CCR2 Receptor Ligands Inhibit Ca$_{v}$3.2 T-Type Calcium Channels

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Received June 30, 2009; accepted October 28, 2009

ABSTRACT

Monocyte chemoattractant protein-1 (MCP-1) is a cytokine known to be involved in the recruitment of monocytes to sites of injury. MCP-1 activates the chemokine (C-C motif) receptor 2 (CCR2), a seven-transmembrane helix G protein-coupled receptor that has been implicated in inflammatory pain responses. Here we show that MCP-1 mediates activation of the CCR2 receptor and inhibits coexpressed N-type calcium channels in tsA-201 cells via a voltage-dependent pathway. Moreover, MCP-1 inhibits Ca$_{v}$3.2 calcium channels, but not other members of the Cav3 calcium channel family, with nanomolar affinity. Unlike in N-type channels, this modulation does not require CCR2 receptor activation and seems to involve a direct action of the ligand on the channel. Whole-cell T-type calcium currents in acutely dissociated dorsal root ganglia neurons are effectively inhibited by MCP-1, consistent with the notion that these cells express Ca$_{v}$3.2. The effects of MCP-1 were eliminated by heat denaturation. Furthermore, they were sensitive to the application of the divalent metal ion chelator diethylenetriaminepentaacetic acid, suggesting the possibility that metal ions may act as a cofactor. Finally, small organic CCR2 receptor antagonists inhibit Ca$_{v}$3.2 and other members of the T-type channel family with micromolar affinity. Our findings provide novel avenues for the design of small organic inhibitors of T-type calcium channels for the treatment of pain and other T-type channel linked disorders.

N- and T-type calcium channels are key mediators of nociceptive signaling in primary afferent pain fibers (Altier and Zamponi, 2004). T-type calcium channels are expressed in nerve endings of pain-sensing neurons, where they regulate neuronal excitability (Todorovic and Jevtovic-Todorovic, 2007). N-type calcium channels, on the other hand, are expressed at presynaptic nerve terminals in laminae I and II of the dorsal horn of the spinal cord, where they regulate the release of neurotransmitters such as substance P and glutamate and thus the communication between the primary afferent fibers and neurons projecting to the brain (for review, see Zamponi et al., 2009). Consequently, inhibition of either N- or T-type calcium channels has been shown to mediate analgesia. For example, intrathecal injection of the T-type channel inhibitor ethosuximide (Matthews and Dickenson, 2001) or antisense depletions of Ca$_{v}$3.2 T-type calcium channels (Bourinet et al., 2005) mediates potent analgesia in rodents. Likewise, gene knockout or in vivo knockdown of specific N-type channel splice isoforms (Saegusa et al., 2001; Altier et al., 2007), or their direct inhibition by peptide toxins isolated from fish-hunting cone snails (Staats et al., 2004) depresses pain signaling. Besides direct block by peptidergic or small organic calcium-channel blockers, voltage-gated calcium channels can also be inhibited by activation of certain types of G protein-coupled receptors, such as $\mu$-opioid receptors, which reduce N-type calcium channel activity via a voltage-dependent pathway that involves binding of G$\beta\gamma$ subunits to the channel protein (for review, see Tedford and Zamponi, 2006).

Although activation of some types of receptors proves beneficial with regard to treating pain, other types of G protein-coupled receptors are pronociceptive (Negri et al., 2006). One such example is CCR2, a chemokine receptor that is linked to G$\alpha$$_{12}$. Its ligand, monocyte chemoattractant protein-1 (MCP-1; also known as CCL2), is a cytokine that is involved in the recruitment of monocytes to sites of injury (White et al., 2005a; Zhang and De Koninck, 2006). MCP-1 is ex-
pressed in sensory neurons, and its levels are up-regulated during nerve injury (Tanaka et al., 2004; White et al., 2005b). Its release may increase the excitability of surrounding neurons within the dorsal root ganglia, thereby resulting in proalgesia (White et al., 2007). This may be further exacerbated by release of MCP-1 from nerve terminals of primary afferent fibers, which has been shown to activate microglia in the spinal cord (Zhang et al., 2007; Thacker et al., 2009).

