Nitric Oxide Transiently Converts Synaptic Inhibition to Excitation in Retinal Amacrine Cells

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Hoffpauir, Brian, Emily McMains, and Evanna Gleason. Nitric oxide transiently converts synaptic inhibition to excitation in retinal amacrine cells. J Neurophysiol 95: 2866–2877, 2006. First published February 8, 2006; doi:10.1152/jn.01317.2005. Nitric oxide (NO) is generated by multiple cell types in the vertebrate retina, including amacrine cells. We investigate the role of NO in the modulation of synaptic function using a culture system containing identified retinal amacrine cells. We find that moderate concentrations of NO alter GABA_A receptor function to produce an enhancement of the GABA_gated current. Higher concentrations of NO also enhance GABA_gated currents, but this enhancement is primarily due to a substantial positive shift in the reversal potential of the current. Several pieces of evidence, including a similar effect on glycine-gated currents, indicate that the positive shift is due to an increase in cytosolic Cl^-.

INTRODUCTION

Amacrine cells are interneurons in the inner retina that extend laterally and form synaptic connections with bipolar, ganglion, and other amacrine cells. These lateral interactions play a key role in determining the nature of retinal output (for reviews, see Lagnado 1998; Taylor and Vaney 2003), understanding the function and regulation of amacrine cells is critical to understanding retinal signal processing.

Nitric oxide (NO) has been implicated as a signaling molecule at all levels of the visual system (for review, see Cudeiro and Rivadulla 1999). Nitric oxide synthase (NOS) catalyzes the production of NO and citrulline from arginine. The neuronal form of this enzyme (nNOS) is constitutively expressed and stimulated by elevations of cytosolic Ca^{2+}. In the canonical pathway, NO stimulates soluble guanylate cyclase (sGC) activity. NO is also known to affect target protein function through S-nitrosylation (Davis et al. 2001; Stamler et al. 1997) and by other direct interactions including formation of dinitrosyl iron complexes (Rogers et al. 2003).

Neuronal NOS has been found in subsets of each class of neuron in the vertebrate retina (Blute et al. 1997; Chun et al. 1999; Fischer and Stell 1999; Kim et al. 1999; Rios et al. 2000; Shin et al. 1999), and NO itself has been detected in a similar array of retinal cells (Blute et al. 2000, 2003; Neal et al. 1998). In the chicken retina, a subset of amacrine cells expresses high levels of nNOS, and distinct sublaminae of nNOS labeling occur throughout the inner plexiform layer of the retina (Crousillat et al. 2003; Fischer and Stell 1999; Rios et al. 2000). Furthermore, measurements at the inner surface of the retina indicate that this tissue can generate high (micromolar) levels of NO (Donati et al. 1995; Gropp et al. 2003; Heiduschka and Thanos 1998).

The physiological effects of NO production have been examined for some cell types that signal in the inner retina. In the rabbit retina, NO reduces gap-junction coupling between all amacrine cells and cone bipolar cells (Mills and Massey 1995). Wexler and colleagues (1998) have shown that NO depresses GABA_A receptor function in cultured rat amacrine cells. In the ferret retina, recordings of ganglion cell activity reveal a dramatic NO-dependent decrease in light responses (Wang et al. 2003). Although effects of NO have been identified in multiple retinal cell types, the full range of NO function in the inner retina remains unknown.

To further examine how NO influences amacrine cell signaling, whole cell recordings were made from cultured GABAergic amacrine cells and amacrine cell synaptic pairs derived from embryonic chick retinae. We show that NO alters amacrine cell activity by affecting the functional properties of GABA_A receptors and, much more dramatically, by converting inhibitory synapses to excitatory synapses through a GABA receptor-independent mechanism. This mechanism involves an NO-induced redistribution of Cl^-.

METHODS

Cell culture

Retinal cultures were prepared from 8-day-old chick embryos and maintained as previously described (Hoffpauir and Gleason 2002). Experiments were performed on isolated amacrine cells or isolated pairs of amacrine cells 6–14 days (EE 14 to PE 1) after plating. After 6 days in culture, these cells are considered to be mature, based on
TABLE 1. External Solutions

<table>
<thead>
<tr>
<th></th>
<th>NaCl</th>
<th>KCl</th>
<th>CaOH</th>
<th>CaCl₂</th>
<th>MgCl₂</th>
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</table>

Contents of external recording solutions are given in millimolar. The pH of external solutions was adjusted to 7.4 using an appropriate base. Glucose concentration was varied ±10% to alleviate deviations from the normal osmolarity for some of the solutions. NMG, N-methyl-D-glucamine; TEA, tetraethylammonium; iseth, isethionate.

several physiological criteria including expression of the appropriate voltage- and ligand-gated ion channels (Huba and Hofmann 1991; Huba et al. 1992) and the formation of functional GABAergic synapses with other GABAergic amacrine cells. The properties of the amacrine-to-amacrine cell GABAergic synapses formed in culture have been previously characterized (Gleason et al. 1993). The uniformity of neurotransmitter phenotype indicates that the amacrine cells in culture represent a subset of amacrine cell phenotypes found in the intact retina.

