PO < 0.05 (Fig. 9 A). The number of O_L states between consecutive C_L states ranged from 0 to 40 while runs of C_L between consecutive O_L states ranged in number from 0 to 14. Somewhat surprisingly, their overall dependence on PO was the same as in the patch with a higher PO (compare insets in Figs. 9 A and 8 A). It can be concluded that, despite a considerable difference in overall PO, periods with similar PO are characterized by a similar number of consecutive O_L or C_L states. Thus, the major factor that determines a higher overall PO appears to be a high frequency of periods of high PO (compare histograms in Figs. 9 A and 8 B).

Plotting PO measured in consecutive 5-s intervals versus time revealed even better defined oscillations (Fig. 9 B, note that raw data are plotted, i.e., no moving average was used). Analysis of all 11 patches studied showed that the period between peaks of PO well correlated with the mean PO value which ranged from 0.18 to 0.78 (R = −0.9; P = 0.0002).

Fig. 9 C illustrates a complete sequence of changes in channel gating kinetics during a single PO oscillation indicated by the horizontal bar in Fig. 9 B, which corresponds to one complete cycle of PO. Note that PO values of ~0.5 result from mixed gating (compare with the major peak in Fig. 8 B), whereas periods of very low and very high PO clearly result from gating in, respectively, C1-O1 and C4-O4 pairs of states according to Scheme 1. The dotted line shows the closed level.
The Origin of Voltage Dependence of \( m_{\text{ICAT}} \)

The whole-cell current displays a distinctive I-V relationship that is prominently U-shaped at negative potentials, whereas around the reversal potential there is another characteristic region of double rectification (Fig. 13 B). At the time this was discovered this seemed a unique property of \( m_{\text{ICAT}} \) (Benham et al., 1985), but now it is recognized as a common property of cationic channels formed by TRP proteins, particularly in the case of TRPC3 to TRPC7 (for review see Clapham, 2003). As was already mentioned, it is likely that the muscarinic cationic channel also belongs to this group. The origin of this complex I-V relationship is not so clear. Previous studies have established that the voltage dependence of \( P_O \) explains the U-shaped I-V relationship in the negative potential range, whereas around 0 mV and at more positive potentials channel openings and closings could not be resolved even in the absence of intracellular Mg\(^{2+}\) or polyamines (Inoue et al., 1987; Kang et al., 2001). Thus, the aim of the next series of experiments was to discover which changes in channel kinetics are responsible for the voltage dependence of \( P_O \) and through this to find out which transitions in the underlying Markov chain are sensitive to membrane potential.

Fig. 10 A shows an example of open and closed times histograms obtained by observing cationic channel activity in an outside-out patch which was exposed to carbachol and recorded either at \(-40\) mV (408 s, mean \( P_O = 0.59 \)) or at \(-80\) mV (334 s, mean \( P_O = 0.34 \)). Fitting exponential components revealed that the decrease of \( P_O \) evoked by membrane hyperpolarization was associated with changes of the mean dwell times (particularly in the case of C1 and C2 states), but at the same time there was only a small net redistribution between the states, i.e., relative areas of the components changed little.

Channel activity over a wide range of test potentials was investigated using an outside-out patch formed after whole-cell \( m_{\text{ICAT}} \) was fully activated in response to intracellular application of GTP\(\gamma\)S (see examples in Fig. 11 A). Analysis of exponential components of closed and open time distributions revealed that the time constants showed voltage dependence while the relative areas (e.g., probability of being in one of eight closed or open states) were little affected; the latter showed some scatter but there was no particular voltage-dependent trend (Fig. 10 B, bottom).

It can be seen that membrane depolarization increases both the frequency of openings and their durations (Fig. 11 A). If a step from \(-50\) to 30 mV was applied then channel flicker developed instantaneously but this was lost when the membrane potential was stepped back to \(-50\) mV. A trace at the bottom shows this flicker behavior at a higher resolution. Individual openings and closings could not be resolved, in fact even the baseline current level was hard to determine as the channel spent most of the time in the open state, which was extremely noisy and of much reduced amplitude because of high frequency partially resolved closings. Thus, analysis of channel kinetics was restricted to potentials negative to 0 mV.