MCP-1 is also expressed in astrocytes of the CNS and has been implicated in pain sensitization at the central level (Gao et al., 2009). Consistent with a proalgesic action of MCP-1, knockout of CCR2 receptors reduces inflammatory pain and prevents the occurrence of neuropathic pain as a result of chronic construction injury (Abbadie et al., 2003). Likewise, intrathecal administration of CCR2 receptor antagonists alleviates neuropathic pain (Dansereau et al., 2008; Abbadie et al., 2009). Given these proalgesic actions of MCP-1, we wondered whether they might in part arise from an enhancement of activation of N- or T-type calcium channel activity. As we show here, the exact opposite is the case as MCP-1 inhibits N-type calcium channels via a G protein-coupled pathway, whereas T-type calcium channels of the Ca$_{3.2}$ subtype are inhibited directly and with high affinity through a receptor-independent pathway. Moreover, Ca$_{3.2}$ channels can be inhibited by CCR2 receptor antagonists, which could thus serve as initial structural scaffolds for the development of higher affinity T-type channel blockers.

Materials and Methods

**CDNA Constructs.** Human Ca$_{3.2}$, rat Ca$_{1.2}$, Ca$_{2.1}$, Ca$_{2.2}$, and Ca$_{3.2}$ a1 subunits, and ancillary rat Ca$_{b}$ and a2-S1 subunits were kindly provided by Dr. Terrance Snutch (University of British Columbia, Vancouver, BC, Canada). Human Ca$_{3.3}$ was obtained from Dr. Arnaud Monteil (Universités Montpellier I & II, Montpellier, France), and human Ca$_{3.1}$ was as we described previously (Beedle et al., 2002). Human CCR2a receptor cDNA was purchased from Missouri STC DNA Resource Center (Rolla, MO). The construction of G$\beta$y binding peptide barK-crt encoding cDNA in pIRE2-EGFP expression vector (Clontech, Mountain View, CA) was described previously (Maggia et al., 2000).

**Chemicals.** Unless stated otherwise, chemicals and drugs were purchased from Sigma (St. Louis, MO). MCP-1 was obtained from R&D Systems (Minneapolis, MN) and BMS CCR2 22, RS102895 hydrochloride, and RS504393 were purchased from Tocris Bioscience (Ellisville, MO) and BMS CCR2 22, RS102895 hydrochloride, and RS504393 were purchased from Sigma (St. Louis, MO). MCP-1 was purchased from R&D Systems (Minneapolis, MN) and BMS CCR2 22, RS102895 hydrochloride, and RS504393 were purchased from Sigma (St. Louis, MO). MCP-1 was purchased from Tocris Bioscience (Ellisville, MO) and BMS CCR2 22, RS102895 hydrochloride, and RS504393 were purchased from Sigma (St. Louis, MO). MCP-1 was purchased from R&D Systems (Minneapolis, MN) and BMS CCR2 22, RS102895 hydrochloride, and RS504393 were purchased from Sigma (St. Louis, MO).