Hippocampal cultures were made from 18-day-old rat (Fischer 344) embryos. Micro-dissected hippocampal tissue was obtained from Neuronsics (Bloomington, MN) and prepared and maintained according to the supplier’s protocols. Recordings from single hippocampal neurons were made after 4–7 days in culture. No physiological assessments of the relative maturity of these cells have been made. According to their developmental timeline alone, they would be considered embryonic (EE 22–25).

Electrophysiology

Whole-cell recordings were made using an Axopatch 1-D amplifier, Digidata 1322A data-acquisition board, and Clampex 9.2 software (Axon Instruments, Union City, CA). A reference Ag/AgCl pellet in 3 M KCl was connected to the culture dish via an agar bridge upstream of a manifold feeding one common barrel. The compositions of external and internal solutions are shown in Tables 1 and 2, respectively. TTX (300 nM) and LaCl₃ (25–50 μM) were added to external solutions (with the exception of the 0 Cl⁻ external solution) for single-cell voltage clamp (but not current clamp) recordings to block voltage-gated Na⁺ and Ca²⁺ currents, respectively. For ruptured-patch recordings, the following reagents were added to internal solutions (Cs⁺, unless otherwise indicated): 50 μM creatine phosphokinase, 3 mM adenosine 5’-triphosphate (ATP) dipotassium salt, 1 mM ATP-disodium salt, 20 mM phosphocreatine (Calbiochem, La Jolla, CA), 2 mM guanosine 5’-triphosphate (GTP) sodium salt. For perforated-patch recordings, either amphotericin B (synaptic pairs, Fig. 4) or gramicidin (Figs. 5 and 6) were added to normal internal or Cs⁺ internal, respectively, to a final concentration of 10 μg/ml.

Solutions

Unless otherwise indicated, all reagents were purchased from Sigma, St. Louis, MO. GABA application was achieved in 10–20 ms through computer-controlled perfusion barrel movements. This method was also used to switch between normal and zero external Cl⁻ for the experiment depicted in Fig. 8A. All other solution changes were achieved in ~500 ms by opening and closing the valves upstream of a manifold feeding one common barrel. The compositions of external and internal solutions are shown in Tables 1 and 2, respectively. TTX (300 nM) and LaCl₃ (25–50 μM) were added to external solutions (with the exception of the 0 Cl⁻ external solution) for single-cell voltage clamp (but not current clamp) recordings to block voltage-gated Na⁺ and Ca²⁺ currents, respectively. For ruptured-patch recordings, the following reagents were added to internal solutions (Cs⁺, unless otherwise indicated): 50 μM creatine phosphokinase, 3 mM adenosine 5’-triphosphate (ATP) dipotassium salt, 1 mM ATP-disodium salt, 20 mM phosphocreatine (Calbiochem, La Jolla, CA), 2 mM guanosine 5’-triphosphate (GTP) sodium salt. For perforated-patch recordings, either amphotericin B (synaptic pairs, Fig. 4) or gramicidin (Figs. 5 and 6) were added to normal internal or Cs⁺ internal, respectively, to a final concentration of 10 μg/ml.

S-Nitroso-N-acetyl-d,l-penicillamine (SNAP), 1-hydroxy-2-oxo-3-(N-ethyl-2-aminoethyl)-3-ethyl-1-triazene (NOC-12), 2,2’-(hydroxy-nitrosohydradino)bisethanamine (NOC-18), and 2-(4-carboxyphenyl)-4,4,5,5-tetramethylimidazoline-1-oxyl-3-oxide, sodium salt (carboxy-PTIO) were obtained from Dojindo Molecular Technologies (Gaithersburg, MD) and stored at ~20°C. The final pH of external solutions containing the nitric oxide donors was readjusted to 7.4 with 1 day with one batch of NO solution. For these experiments, we alternated between the two recording configurations and found no significant differences in the amplitude of the shifts (n = 3 in each configuration; P = 0.999).

TABLE 2. Internal solutions

<table>
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<tr>
<th></th>
<th>Cs Acetate</th>
<th>CsCl</th>
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</table>

Contents of internal recording solutions are given in millimolar. Methane sulfonate is abbreviated MES. Internal solutions Cs⁺⁻A and high Cl⁻ were supplemented with the ATP regeneration system components (see METHODS). Cs⁺⁻H was supplemented with 2 mM disodium ATP. The pH of the internal solutions was adjusted to 7.4 using an appropriate acid or base.
NO was detected in external solution containing 250 nM NO, coming in contact with a cell. For SNAP solutions, solutions to air for 10–30 min. For both fresh and air-exposed NO solutions, NaOH (SNAP and NOC 12), 1H-[1,2,4]oxadiazolo[4,3-a]quinoxalin-1-one (ODQ) was prepared at 10 mM in DMSO. Furosemide and bumetanide were prepared as 300 mM stocks in DMSO.