Unitary and mean patch currents are plotted versus test potential in Fig. 11 B (squares and circles, respectively). These I-V relationships are similar to, respectively, instantaneous and steady-state I-V relationships.
of the whole-cell mICAT (Benham et al., 1985; Inoue and Isenberg, 1990b; Fig. 13 B). Corresponding conductance curves denoted by the same symbols are shown in Fig. 11 C. These show that the major factor that accounts for the decrease of mICAT conductance in the range 0–30 mV is an apparent reduction of both unitary current amplitude and PO as a result of very short but frequent shuttings (Figs. 11 A and 12 A). The combined effect produces an overall N-shaped cationic conductance curve (Fig. 11 C, circles) that is similar to the whole-cell activation curve (Fig. 15 C).

Fig. 12 A shows the voltage dependence of PO described by the Boltzmann function (Eq. 2) with the parameters indicated. Open symbols indicate the values that were estimated from all-points amplitude histograms since a channel event search algorithm could not be used in the presence of channel flicker block. Thus, at positive potentials unitary amplitudes (Fig. 11 B) and PO values (Fig. 12 A) were evaluated from, respectively, peaks and areas of two overlapping Gaussian curves fitted to all-points amplitude histograms. Mean parameters describing the voltage dependence of PO were as follows: PO maximal value 0.81 ± 0.09, potential of half-maximal activation −89.0 ± 7.2 mV and slope factor −19.0 ± 1.5 mV for the V1/2 value and −19.0 ± 1.5 mV for the slope. Paired t test (two-tail) showed no difference between single-channel and whole-cell current voltage dependence (P = 0.24 in case of the V1/2 value and P = 0.81 in case of the slope factor; n = 4). Moreover, when the V1/2 values were analyzed there was significant correlation (P < 0.001) between single channel and whole-cell data. This was absent for the slope factor (P = 0.34).

These values were also within their typical range as found in a whole population of cells in which only whole-cell parameters were examined. Thus, during the steady-state response to 50 μM carbachol the V1/2 value was −98.8 ± 3.2 mV (ranged from −57 to −137 mV; n = 39) and −83.1 ± 1.4 mV in case of GTPγS-induced current (ranged from −63 to −105 mV; n = 48).

Two factors that determined the change in PO when membrane potential was changed were an increase of the open probability as well as a parallel decrease of the mean closed time (Fig. 12, B and C). For both mean dwell times there was an e-fold change per ∼24 mV, similar to the slope factor of the PO voltage dependence.

An important conclusion emerges from this analysis. In the Markov chain of the cationic channel shown in Scheme I all the vertical transitions between adjacent open and closed states are voltage dependent, but there is little horizontal redistribution between the states when membrane potential is changed. Thus, horizontal transitions are likely to be governed by ligands.
that interact to open this channel (see Discussion) and these ligands need not interact with the channel in a voltage-dependent manner.

Markov Chain Predictions for the Whole-cell Current Behavior

A system with states and connections as shown in Scheme I has a substantial potential for shifting behavior. This was previously analyzed in detail for the BKCa channel that has 10 main “condensed” states (Scheme II of Cox et al., 1997). An important analogy is that vertical transitions are voltage dependent, whereas horizontal transitions are ligand but not voltage dependent. Although ligands are different with regard to the mechanisms of their interactions with the channel, in both cases PO is increasing when the gating shifts from left to right simply because more heavily contributing O2, O3, and O4 states generate progressively longer openings. Thus, a roughly parallel negative shift of the activation curve is to be expected according to the formalism of Eq. 4a given by Cox et al. (1997) for BKCa channel:

$$P_O = \frac{1}{1 + B \cdot L(0)} \cdot \exp(-QFV/RT)$$

where B depends on [Ca$^{2+}$], and all the Ca$^{2+}$ dissociation constants for both the closed and open channel, L(0) is the open-to-closed equilibrium constant in the absence of Ca$^{2+}$ at 0 mV, Q is the equivalent channel gating charge, F is Faraday’s constant, V is membrane potential, R is the universal gas constant, and T is the absolute temperature. In the absence of calcium (i.e., B = 1) parameter L(0) thus determines the $V_{1/2}$ value due to intrinsic voltage dependence of the channel, but in the presence of channel ligand (B < 1) the curve shifts negatively.