**Electrophysiology.** Whole-cell voltage-clamp recording for tsA-201 and COS-7 cells were performed 2 to 4 days after the transfection. The external recording solution contained 20 mM BaCl$_2$, 1 mM MgCl$_2$, 10 mM HEPES, 40 mM TEA-Cl, 65 mM CsCl, and 10 mM d-glucose, pH adjusted to 7.2 with TEA-Cl. The external recording solution for DRG neurons was composed of 2 mM CaCl$_2$, 160 mM TEA-Cl, 10 mM HEPES, and 10 mM d-glucose, pH adjusted to 7.4 with TEA-Cl. The external solution for DRG neuron recordings was supplemented with 1&um;M nifedipine. The internal pipette solution was composed of 108 mM Cs-methanesulfonate, 4 mM MgCl$_2$, 9 mM EGTA, and 9 mM HEPES, pH adjusted to 7.2 with CsOH. The internal solution was supplemented with 0.6 mM GTP and 2 mM ATP, which were added directly to the internal solution immediately before use. In some experiments, the GTP/ATP supplement was excluded or replaced with 1 mM guanosine 5'-&thio]diphosphate (GDP) as indicated. We know from our previous work that this is an effective means of interfering with receptor-mediated inhibition of T-type calcium channels (Itinca et al., 2007). Drugs were prepared daily in external solution and were applied locally to cells with the use of a custom microperfusion system that allows solution exchanges in approximately 1 s (Feng et al., 2003). Currents were elicited from a holding potential of –100 mV and were measured by conventional whole-cell patch clamp using an Axopatch 200B amplifier in combination with Clampex 9.2 software (Molecular Devices, Sunnyvale, CA). Data were filtered at 1 kHz (8-pole Bessel) and digitized at 10 kHz with a Digidata 1320 (Molecular Devices). An online leak-subtraction protocol was used in which four pulses of opposite polarity and one-quarter amplitude were acquired immediately before the test protocol. We have described the prepulse facilitation protocol used in N- and L-type calcium channel studies previously (Kislevsky et al., 2008). The extent of G$\beta$y-mediated voltage-dependent inhibition was measured as the amount of prepulse relief, and the voltage-independent inhibition was calculated as the amount of inhibition remaining. For current-voltage relationship studies, the membrane potential was held at –100 mV and was depolarized from –90 to +50 mV with 10-mV increments. For steady-state inactivation studies, the membrane potential was depolarized by test pulses to –20 mV after 3.6-s conditioning prepulses ranging from –110 to 0 mV. The current amplitude obtained from each test pulse was then normalized to the maximum at –110 mV.

**Data Analysis and Statistics.** Data were analyzed using Clampfit 9.2 (Molecular Devices) and Prism 5 software (GraphPad Software Inc., San Diego, CA). Because MCP-1 incompletely inhibited Ca$_{3.2}$ channel activity, concentration-response curves for MCP-1 inhibition were analyzed using a modified Hill equation: $I_{\text{current}}/I_{\text{control}} = C + (1 - C)/1 + (\text{MCP-1})/K_{\text{Hill}}(n_H)^n$, where $C$ reflects the fraction of current that remains at saturating MCP-1 concentrations and $n_H$ is the Hill coefficient. Steady-state inactivation curves were fitted using the Boltzmann equation: $I = I_0(1 + e^{-V - V_{1/2}})$, where $V_{1/2}$ is the half-inactivating potential and $k$ is the slope factor. Current-voltage plots were fitted using the modified Boltzmann equation:
\[
I = I_0 \left( 1 + e^{-\left( V - V_{act} \right)} \right) \times \frac{G \times (V - E_{rev})}{E_{rev}}
\]
where \(V_{act}\) is the maximum slope conductance, \(k\) is a slope factor, and \(V_s\) is the half-activation potential. The time courses of development of block and washout at various MCP-1 concentrations were fitted with monoequations.

Statistical analysis was performed using paired or unpaired t-tests as appropriate. Statistical significance was set at \(P < 0.05\), and all error bars represent S.E.M.