**NO-bubbled solutions**

Pure NO solutions were prepared by bubbling solutions with argon for 15 min followed by 15 min of bubbling with pure soda lime-filtered NO. NO solutions were tightly sealed, protected from light, and stored at 4°C. Although the method for preparing NO was standardized, the efficacy of different batches was variable. For most experiments, injections between 10 and 50 µl were able to elicit shifts of 15–35 mV. When standard volumes of a batch of NO solution became less efficient, a new batch was obtained. The NO solutions were delivered into the perfusion system manually with a Hamilton syringe via in-line injections (10–50 µl depending on potency, see following text). In-line injection of dye-containing solutions indicated that NO exposure was limited to 1–3 s with most of the NO arriving in the first 500 ms. NO was bubbled into either H2O or TEA external. No differences in the effects of NO in the two solutions were observed. For synaptic recordings, NO was bubbled into a 40 mM HEPES solution to minimize low pH effects on Ca2+ channels and other synaptic proteins. The concentration of NO in these solutions was measured using an ISO-NO meter (NOMK2 system) with an ISO-NOP electrode (World Precision Instrument, Sarasota, FL) for a batch and volume that was demonstrated to be effective in eliciting cellular responses. The mean NO concentration measured at the perfusion outlet was 2.0 ± 0.3 µM. This value represents the upper limit of NO coming in contact with a cell. For SNAP solutions, ~100 mM NO was detected in external solution containing 250 mM SNAP (2 h after preparation). With the exception of Fig. 1, the data shown were obtained using NO-bubbled solutions.

"Air-exposed" NO solutions were made by exposing NO-bubbled solution to air for ~10–30 min. For both fresh and air-exposed NO solutions, pH values typically ranged between 2 and 3. Injections of the appropriate amount of pH 2.5, NO-free solutions were routinely used as controls and none of the effects reported here were reproduced by low pH alone. Although extreme care has been taken to standardize the preparation, handling and injections of these volatile solutions, some variability remains. As such, only those cells receiving the same volumes, from the same batch of NO-bubbled solutions were used for quantitative comparisons. Data are reported as means ± SD and statistical significance was determined using the *t*-test. Data shown in Figs. 5, B and D, and 6F were analyzed using the paired *t*-test.

**Results**

Effects of NO on GABA-gated currents

To explore the effects of NO, we recorded whole cell GABA<sub>A</sub> receptor currents (Hoffpaur and Gleason 2002) from individual amacrine cells. For these experiments, Cs<sup>+</sup>-A internal and TEA-A external solutions were used, and recordings were made in the ruptured-patch recording configuration. Under these conditions, we find that NO produces three effects in amacrine cells. First, moderate NO donor concentrations (250 µM SNAP, ~100 nM NO, see METHODS) caused a small (~15%) enhancement of the GABA-gated current amplitude that was not due to alteration in the reversal potential of the current (*E<sub>GABA</sub>*, Fig. 1). Similar effects were observed with NOC 12 (250 µM) and NOC 18 (300 µM, not shown). The SNAP-dependent enhancement was significantly inhibited in the presence of the NO scavenger carboxy-PTIO, indicating that NO rather than donor end products underlie the GABA<sub>A</sub> current enhancement (Fig. 1C, *P* = 0.002).

Second, higher concentrations of NO (hundreds of nanomolar to low micromolar, NO-bubbled solutions, see METHODS) produced a transient (1–3 s), GABA-independent inward cur-
rent (Figs. 2, A and C, and 7Bi, asterisks). Based on reversal potential measurements, this NO-dependent, GABA-independent, inward current is a cation current ($E_{\text{rev}} = +23.4 \pm 6.6\text{mV}, n = 5$).