Fig. 13 A illustrates one of our standard whole-cell experiments designed to activate cationic channels directly by intracellular application of GTPγS, which was usually followed by patch excision after mICAT reached a maximum. In this experiment, however, slow voltage ramps were applied at 20-s intervals starting immediately after break-through (Fig. 13 A, triangle). As can be seen in Fig. 13 B, pronounced changes of the shape of the I-V curve accompanied current development. These were translated into conductance curves plotted in Fig. 13 C and fitted by the Boltzmann function (Eq. 2) in the range −120 mV to about −40 mV. Superimposed fitted functions were extended to 80 mV, which allowed evaluation of the effect of the flicker block of the channel described above but only the unblocked part of each trace was included in the fit range. There was, as expected, a roughly parallel negative shift of the activation curve during the time course of mICAT development that, in turn, was presumably due to the accumulation of GTPγS-bound α subunits of G-proteins (note that GTP was not added to the pipette solution when GTPγS was used). A similar phenomenon exists when carbachol concentration is increased but the opposite shift is seen during desensitization in the absence of GTP (Zholos and Bolton, 1994, 1996). For 13 fitted traces the slope factor was $-19.7 \pm 1.7$ mV, very close to the value of $-19.9 \pm 4.0$ mV ($n = 4$) describing the slope of PO voltage dependence (Fig. 12 A). The $V_{1/2}$ value shifted $\sim 40$ mV in the negative direction simultaneously with the increase of the maximal conductance (Fig. 13 D). It can be noted that in this example the $V_{1/2}$ shifted negatively by $\sim 20$ mV more compared with the typical value of $-83$ mV but the starting value was also somewhat negative.

A fit of the same quality could be obtained using an
equation similar to Eq. 4 (P_o substituted for by relative conductance; not depicted). This allowed an estimate of the gating charge, which was found to be $1.4 \pm 0.2e$ ($n = 13$) as well as the value of $L(0) = 0.134 \pm 0.017$ ($n = 13$). These values predict intrinsic gating of the channel in the absence of ligands with $V_{1/2} = -36$ mV. It can be speculated that the variable and more negative starting value of the $V_{1/2}$ depends on the amount of spontaneous coupling between constitutively active muscarinic receptors (and possibly other GPCRs) and their associated G-proteins.

**Discussion**

*Channel States*

Although three types of cation channel were observed upon muscarinic receptor activation in single patches, or during the action of GTP\(_S\), there seems little doubt that the 57-pS cation channel studied here is the major contributor to the cation current observed in response to muscarinic receptor activation of longitudinal intestinal smooth muscle cells (Benham et al., 1985; Zholos and Bolton, 1994). On the one hand the 130-pS channel did not show the required voltage-dependent behavior typical of whole-cell mICAT as its integral patch current was almost a linear function of the membrane potential. When $[Ca^{2+}]_i$, was clamped at 500 nM $\sim$50% of mICAT was insensitive to voltage and it is likely that the 130-pS channel is the main contributor to this component (Tsyttsyura et al., 2000; Zholos et al., 2003). The 10-pS channel was often seen but calculations showed its contribution to whole-cell current could seldom exceed 5% at negative potentials. The 57-pS channel on the other hand showed many of the characteristics of mICAT: its voltage dependence closely resembled that of mICAT and the double rectification of mICAT around 0 mV (in symmetrical Cs\(^+\) solutions) could be attributed to the flicker block of the 57-pS channel in this potential region, so it seems clear that this channel contributes most of the current to mICAT under normal circumstances. However, other features such as the sensitivity to $[Ca^{2+}]_i$, have yet to be explored in detail.

The density of the 57-pS channel in the membrane can be estimated. Previous noise analysis of the whole-cell current suggested a mean maximal $P_o$ at $-40$ mV of $0.48 \pm 0.05$ and the number of channels to be 749 $\pm$ 76 ($n = 9$) (Zholos et al., 2003). This $P_o$ value is consistent with the present single-channel measurements (Table I), whereas the number of channels can now be estimated more directly by taking into account the average whole-cell cationic conductance of 20.4 nS (from 1.020 $\pm$ 66 pA average current activated by 50 \(\mu\)M carbachol application at $-50$ mV, $n = 112$; Yan et al., 2003), a single-channel conductance of 57 pS and $P_o = 0.43$. These values predict 832 channels, or 1 channel
per 6.45 $\mu^2$ as the average membrane capacitance is $53.7 \pm 1.2 \text{ pF (} n = 112)$. 

Low-channel density and their significant clustering can explain why 61% of outside-out patches were blank. Average cation channel density is $\sim 0.2$ $\mu^2$. Clearly channels are not evenly distributed over the cell surface as two thirds of patches were without channel activity although it is conceivable that channels in blank patches are simply inactive for some reason. However, one fifth of patches were encountered with two to seven active channels, so clearly clustering of active channels occurs. This may reflect structural arrangements, such that channels are inserted only in certain regions, or equally it may suggest that channel activity reflects localization of channel-activating factors.