**Results**

**CCR2 Receptor Activation Mediates Voltage-Dependent Inhibition of N-Type Calcium Channels.** To determine the effects of CCR2 receptor activation on voltage-gated calcium channels, initially one member of each of the major classes of calcium channels (i.e., Cav1, Cav2, and Cav3) was coexpressed in tsA-201 cells with cDNA encoding for the CCR2 receptor. In the case of high-voltage-activated channels, the auxiliary \(\beta\) and \(\alpha_2\beta\) subunits were coexpressed. The cells were then functionally assayed using whole-cell patch-clamp recordings and a double-pulse protocol in which a test pulse to +20 mV was followed by a strong depolarizing prepulse to +150 mV before application of a second test pulse to +20 mV. As shown in Fig. 1A, Cav1.2 (i.e., L-type) channels were insensitive to CCR2 receptor activation by 100 nM MCP-1. In contrast, N-type Cav2.2 channels underwent a pronounced receptor-mediated inhibition that could be almost completely reversed by the depolarizing prepulse, consistent with membrane delimited, \(G\beta\gamma\)-mediated inhibition (Tedford and Zamponi, 2006). Cav3.2 (T-type) calcium channels also underwent a pronounced MCP-1-induced inhibition. Figure 1B summarizes the inhibitory effects of MCP-1 on the three calcium channel subtypes, revealing an overall inhibition of 50% for Cav2.2 and Cav3.2 channels. Figure 1C examines the extent of prepulse relief from Cav2.2 channels in the absence and presence of cotransfected CCR2 receptors. As seen from the figure, no prepulse relief occurred in cells lacking the CCR2 receptor, irrespective of agonist application. A small degree of prepulse relief was observed simply upon coexpression of the receptor in the absence of agonist and was significantly augmented after agonist application. Overall, the data obtained with Cav2.2 are consistent with those obtained with a wide range of G\(\alpha\)-linked receptors (Tedford and Zamponi, 2006). The observation that most of the inhibition was voltage-dependent (Fig. 1D), however, contrasts with findings obtained with other receptor types such as dopamine (Kisilevsky and Zamponi, 2008) or nociceptin receptors (Beedle et al., 2004).

**Ca_{3.2} Channels Undergo Receptor Independent Inhibition by MCP-1.** To determine whether the MCP-1 effects on Cav2.2 and Cav3.2 channels were mediated by CCR2 receptor activation, we applied 100 nM MCP-1 to cells lacking the receptor. As shown in Fig. 2B, Cav2.2 channels were not inhibited by MCP-1 in the absence of a coexpressed CCR2 receptor. These data confirm the involvement of a CCR2 receptor in the inhibition of N-type channel activity; furthermore, they indicate that tsA-201 cells do not endogenously express significant levels of functional CCR2 receptors. It is noteworthy that MCP-1 was as effective in inhibiting Cav3.2 channel activity in the absence of CCR2 (Fig. 2, A and B) as in its presence (Fig. 1, A and B). In contrast, neither Cav3.1 nor Cav3.3 channels were inhibited by MCP-1 (Fig. 2, A and B), and there was no effect on Cav2.1 (P/Q-type) and Cav2.3 (R-type) channels. The inhibitory effects of MCP-1 on Cav3.2 channels were not a specific feature of tsA-201 cells, because a similar degree of inhibition was observed for Cav3.2 channels expressed in COS-7 cells (Fig. 2B). The effects of MCP-1 on transiently expressed Cav3.2 channels were maintained upon inclusion of GDP\(\beta\)S in the patch pipette and after removal of intracellular GTP and ATP (Fig. 2C). Finally, coexpression of the \(G\beta\) binding peptide \(\alpha\)ark-ct, which we...
have shown previously to prevent Gβγ modulation of N-type channels (Magga et al., 2000), did not affect MCP-1 inhibition of Ca\(_{3.2}\) channels (Fig. 2C). This indicates that Ca\(_{3.2}\) channel activity is not inhibited via the Gβγ pathway described previously (Wolfe et al., 2003; DePuy et al., 2006). Taken together, these data indicate that MCP-1 inhibits Ca\(_{3.2}\) channels via a receptor-independent pathway that may involve a direct inhibition of channel activity by MCP-1.