The third effect of NO is the most dramatic and will form the main focus of this work. We find that brief (1–3 s) exposure to higher NO concentrations also produced a several-fold enhancement of the GABA-gated current (Fig. 2A) due to a
transient positive shift in \( E_{\text{GABA}} \) (shift = 24.8 ± 4.2 mV; Fig. 2, C–E). The slight inhibition of GABA-gated current amplitude after exposure to air-exposed NO solution (Fig. 2B) is most likely due to the acidic nature of these solutions (see METHODS) (Huang and Dillon 1999). Note that the time course of recovery for the (higher concentration) NO-induced current enhancement (Fig. 2A) is consistent with the recovery time course for \( E_{\text{GABA}} \) (Fig. 2E). Similar shifts in \( E_{\text{GABA}} \) were obtained with high concentrations (2 mM) of the NO donor NOC 12 (not shown) indicating that the mechanism responsible for the shift in \( E_{\text{GABA}} \) can be activated by either NO delivery method as long as the concentration of NO is in the correct concentration range. A small increase in the slope of the I-V relationship for the GABA-gated current (1st NO effect) was also detectable with higher NO concentrations (Fig. 2D, inset). The role of soluble guanylate cyclase (sGC) activation in the NO-induced shift in \( E_{\text{GABA}} \) was investigated using the sGC inhibitor ODQ. Prolonged (>10 min) preincubation with the inhibitor did not block the NO-induced shift in \( E_{\text{GABA}} \) indicating that sGC activity is not involved in this mechanism (Fig. 2, F and G). The nonsignificant trend toward larger responses in ODQ suggests that basal sGC activity might have a suppressive effect on the mechanism underlying the shift in \( E_{\text{GABA}} \). Finally, the NO-dependent current (2nd NO effect) may be related to the shift in \( E_{\text{GABA}} \) but does not seem to be an absolute requirement because we have observed the shift in the absence of this current.

**NO-induced shift in \( E_{\text{GABA}} \) is due an elevation in cytosolic Cl\(^{-}\)**

Three possible explanations for the NO-induced shift in \( E_{\text{GABA}} \) were examined: a change in ion selectivity of the GABA\(_A\) receptors, the introduction of another permeant anion into the cell, or an increase in intracellular Cl\(^{-}\) concentration. To determine whether NO increases the selectivity of GABA\(_A\) receptors to acetate (the only other anion in the internal solution), internal acetate was substituted with methanesulfonate, a bulky anion unlikely to permeate the receptors. This substitution, however, did not prevent the NO-induced shift in \( E_{\text{GABA}} \) as indicated by the several-fold enhancement of the GABA-gated current (Fig. 3A). This suggests that the NO-induced shift in \( E_{\text{GABA}} \) is not due to a change in the ion selectivity of the channels.

The shift could be due to the production of nitrate (NO\(_3\)) that occurs when NO reacts with O\(_2\) and H\(_2\)O. Because NO\(_3\) is quite permeable through GABA\(_A\) receptors (Biscoe and Duchen 1985; Bormann et al. 1987), it is possible that trapped cytosolic NO\(_3\) (from inwardly diffusing NO) contributes to the shift in \( E_{\text{GABA}} \). Furthermore, although the recording solutions are HCO\(_3\)-free, it is also possible that NO transiently stimulates the production of HCO\(_3\), another anion that can permeate GABA\(_A\) receptors (Bormann et al. 1987). In zero Cl\(^{-}\) internal and zero Cl\(^{-}\) external solutions, no GABA-gated currents were observed either before or after application of NO (Fig. 3B). This argues against the possibility that the shift is due to an increase in intracellular NO\(_3\), or HCO\(_3\), or any other permeant anion.

If the effect of NO is to raise internal Cl\(^{-}\), then a similar shift in reversal potential should also be observed when glycine receptors are activated. Agonist-gated currents were elicited...
with pulses of 20 μM glycine or 20 μM GABA delivered during voltage ramps. Addition of NO caused a shift in the reversal potential to more positive values for both agonists (Fig. 3C; GABA shift: 33.6 ± 11.5 mV; glycine shift: 30.0 ± 14.0 mV; P = 0.67; n = 5), indicating that NO is stimulating a redistribution of Cl⁻ in these cells. An increase in the slope of the glycine-gated current was also observed, indicating an enhancing effect of NO on glycine receptor function. The ability to change the internal Cl⁻ concentration in the face of diffusion from the pipette may be unexpected, but it is not unprecedented. Cl⁻ transport has been shown to be effective in opposing diffusion from the recording pipette (Staley et al. 1996) and changes in cytosolic Cl⁻ have been measured by optical methods in the ruptured patch recording configuration (Isomura et al. 2003). It is also possible that the redistribution of Cl⁻ is not a global event, but one that occurs locally, possibly in neuronal processes.

Current-clamp recordings were made to determine how the NO-induced shift in E_{Cl⁻} affects GABA- and glycine-dependent changes in membrane potential (Fig. 3D). Resting membrane potentials were −60.1 ± 13.2 mV (n = 5). Under control conditions, application of GABA or glycine hyperpolarized these cells to −70.9 ± 2.7 and −68.7 ± 5.3 mV, respectively. For the first agonist pulse after NO application, GABA depolarized the cells to −31.8 ± 25.2 mV and glycine depolarized the cells to −34.4 ± 18.4 mV. One cell responded to both GABA (not shown) and glycine (Fig. 3D) with a single action potential followed by a steady depolarization. This is the typical voltage response for these cells given sufficient depolarization (Gleason et al. 1993). It is important to note, however, that action potentials are not required for Ca²⁺-dependent neurotransmitter release from these cells (Gleason et al. 1993). These current-clamp recordings demonstrate that NO can change the sign of whole-cell voltage responses to GABA and glycine.