However, it remains to be explained why so few successful recordings were obtained when carbachol was applied in the pipette alone (0%) or to the cell in the conventional cell-attached patch configuration (5%), or when carbachol was applied after an outside-out patch has been formed (9%) as opposed to when carbachol was applied before first forming an outside-out patch (30%). Our suggestion at present is that loss of phosphatidylinositol 4,5-bisphosphate (PIP$_2$) from the membrane when M3 receptors are activated is crucial for the mICAT response and opening of the 57-pS channels, so prior depletion of PIP$_2$ is necessary for M2 receptor activation to be effective. There are four times as many M$_2$ as M$_3$ receptors, so that in cell-attached patches the numbers of M$_3$ receptors may be insufficient to produce the required threshold depletion of PIP$_2$ and activation of mICAT upon M$_2$ receptor stimulation. Outside-out patches are bigger than inside-out or cell-attached patches so the paucity of M$_3$ receptors may not be so limiting; thus, carbachol activated channels in 9% of outside-out patches. GTPyS will deplete PIP$_2$ directly, independently of M$_3$ stimulation so would be expected, as found, to be more reliable in evoking mICAT. The coupling of receptor stimulation to mICAT does not seem to involve any diffusible factors as 57-pS channel activity was remarkably persistent in isolated patches.

Our previous whole-cell experiments have showed the involvement of both the M$_2$/Go$_o$ system (Yan et al., 2003) and the M$_5$/PLC system without significant participation of either InsP$_3$, DAG, or Ca$^{2+}$ store depletion (Zholos et al., 2004). The proposed mICAT TRPC connection (Walker et al., 2001; Lee et al., 2003) is consistent with PLC-dependent signaling (for review see Clapham, 2003) as the two main PLC metabolites also do not activate TRPC4 and TRPC5 proteins, while heterologous expression studies showed they have remarkably similar I-V relationships and single-channel activity patterns (Schaefer et al., 2002; for review see Clapham, 2003) to the 57-pS channel we observe.

The most impressive characteristic of the 57-pS channel was the relationship of long closings and short openings, and vice versa; this reciprocal relationship extended throughout the open/closed time ranges (Fig. 6 C) and indicates a model of the channel with pairs of open-closed states so that the greater probability would be that the channel transitions within open-closed state pairs. This follows from the high degree of negative correlation between the durations of open and closed states, which indicates more than a single pathway between open states (connectivity greater than unity, see Colquhoun and Hawkes, 1995) and excludes linear schemes where connectivity is unity.

Recordings showed a highly heterogeneous distribution of the probabilities of the open state (Figs. 8 B and 9 A). Horizontal transitions according to Scheme I are likely to be the main cause of the oscillatory behavior of P$_O$, which could not be attributed to some artifact of the signal averaging procedure (Figs. 1 D, 8 D, and 9, B and C). Intervals where P$_O$ approached unity were characterized by a series of consecutive long openings characterized by the long dwell times of the O4 state (Fig. 9 C); conversely, when P$_O$ within an interval was close to zero, such long openings were rare or absent, and the number of openings with the long O4 dwell time correlated well with the P$_O$ of the interval (Fig. 8 A and Fig. 9 A, inset). Intervals of mixed gating resulting in a mean interval P$_O$ of $\sim 0.5$ were also present (e.g., traces 3–5 and 9–10 in Fig. 9 C); the corresponding peak was particularly pronounced in Fig. 8 B, but when the mean P$_O$ was lower the number of 5-s intervals with P$_O < 0.05$ became dominant (Fig. 9 A). The explanation of these oscillations in P$_O$ with a P$_O$-dependent frequency is at present obscure.