**Biophysical Characterization of MCP-1 Block of Ca\(_{3.2}\) Channels.** Application of MCP-1 to Ca\(_{3.2}\) channels did not affect the voltage dependence of activation, as is evident from the whole-cell current waveforms shown in Fig. 3A and from the ensemble current-voltage relationships in Fig. 3B. These data indicate that MCP-1 does not act as a gating inhibitor as observed with peptides such as kurtoxin (Sidach and Mintz, 2002). In contrast, there was a statistically significant hyperpolarizing shift in the midpoint of the steady-state inactivation curve of the channel by approximately 6 mV, which would be expected to produce further inhibitory effects at a normal neuronal resting potential (Fig. 3C). Examination of the dose dependence of MCP-1 action (Fig. 3D) reveals that MCP-1 is a partial inhibitor of Ca\(_{3.2}\) with a maximum inhibition of approximately 50% at 100 nM MCP-1. The concentration required to reach half of this maximal inhibition (referred here as IC\(_{50}\)) was 5.6 nM, suggesting a relatively high-affinity interaction between the channel and the MCP-1 molecule. A kinetic analysis of the time course of development of block and washout at various MCP-1 concentrations revealed only a weak linear dependence of the inverse of the time constant for development of block on MCP-1 concentration (Fig. 3, E and F). Assuming a 1:1 blocking interaction, the slope of the regression line and intercept on the ordinate would suggest blocking (k\(_{on}\)) and unblocking (k\(_{off}\)) rate constants of, respectively, 3.29 \times 10^{-4} \text{ nM}^{-1} \text{s}^{-1} and 0.040 s\(^{-1}\). Although the latter value is similar to that obtained from the washout of the MCP-1 effect (k\(_{off}\) = 0.048 \pm 0.012 s\(^{-1}\), n = 6), the ratio of unblocking to blocking rate constant obtained from the regression analysis yields an equilibrium dissociation constant of 121 nM, which is approximately 20-fold larger than the value obtained from the dose-response curve shown in Fig. 3D. Hence, our data are inconsistent with a simple 1:1 interaction between MCP-1 and the channel, suggesting a more complex action of MCP-1 on the channel, perhaps at more than one site.

Ca\(_{3.2}\) channels are known to be potently inhibited by divalent metal ions, such as zinc (Traboulse at el., 2007), and to a much greater extent than other members of the T-type channel family. Application of zinc to Ca\(_{3.2}\) channels revealed only a weak linear dependence of the inverse of the time constant for development of block on zinc concentration (Fig. 3, E and F). Assuming a 1:1 blocking interaction, the slope of the regression line and intercept on the ordinate would suggest blocking (k\(_{on}\)) and unblocking (k\(_{off}\)) rate constants of, respectively, 3.29 \times 10^{-4} \text{ nM}^{-1} \text{s}^{-1} and 0.040 s\(^{-1}\). Although the latter value is similar to that obtained from the washout of the zinc effect (k\(_{off}\) = 0.048 \pm 0.012 s\(^{-1}\), n = 6), the ratio of unblocking to blocking rate constant obtained from the regression analysis yields an equilibrium dissociation constant of 121 nM, which is approximately 20-fold larger than the value obtained from the dose-response curve shown in Fig. 3D. Hence, our data are inconsistent with a simple 1:1 interaction between zinc and the channel, suggesting a more complex action of zinc on the channel, perhaps at more than one site.

**Fig. 2.** Effect of 100 nM MCP-1 on Ca\(_{2}\) and Ca\(_{3}\) channels in the absence of coexpressed CCR2. A, representative current traces for MCP-1 inhibition of Ca\(_{3.1}\), Ca\(_{3.2}\), and Ca\(_{3.3}\) T-type calcium channels. B, peak current block induced by application of 100 nM MCP-1 of various channels expressed in tsA-201 cells and of Ca\(_{3.2}\) expressed in Cos7 cells. C, effect of GDP\(_{\beta}\$S\), removal of intracellular GTP and ATP, or coexpression of the sark-ct on MCP-1 inhibition of Ca\(_{3.2}\). Error bars represent S.E.; numbers in parentheses reflect numbers of experiments.