**NO-induced shift in E_{Cl⁻} occurs at synapses**

To examine the influence of NO specifically at retinal amacrine cell synapses, dual perforated-patch recordings were made from pairs of cultured GABAergic amacrine cells. It is well established that GABAergic amacrine cell synapses are normally inhibitory, both in the retina (Lagnado 1998) and in these cultures (Gleason et al. 1993). Recordings from isolated pairs of amacrine cells demonstrate that brief exposure to NO can transiently change the sign of GABAergic synapses (Fig. 4). With both pre- and postsynaptic cells in the voltage-clamp configuration, a depolarizing voltage step in the presynaptic cell produced a small outward current in the postsynaptic cell (A). Depolarization of the presynaptic cell from −70 to −10 mV elicits a small outward current in the postsynaptic cell (black trace, V_{hold} = −66 mV). After NO, depolarization of the presynaptic cell produces a large inward current in the postsynaptic cell (gray trace). Traces immediately after NO application were contaminated by the NO-dependent current. The trace shown was collected −15 s after NO. NO exposure time is 2–3 s (see METHODS). Scale bars are 200 pA, 50 ms. B: current-clamp recordings from the same postsynaptic cell as in A. Depolarization of the presynaptic cell (to 0 mV, in voltage clamp) produces only a slight hyperpolarization in the postsynaptic cell (black trace) because the resting potential of this cell (−67 mV) is near the predicted E_{Cl⁻} (−70 mV). A record collected −20 s after NO exposure shows that the postsynaptic response is now depolarizing (gray trace). Scale bars are 5 mV, 100 ms. Records were collected with normal internal containing amphotericin B and TEA-A external solutions.

**nkcc does not mediate the increase in cytosolic Cl⁻**

What mechanism underlies the increase in cytosolic Cl⁻? The plasma membrane Na⁺/K⁺/Cl⁻ co-transporter (NKCC) and the K⁺/Cl⁻ co-transporter (KCC2) are Cl⁻ co-transport mechanisms known to regulate the distribution of Cl⁻ across neuronal plasma membranes (Kakazu et al. 2000; Russell...
2000). It is now well established that changes in Cl⁻ co-
transporter expression determine the effects of GABA during
development (for review, see Payne et al. 2003). In the adult
retina, $E_{\text{Cl}^-}$ varies among cell types and subcellular locations,
and this correlates with the expression pattern of NKCC and
KCC2 (Vardi et al. 2000). Furthermore, the response properties
of retinal starburst amacrine cells are dependent on the activity
of NKCC and KCC2 (Gavrikov et al. 2003). Given the estab-
lished role of these transporters in determining $E_{\text{Cl}^-}$
of NKCC and KCC2 (Vardi et al. 2000). Furthermore, the response properties
of retinal starburst amacrine cells are dependent on the activity
of NKCC and KCC2 (Gavrikov et al. 2003). Given the estab-
lished role of these transporters in determining $E_{\text{Cl}^-}$, we investi-
gated the role of NKCC and KCC2 in the NO-induced shift
in $E_{\text{Cl}^-}$.

NKCC typically transports 2 Cl⁻, 1 Na⁺, and 1 K⁺ into the
cell and the neuron specific K⁺-Cl⁻ co-transporter, KCC2,
transports 1 Cl⁻ and 1 K⁺ out of the cell. Thus the NO-induced
shift in $E_{\text{GABA}}$ could be due to an increase in NKCC activity or a
decrease in KCC2 activity. To determine if these mechanisms
were involved, perforated-patch recordings were made with
Cl⁻-impermeant gramicidin in the pipette and the co-transport
inhibitors, bumetanide (300 µM) and furosemide (300 µM)
were used to block NKCC and KCC2 activity. Both inhibitors
shifted $E_{\text{Cl}^-}$ to more negative potentials, indicating a dominant
inhibitory effect on NKCC (Fig. 5, A and C). Neither blocker,
however, inhibited the NO-induced shift in $E_{\text{Cl}^-}$ (Fig. 5, B and
D). To assess the variability of responses under control condi-
tions, the effects of two separate NO applications were also
examined and we found no significant difference between the
two trials ($P = 0.69, n = 5$, not shown). At lower concentra-
tions (10 µM), bumetanide is selective for NKCC (Russell
2000). In similar experiments, bumetanide at 10 µM was also
ineffective in blocking the shift in $E_{\text{Cl}^-}$ (not shown).