For the K$_{ACh}$ channel gated by the G$\beta$y subunit, different frequency of openings encoded P$_O$ modes (Ivanova-Nikolova et al., 1998), but in the case of the muscarinic cation channel gated by Go$_o$-GTP in a PLC-dependent manner, the increase of P$_O$ results from more frequent transitions into C4-O4 gating. It is characterized by very long, up to 1 s channel openings (Fig. 9 C), which suggest the existence of relatively stable complexes. However, the frequency limitations of the recording method means that there may be some unsuspected short-lived states (with the time constants $<100 \mu$s) that are undetectable, thus producing more than the four pairs of states that we have resolved. In addition, there must be more states of the channel since inactivation of mICAT at very positive potentials has been observed in whole-cell recordings from which no or very little recovery was possible (Zholos et al., 2003). In single-channel experiments this was seen as an abrupt loss of channel activity without obvious prior alteration in channel kinetics. At present there is no evidence how this inactivated/desensitized state(s) is re-
lated to the four postulated pairs of open-closed states. Channel flicker block seen at positive potentials is also not formally represented in our Scheme I, which is therefore applicable only to potentials in the negative range. Our scheme thus represents the most parsimonious one, as, with many more than the 10,000 or so events which we were able to analyze, more than four pairs of open-closed states may have been detected, as well as other embellishments of our model.

Effects of Membrane Potential on Channel Gating

Membrane depolarization caused a significant increase of channel $P_O$ (Fig. 12 A). According to the 8-state Markov chain (Scheme I), several different changes in channel gating could potentially contribute to this effect: (a) shortening of channel shuttings, which is equivalent to increased frequency of openings; (b) prolongation of openings, which could be accompanied conversely by the reduction of their frequency; and (c) shifting of the gating such that channel states on the right of the scheme become more populated, i.e., relative contributions of C4 and O4 states increase. However, the latter effect was not observed as voltage had no or little effect on the relative times spent in the four postulated pairs of open-closed states (Fig. 10) implying that potential does not much affect the horizontal equilibrium in Scheme I. Channel $P_O$ was a sigmoid function of potential (Fig. 12 A) mainly due to a change in channel mean closed time (Fig. 12 C) and some change in channel mean open time positive to $-40 \text{ mV}$ (Fig. 12 B). The latter effect argues for some greater effect on open-closed transition rates, or on the longest opening/shortest closing pair of states.

Cationic Channel Ligands and Whole-cell Current Predictions

The 57-pS channel showed a very low $P_O$ in the absence of receptor activation in some recordings in symmetrical $\text{Cs}^+$ solutions; in physiological ion gradients this $P_O$ is likely to be even lower (Kang et al., 2001). Activation of the muscarinic receptors or G-proteins greatly increased $P_O$ and long openings correlated well with open probability (Figs. 8 A and 9 A, inset). There is an implication that G-protein binding to the channel affects transitions between, rather than within, pairs of open-closed states. However, this was not tested in the present experiments by applying different concentrations of carbachol for example, or recording channel activity as the effects of GTPyS develop. If $[\text{Ca}^{2+}]_i$ is buffered to very low levels then $\text{mICAT}$ does not develop or is exceedingly small (Inoue and Isenberg, 1990c), indicating that most likely the cation channels are virtually fixed in the longest closed state under these conditions and that raising $[\text{Ca}^{2+}]_i$ affects transitions between channel pairs toward those with longer open times. Further work will be needed to test this prediction. However, the results of our analysis of changes of the whole-cell I-V relationships (Fig. 13) with reference to Scheme I are generally consistent with the hypothesis that along with accumulation of activated G-proteins there is a horizontal gating shift toward C4-O4 pair of states.

The cation channel probably exists as part of a complex with a number of other types of molecule. Two key molecules that are involved in cation channel opening, Gto (Yan et al., 2003) and PLCβ (Zholos et al., 2004), are attached to the membrane via lipid modification (Hamm, 1998) and pleckstrin homology domains (Philip et al., 2002). The absence of these and other cofactors for channel opening may render inactive otherwise potentially active channels. The observation that both M2 and M3 subtypes of muscarinic receptor are required for channel opening (Zholos and Bolton, 1997; Bolton and Zholos, 2003; Unno et al., 2003) may suggest that a heterocomplex of these with the G-protein, cation channel, and other cofactors may exist.

In conclusion, the main strength of the channel scheme we suggest is that it accounts for the strong inverse relationship between open and closed time durations. It does not, however, take account of desensitization, inactivation or flicker block, and is limited by the inability of the recording system to detect events $<0.1 \text{ ms}$. Changes in potential do not seem to alter the transitions between pairs of open-closed states much, having their major effect on the rates of transitions within pairs, particularly the longest opening-shortest closing pair of states. As for the effects of $[\text{Ca}^{2+}]_i$ and G-proteins, our scheme predicts these should favor longer-lived open states by affecting transitions between pairs of open-closed states and further work will be needed to test this possibility.

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