**Fig. 3.** Biophysical properties of MCP-1 block of Ca\(_{3.2}\) channels. A, representative families of whole cell currents of Ca\(_{3.2}\) in the absence and presence of 100 nM MCP-1. The current traces were elicited by a step depolarization from a holding potential of -100 mV. B, normalized current-voltage relations of Ca\(_{3.2}\) channels before and after application of 100 nM MCP-1. The half-activation potentials were -30.5 ± 4.1 mV and -30.8 ± 3.7 mV before and after application of MCP-1, respectively (inset, P < 0.05, paired t test). C, steady-state inactivation curves obtained from Ca\(_{3.2}\) channels before and after application of MCP-1. The half-inactivation potentials were -56.9 ± 0.5 mV and -63.1 ± 1.2 mV before and after the treatment with MCP-1, respectively (inset, P < 0.05, paired t test). D, dose dependence of inhibition and washout were fitted monoexponentially. E, the inverse of the time constant for development of block as a function of MCP-1 concentration. The time courses of inhibition and washout were fitted monoeXponentially. F, the inverse of the time constant for development of block as a function of MCP-1 concentration. The slope of the regression is 3.29 \times 10^{-4} \text{ nM}^{-1} \text{s}^{-1} and the y-intercept is 4.0 \times 10^{-2} \text{ s}^{-1}. Error bars represent S.E.; numbers in parentheses reflect numbers of experiments.
channel family. To rule out the possibility that the selective inhibition of Ca\textsubscript{3.2} channels by MCP-1 might be mediated by trace amounts of metal ions in the MCP-1 sample, we examined MCP-1 action in the presence of the divalent metal ion chelator DTPA (Nelson et al., 2007). Application of 200 μM DTPA resulted in an enhancement of Ca\textsubscript{3.2} currents by 34.6% \( (n = 5) \), suggesting that a fraction of the Ca\textsubscript{3.2} channels are tonically inhibited by metal ions. Curiously, subsequent application of MCP-1 in the continued presence of DTPA inhibited Ca\textsubscript{3.2} channel activity only weakly (1.9% inhibition at 100 nM MCP-1, \( n = 5 \)). This was not due to a direct effect of DTPA on MCP-1, because MCP-1-mediated inhibition of Ca\textsubscript{2.2} channels by CCR2 receptors was unaffected by the chelator (56.7% inhibition, \( n = 3 \)). Although this could suggest that the observed effects of MCP-1 on Ca\textsubscript{3.2} channel activity might be due to contaminating metal ions, this is unlikely for two reasons. First, divalent metal ions such as zinc, copper, and nickel are known to mediate complete inhibition of Ca\textsubscript{3.2} channel activity (see Traboulsi et al., 2007), whereas the effects of MCP-1 did not exceed approximately 50% inhibition, even at concentrations 60 times higher than the IC\textsubscript{50}. Moreover, when MCP-1 was denatured by heating (100°C for 5 min), its inhibitory effects on Ca\textsubscript{3.2} channels were largely abolished (2.3% inhibition at 100 nM, \( n = 4 \)). Finally, we noted on two occasions that prolonged storage (2 months) of dissolved MCP-1 at −20°C resulted in a loss of channel-blocking activity, altogether supporting a specific action of MCP-1 on Ca\textsubscript{3.2} rather than the involvement of a metal ion contaminant.

### MCP-1 Blocks Native T-Type Currents

To rule out expression system artifacts and to determine whether native Ca\textsubscript{3.2} channels are subject to MCP-1 inhibition, we examined the effects of MCP-1 on native T-type currents in acutely dissociated rat DRG neurons. These cells express large T-type currents that are carried predominantly by Ca\textsubscript{3.2} (Bournet et al., 2005; Todorovic and Jevtovic-Todorovic, 2008). As shown in Fig. 4, application of 100 nM MCP-1 mediated a reversible inhibition of native T-type currents to an extent similar to that observed in tsA-201 cells. Hence, Ca\textsubscript{3.2} channel inhibition by MCP-1 is readily observed in native cells and, in particular, in a cell type relevant to the transmission of pain signals.