Removal of the externally required co-transported ions
shifted $E_{\text{Cl}^-}$ to more negative potentials. Furthermore, for those
cells that were exposed to both zero K⁺ and zero Na⁺ solu-
tions, $E_{\text{Cl}^-}$ was considerably more negative in zero K⁺ solu-
tions than in zero Na⁺ solutions (Fig. 6A). In some cases,
switching to zero K⁺ shifted $E_{\text{Cl}^-}$ by tens of millivolts in as
few as 15 s (Fig. 6B). These results are consistent with the
prediction that zero external K⁺ would prevent inward Cl⁻
transport through NKCC and promote outward Cl⁻ transport
through KCC2. Despite these effects, none of these manipula-
tions blocked the NO-induced shift in $E_{\text{Cl}^-}$ (Fig. 6, C–E).

Figure 6F shows that removal of co-transported ions did not
cause a statistically significant ($P = 0.26; 0.17$) change in the
magnitude of the NO-induced shift in $E_{\text{Cl}^-}$. Interestingly, a
nonsignificant trend toward larger shifts was observed in the
absence of co-transported ions. This may relate to an enhanced
Cl⁻ gradient between the cytosol and an internal compartment
(see following text). The roles of two other known plasma
membrane Cl⁻ transport mechanisms have also been investi-
gated. Neither 4,4’-disothiocyanostilbene-2,2’-disulfonic
acid (DIDS, 40 µM, $n = 5$) a HCO₃⁻/Cl⁻ transport inhibitor,
or ethacrynic acid (10 µM, $n = 4$), an inhibitor of ATP-
dependent, Na⁺-independent Cl⁻ transport, blocked the shift
in $E_{\text{Cl}^-}$ (not shown).

**Shift in $E_{\text{Cl}^-}$ is independent of extracellular Cl⁻**

The lack of involvement of known plasma membrane Cl⁻
transporters indicates that NO is either stimulating an unexam-
ined Cl⁻ transport mechanism or releasing Cl⁻ from inside the
cell. Endosomal compartments are known to maintain rela-
tively high Cl⁻ concentrations to offset the membrane poten-
tials generated by inward proton pumping and endosomal
acidification (Faundez and Hartzell 2004; Sonowane and Verk-
man 2003). To determine whether NO was releasing Cl⁻ from
an internal compartment, external Cl⁻ was reduced to match

![Fig. 5. Inhibition of Na⁺-K⁺-Cl⁻ co-transporter (NKCC) and K⁺-Cl⁻ co-transporter (KCC) Cl⁻ co-transporters does not block the NO-induced shift in $E_{\text{Cl}^-}$. A and C: leak-subtracted currents from voltage ramps delivered in the presence of GABA under control conditions (no NO), in the presence of inhibitor (bumetanide (B) or furosemide (F)) and after NO exposure in bumetanide- or furosemide-containing solutions (gray trace). Records were obtained in the perforated-patch configuration with gramicidin in the pipette (Cs⁺-B internal, TEA-A external). B and D: $E_{\text{Cl}^-}$ co-transporter inhibitors do not significantly (bumetanide $P = 0.66$; furosemide $P = 0.17$) reduce the NO-induced shift in $E_{\text{Cl}^-}$. NO-induced shifts in $E_{\text{Cl}^-}$ in the presence of each inhibitor were compared with control applications of NO in the same cells.](http://jn.physiology.org/)}
the internal Cl\(^-\) concentration (14.2 mM). NO was applied while cells were held at the reversal potential for Cl\(^-\). Under these conditions, subsequent records collected during pulses of GABA demonstrated that the NO-induced redistribution of Cl\(^-\) persisted in the absence of an electrochemical gradient for chloride across the plasma membrane (Fig. 7A, see also Fig. 2C). To determine whether external Cl\(^-\) was required at all, NO was also applied in the absence of external Cl\(^-\). For these experiments (Fig. 7B), control ramps (Bi) and the NO applications (Bii) were conducted in zero Cl\(^-\) external solution. The arrival of NO in zero Cl\(^-\) was marked by the presence of the NO-dependent inward current (asterisk). After switching to normal Cl\(^-\) external solution (TEA-A), so that the reversal potential of the current could be measured, another set of ramps was delivered (Biii). Values for the reversal potentials of the GABA-gated currents after NO application (mean shift: 26.6 ± 9.9 mV, n = 9) indicate that an increase in internal Cl\(^-\) occurred in the absence of external Cl\(^-\). Control experiments were performed in the same manner but without NO application (Fig. 7, D and E). Only slight fluctuations (1–2 mV) in reversal potential resulted from just switching between 0 Cl\(^-\) internal and normal external solutions.