### MCP-1 Receptor Antagonists Inhibit Ca\textsubscript{3.2} Channels

The effects of MCP-1 on Ca\textsubscript{3.2} channels suggest the existence of an MCP-1 binding site on the channel protein that may share some structural features with the ligand binding pocket on the CCR2 receptor. To examine this possibility, we tested the effects of three other CCR2 ligands on Ca\textsubscript{3.2} channels transiently expressed in tsA-201 cells. There are several high-affinity small organic CCR2 receptor antagonists (Mirzadegan et al., 2000; Cherney et al., 2008), with binding affinities in the low to mid nanomolar range. At a concentration of 10 μM, all of these compounds inhibited transiently expressed Ca\textsubscript{3.2} channels. A more detailed analysis for RS504393 revealed that Ca\textsubscript{3.2} channels are inhibited in a concentration-dependent manner, with greater than 90% inhibition at 30 μM, in contrast with the partial block seen with MCP-1. For transiently expressed Ca\textsubscript{3.2} channels, a ∼10-mV hyperpolarizing shift in the steady-state inactivation curve was observed after application of 10 μM RS504393 (Fig. 5B), consistent with a higher affinity of this compound for inactivated channels. RS504393 also inhibited native T-type currents in DRG neurons (Fig. 5C). Unlike the selective effects of MCP-1 on Ca\textsubscript{3.2}, RS504393 inhibited a wide range of voltage-gated calcium channels, including other members of the Ca\textsubscript{3} channel family, as well as N-, P/Q-, L-, and R-type channels. Taken together, these data indicate that several types of CCR2 receptor antagonists have the propensity to block voltage-gated calcium, albeit at concentrations higher than those required for CCR2 receptor inhibition.

### Discussion

#### Possible Mechanism of Action of MCP-1

Our data show that in addition to inhibiting N-type channels via activation of CCR2 receptors, MCP-1 also inhibits Ca\textsubscript{3.2} calcium channels independently of G protein activation. In principle, it may be possible that the channels could be inhibited via a G protein-independent “transinactivation” mechanism mediated by endogenously expressed receptors; however, this is unlikely considering our observations that endogenous CCR2 receptor levels are sufficiently low to preclude receptor-mediated inhibition of N-type channels in the same cell system. Hence, the most likely mechanism involves a direct interaction between MCP-1 and the Ca\textsubscript{3.2} channel. MCP-1 did not affect the half-activation potential of the channel; hence, we can rule out the possibility that MCP-1 is a gating inhibitor similar to kurtoxin (Sidach and Mintz, 2002). It is also unlikely that MCP-1 reduces the numbers of channels in the plasma membrane, because the effects of MCP-1 had a fast rate of onset and were rapidly reversible upon washout. The observation that MCP-1 mediated only partial block of Ca\textsubscript{3.2} could be due to either an allosteric effect of MCP-1 on channel activity (for example, a reduction of the maximal open probability), or partial occlusion of the pore, as has been reported for certain types of large calcium channel-blocking peptide toxins (Mintz, 1994), and thus a reduced single-
channel conductance. Although partial pore block can account for the general observations with MCP-1, the detailed kinetic analysis of the time course of development of block argues against a simple 1:1 blocking interaction between the channel and the MCP-1 molecule. Future experiments examining the effects of known T-type channel inhibitors on MCP-1-bound channels, and permeation studies on channels partially inhibited by MCP-1, may provide further insights into the mechanism of MCP-1 action.

The observation that the metal ion chelator DTPA prevented the actions of MCP-1 suggests that the presence of metal ions is required for MCP-1 to exert its effects. This is reminiscent of observations by Nelson and colleagues (2007), who showed that the selective inhibitory actions of ascorbate on Ca_{3.2} channel activity required the presence of zinc ions that are present at trace amounts in the external recording solution, although the actions of ascorbate are likely distinct from those of MCP-1. Ca_{3.2} channels contain a unique histidine residue in position 191 that functionally interacts with metal ions such as zinc and nickel (Kang et al., 2006; Nelson et al., 2007). It remains to be determined whether this residue is involved in the actions of MCP-1.

**Mixed CCR2/T-Type Channel Antagonists—A New Approach to Treating Pain?** Our data reveal an unexpected action of CCR2 receptor ligands on both native and transiently expressed T-type calcium channels. Both CCR2 receptors and T-type channels have a pronociceptive function. Knockout of CCR2 receptors results in a phenotype that is hyposensitive to pain (Abbadie et al., 2003), and intrathecal delivery of CCR2 receptor antagonists is beneficial in the treatment of neuropathic pain (Dansereau et al., 2008; Abbadie et al., 2009). Either short-term block or antisense depletion of Ca_{3.2} T-type calcium channels also mediates analgesia (Matthews and Dickinson, 2001; Bourinet et al., 2005). Our experiments indicate that CCR2 receptors do not directly modulate T-type calcium channels (i.e., all of the observed MCP-1 effects on T-type channel function occurred independently of the receptors). One might therefore expect that dual CCR2/Ca_{3.2} channel antagonists would have additive effects in blocking pain behavior. In this context, it will be interesting to determine the effect of compounds such as RS504393 in animal models of pain. A recent study has reported analgesic effects of a novel proprietary CCR2 receptor antagonist (Jung et al., 2009). At this point, it remains to be determined whether the analgesic actions of this compound are due purely to CCR2 receptor antagonist activity or if inhibition of Ca_{3.2} channels might also be involved.

A number of compounds with diverse chemical structures have been shown to inhibit T-type calcium channels (Belardetti and Zamponi, 2008). The chemical structures of the CCR2 receptor antagonists investigated here diverge from known T-type channel-blocking pharmacophores. These CCR2 receptor antagonists could potentially serve as novel scaffolds for the development of higher affinity (i.e., in the mid nanomolar range, as seen with CCR2 receptor affinity) T-type channel inhibitors, but with increased selectivity for Ca_{3.2} over other calcium channel isoforms. If CCR2 receptor antagonist activity can be maintained, then this might indeed provide the potential for novel and highly efficacious analgesics with a dual mode of action. Finally, it is worth noting that CCR2 receptor activation resulted in inhibition of N-type calcium channels in tsA-201 cells. Although the receptors are clearly capable of inhibiting N-type channel activity under conditions in which they are artificially coexpressed, it remains to be determined whether such a regulation can occur in intact presynaptic nerve terminals in the dorsal horn of the spinal cord. Indeed, there is recent evidence that CCR2 activation occurs both at sites of injury and in the dorsal root ganglia, but not in the spinal cord (Jung et al., 2009), where N-type channels control neurotransmitter release from primary afferent fibers. The notion that CCR2 receptor activation is associated with pronociceptive effects (Dansereau et al., 2008) rather than analgesia further suggests that N-type calcium channels in the dorsal horn of the spinal cord may not be physiological targets of CCR2 receptor activation.

Overall, our data reveal a novel action of the cytokine MCP-1 in regulating T-type calcium channel activity though direct inhibition. The existence of binding site on Ca_{3.2} that

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**Fig. 5.** Inhibitory effects of CCR2 antagonists on transiently expressed and native calcium channels. A, summary of peak current block of Ca_{3.2} channel by 10 μM BMS CCR2 22, RS102895, and RS504393. B, steady-state inactivation curves obtained from Ca_{3.2} channels before and after application of 10 μM RS504393. The half-inactivation potentials were −54.2 ± 1.8 and −62.7 ± 4.3 mV before and after the treatment with RS504393, respectively (inset, P < 0.05, paired t-test). C, inhibition of native T-type calcium channels in DRG neurons and of various voltage-gated calcium channels expressed in tsA-201 cells by 10 μM RS504393. Error bars represent S.E.; numbers in parentheses reflect numbers of experiments.
can interact with CCR2 receptor ligands may provide for a substrate for the development of novel analgesics.

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