The switch back to normal external Cl\(^-\) concentration before measuring the GABA-gated current reversal potentials leaves open the possibility that rapid Cl\(^-\) influx could occur just prior to measuring the reversal potential. To avoid this possibility, we also examined the large NO-induced change in the amplitude of the GABA-gated currents at −70 mV that results from the positive shift in reversal potential. In this way, the effects of NO can be evaluated without re-introducing external Cl\(^-\). In this experiment, both NO and GABA are applied in zero external Cl\(^-\). Substantial increases (2.9 ± 0.7-fold) in the GABA-gated current amplitude were observed in all cells tested (n = 5; Fig. 8A). Because external Cl\(^-\) is absent for both the NO injection and the enhancement of the GABA-gated current, the Cl\(^-\) must be coming from the inside of the cell. Why, in the absence of internal and external Cl\(^-\) (Fig. 3B), did the NO-induced release of Cl\(^-\) from internal stores not produce an inward GABA-gated current? It is plausible that under Cl\(^-\)-free conditions, the Cl\(^-\) store becomes depleted. Clearly, much remains to be understood about the dynamics of intracellular Cl\(^-\) fluxes.

Aside from the removal of both internal and external Cl\(^-\), the only manipulation that blocked the NO-induced shift in
NO-induced shift in $E_{Cl^-}$ is not confined to the avian retina

Does the NO-induced shift in $Cl^-$ distribution rely on an amacrine cell-specific mechanism or is the underlying mechanism more widely expressed? To explore this, we made similar recordings from cultured rat hippocampal neurons. We find that NO also induces a shift in $E_{Cl^-}$ in hippocampal neurons (Fig. 9A; mean shift 38 ± 19.6 mV, n = 6). An inward GABA-independent/NO-dependent current was also observed in hippocampal neurons (Fig. 9C, asterisk). To determine whether the shift in $E_{Cl^-}$ was also due to internal release of $Cl^-$, we repeated the experiment shown in Fig. 7B. Removal of extracellular $Cl^-$ during NO application did not inhibit the shift in $E_{Cl^-}$, suggesting that, as for amacrine cells, NO stimulates the release of $Cl^-$ from an internal store in hippocampal neurons (Fig. 9D).

DISCUSSION

These results indicate that NO can modulate GABAergic signaling through two distinct mechanisms. Prolonged and moderate (~100 nM) release of NO from donors enhances GABA-gated currents by modifying receptor activity. Brief pulses of higher concentrations of NO (hundreds of nanomolar, NO-bubbled solutions) produce sGC-independent increases in intracellular $Cl^-$ and shift $E_{GABA}$ to more positive potentials. Furthermore, we show that the shift in the $Cl^-$ reversal potential occurs at synaptic sites and is sufficient to promote excitation at GABAergic synapses. Finally, our results indicate that the redistribution of $Cl^-$ underlying this change results from a release of $Cl^-$ from an internal compartment.

Role of NO in the retina

Measurements indicate that the concentration of NO at the cell in NO-bubbled solutions is in the hundreds of nanomolar to low micromolar range. Is this range of concentrations relevant to the levels of NO generated in the retina? NO electrode measurements at the inner retinal surface yield values ranging from 6 to 15 μM (Donati et al. 1995; Groppe et al. 2003). Consistent with the electrode measurements, a biochemical assay (the Griess method) also shows retinal NO produc-
tion well into the micromolar range (Heiduschka and Thanos 1998). These intraocular measurements indicate that NO concentrations can be substantial and that the doses of NO used in our experiments are within the physiological range.

Recently, NO electrode measurements have been made near the surface of an individual cell in the ganglion cell layer of the turtle retina (Eldred and Blute 2005). An NO concentration of ~200 nM was detected. It is important to note, however, that imaging of NMDA-stimulated NO production in the same retina has demonstrated that the NO signals generated are often highly localized to individual cells and even discrete boutons in the inner synaptic layer (Blute et al. 2000). This observation suggests that some of the downstream effects of NO signaling occur primarily in nNOS-expressing cells and their immediate synaptic partners, where NO concentrations would be higher.

How might the NO-induced changes we show for cultured amacrine cells affect GABAergic signaling between amacrine cells in the inner retina? The diversity of synaptic partners and complex synaptic arrangements of amacrine cells in the IPL (Dowling and Boycott 1965; Hartveit 1999; Kolb 1997; Marc and Liu 2000) complicate this issue. The cartoon in Fig. 10 depicts a simplified subset of interactions in the inner retina. The cell on the left is a GABAergic or glycinergic, nNOS-

![FIG. 8. NO promotes release of Cl\(^-\) from an internal source. A: voltage-clamp recording is shown from a representative amacrine cell held at −70 mV (normal internal, TEA external). In the control panel, the external solution was switched to 0 Cl\(^-\) − 90 s before the pulse of GABA. In this experiment, the rapid perfusion method usually used to apply GABA (METHODS) was used to switch between normal and 0 external Cl\(^-\). The return to normal external Cl\(^-\) reduces the size of the current due to the reduction in driving force on Cl\(^-\). In the same cell, the protocol was repeated with an NO injection delivered into 0 Cl\(^-\) external 15 s before the onset of GABA delivery. The NO-dependent current was observed but is not plotted. The amplitude of the GABA-gated current is enhanced −3.5-fold, consistent with a substantial positive shift in \(E_{\text{Cl}}\). B: GABA-gated currents recorded with high Cl\(^-\) internal (TEA-B external, predicted \(E_{\text{Cl}} = 0 \text{ mV}\)) before (black trace) and after (overlapping gray trace) NO.

![FIG. 9. NO-induced shift in \(E_{\text{Cl}}\) occurs in rat hippocampal neurons. A: GABA-gated currents recorded from a hippocampal neuron during voltage ramps before (black trace) and after (gray trace) NO application. (ruptured-patch, normal hippocampal external and internal solutions). B–D: current records elicited by the voltage protocol depicted in Fig. 7B. B: GABA-gated current collected in 0 external Cl\(^-\). C: NO-dependent current (asterisk) recorded in 0 chloride indicates timing of NO arrival. Scale bar, 2 s. D: after returning to normal (TEA-H) external solution, a shift in \(E_{\text{GABA}}\) is revealed. The gray trace is recorded 30 s after return to normal \(\left[\text{Cl}^\text{−}\right]_o\), and the black trace is recorded 1 min after return to normal \(\left[\text{Cl}^\text{−}\right]_o\). Recordings in A–D are from the same cell. Recordings were made in the ruptured-patch configuration with TEA-H or 0 Cl\(^-\)-H external solutions and Cs\(^+\)-H internal solution.

![FIG. 10. Model for NO effects on amacrine cell signaling. An nNOS-expressing GABA- or glycineric amacrine cell receiving both inhibitory and excitatory input generates a moderate inhibitory output (left). After NO, \(E_{\text{Cl}}\) shifts positive (darker shading), all inputs become excitatory, and inhibitory output from the amacrine cell is enhanced. The cells depicted are highly simplified in that amacrine cell synaptic inputs and outputs are not typically segregated.](http://jn.physiology.org/ by 10.220.33.5 on August 28, 2017)
expressing amacrine cell that receives a mixture of excitatory (glutamatergic, from bipolar cells) and inhibitory (GABA- and/or glycineergic, from other amacrine cells) inputs. The net effect of these inputs is to determine the strength of the inhibitory output from the cell onto its postsynaptic partners (ganglion cells, bipolar cells, and/or amacrine cells). If the cell is exposed to a relatively high concentration of NO (presumably via its own nNOS activity), the distribution of chloride shifts in that amacrine cell so the balance of its input becomes more excitatory and the inhibitory output of this cell is enhanced. Consistent with this proposal, Wang et al. (2003) demonstrate an NO-dependent suppression of ganglion cell light responses that is due to alterations in presynaptic (probably amacrine cell) input. This observation would be consistent with an NO-dependent shift in the amacrine cell E_{Cl} that results in an enhancement of inhibitory output onto ganglion cells.

Potential source of internal Cl\(^-\)

Our results indicate that the NO-induced redistribution of Cl\(^-\) is due to Cl\(^-\) release from inside the cell. Endosomal compartments are a potential source of internal Cl\(^-\). Cl\(^-\) is thought to enter these compartments as a counter ion for protons being pumped in by vacuolar proton pumps (Sonawane and Verkman 2003). Movement of Cl\(^-\) across endosomal membranes is thought to be mediated by the CLC family of Cl\(^-\) transport proteins. CLC-7 are found on intracellular membranes (for review, see Faundez and Hartzell 2004; Jentsch et al. 2002). Of these, CLC3 may be the most relevant because it is highly expressed in the brain and has been shown to be expressed on endosomes, including synaptic vesicles. Interestingly, knockouts of the CLC3 gene resulted in marked tissue degeneration specifically in the hippocampus and the retina (Stobrawa et al. 2001). Although physiological evidence for a role for CLC transport proteins in the NO-induced shift in E_{Cl} awaits further experimentation, we have found that a polyclonal antibody raised against a conserved peptide from CLC3 gives an intense and punctuate labeling pattern that appears to be located intracellularly (McMains and Gleason, unpublished observations). It may be that the efflux of Cl\(^-\) from endosomes via CLC3 contributes to the NO-induced shifts in E_{GABA} and E_{glycine} and the transitions between inhibition and excitation.

Interestingly, NO has been shown to reversibly inhibit the vacuolar proton pump through S-nitrosylation (Forgac 1999). Although the mechanism by which NO stimulates Cl\(^-\) efflux is not yet known, given the established relationship between proton pumping and Cl\(^-\) movement across endosomal membranes, it is plausible that proton flux is somehow involved. However, the Cl\(^-\) efflux is achieved, the demonstration that it does occur and that it may be a broadly expressed mechanism is sure to impact our view of GABA and glycine-dependent synaptic signaling in the CNS.

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References


Heiduschka P and Thamnos S. NO production during neuronal cell death can be directly assessed by a chemical reaction in vivo. Neuroreport 9: 4051–4057, 1998.


