Olfactory Nerve Stimulation-Induced Calcium Signaling in the Mitral Cell Distal Dendritic Tuft

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Yuan, Q. and T. Knöpfel. Olfactory nerve stimulation-induced calcium signaling in the mitral cell distal dendritic tuft. J Neurophysiol 95: 2417–2426, 2006. First published November 30, 2005; doi:10.1152/jn.00964.2005. Olfactory receptor neuron axons form the olfactory nerve (ON) and project to the glomerular layer of the olfactory bulb, where they form excitatory synapses with terminal arborizations of the mitral cell (MC) tufted primary dendrite. Clusters of MC dendritic tufts define olfactory glomeruli, where they involve in complex synaptic interactions. The computational function of these cellular interactions is not clear. We used patch-clamp electrophysiology combined with whole field or two-photon Ca²⁺ imaging to study ON stimulation-induced Ca²⁺ signaling at the level of individual terminal branches of the MC primary dendrite in mice. ON-evoked subthreshold excitatory postsynaptic potentials induced Ca²⁺ transients in the MC tuft dendrites that were spatially inhomogeneous, exhibiting discrete “hot spots.” In contrast, Ca²⁺ transients induced by backpropagating action potentials occurred throughout the dendritic tuft, being larger in the thin terminal dendrites than in the base of the tuft. Single ON stimulation-induced Ca²⁺ transients were depressed by the NMDA receptor antagonist d-aminophosphonovaleric acid (d-APV), increased with increasing stimulation intensity, and typically showed a prolonged rising phase. The synaptically induced Ca²⁺ signals reflect, at least in part, dendrodendritic interactions that support infraglomerular coupling of MCs and generation of an output that is common to all MCs associated with one glomerulus.

INTRODUCTION

Mitral cells (MCs) are the principal output neurons of the olfactory bulb and represent the first stage of central odor processing. The distally tufted primary dendrites of rodent MCs outline complex structures termed olfactory glomeruli. A given glomerulus is innervated by axons of olfactory receptor neurons (ORNs), each of which expresses the same odor nerve (ON) synapses that release glutamate might mediate Ca²⁺ signals via N-methyl-D-aspartate (NMDA) receptor or mGluR1 (Aroniadou-Anderjaska et al. 1999; Carlson et al. 2000; Ennis et al. 1996; Friedman and Strowbridge 2000; Yuan et al. 2004). In addition, olfactory nerve (ON) synapses that release glutamate might mediate Ca²⁺ signals via N-methyl-D-aspartate (NMDA) receptor or mGluR1 (Aroniadou-Anderjaska et al. 1999; Carlson et al. 2000; Ennis et al. 1996; Friedman and Strowbridge 2000; Hayar et al. 2004; Heinbockel et al. 2004; Isaacson 1999; Trombley and Westbrook 1990).

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In this work, we studied subthreshold synaptic stimulation and bAP-induced signals using combined patch clamp and Ca\textsuperscript{2+} imaging techniques. We characterized Ca\textsuperscript{2+} transients induced by bAPs in the primary dendrite of the MC and used these signals as a reference for synaptically induced signals. We found that focal ON stimulation induced patch-like Ca\textsuperscript{2+} signals that were NMDA receptor dependent and exhibited a prolonged rising phase that, at least in part, reflect dendrodendritic interactions (Isaacson 1999). Our results are consistent with the concept that intraglomerular signaling supports coupling of MCs and generation of an output that is common to all MCs associated with one glomerulus.

METHODS

Slice preparation and electrophysiology

Horizontal slices (350 \mu m) of olfactory bulbs were obtained from 18- to 26-day-old ICR mice of both sexes. Slices were cut by a Vibriscolider (VT 1000S, Leica), recovered at 32°C for the 1st hour and afterwards at room temperature (23–25°C). After more than 1 hour of recovery, slices were transferred into a recording chamber and perfused with artificial cerebrospinal fluid (ACSF) containing (in mM) 118 NaCl, 25 NaHCO\textsubscript{3}, 1 NaH\textsubscript{2}PO\textsubscript{4}, 3 KCl, 1 MgCl\textsubscript{2}, 2 CaCl\textsubscript{2}, and 10 glucose, equilibrated with 95% O\textsubscript{2}/5% CO\textsubscript{2}. Experiments were performed at either room temperature or 32°C. For electrophysiological and fluorescence recordings, slices were placed in an immersion-type perfusion chamber mounted on the stage of an upright microscope (Leica, DMLFS or Nikon, E600FN) and visualized using Nikon 63X water immersion lenses (NA = 0.9). The procedures had approval from the animal ethical committee of the RIKEN Brain Science Institute.

Patch-clamp recordings were carried out in whole cell configuration. Glass pipettes (3.5–5 M\Omega) resistance were pulled from borosilicate glass using a two-stage vertical puller (Narishige, Tokyo). Pipettes contained (in mM) 0.2 Oregon green BAPTA-1, 125 K-gluconate, 2 MgCl\textsubscript{2}, 0.025 CaCl\textsubscript{2}, 10 HEPES, 1 EGTA, 0.5 Na\textsubscript{2}ATP, and 0.7–1.2 nA). In one set of experiments, the Na\textsuperscript{+} channel blocker QX-314 (10 mM) was included in the intracellular solution.

Whole cell patch-clamp recordings were made from the somata of MCs using an Axon Instrument Axonpatch 200B (Axon Instruments, Sunnyvale, CA). Under differential interference contrast visual guide, MCs were identified and selected by their location in the MC layer, the size and shape of the somata (around 25 \mu m diameter), and the distinct single primary dendrite that project into a glomerulus. Cells that had resting membrane potential more negative than −45 mV at zero holding current and without correction for junction potentials were selected for recording. Holding current of ±300 pA was used to hold the membrane potential at rest between −60 and −65 mV. Back propagating APs were generated by current injection (0.7–1.2 nA, 2 ms) through the patch pipette (AP amplitude 128 ± 2.1 mV, overshoot 65.8 ± 2.1 mV; mean ± SE, n = 15 cells). Size and shape of bAPs remained stable throughout the experiments.

The EPSPs were elicited by extracellular stimulation of the olfactory nerve using either a glass pipette (0.8–1.0 M\Omega) containing normal ACSF solution or a miniature bipolar concentric electrode (tip diameter 25 \mu m). Model MCE-100; Rhodes Medical Instruments, Woodland Hills, CA). The electrode was positioned, under visual control, on a small bundle of presynaptic axons just outside the imaged glomerulus. Both types of electrodes produced identical results (in particular, focal Ca\textsuperscript{2+} signals were seen with both types of electrodes).

Drugs applied in the bath were made from aqueous stock solutions. For recording of bAP-induced Ca\textsuperscript{2+} signals in the absence of synaptic transmission, the ACSF contained 50 \mu M \alpha-aminophosphonoovaleric acid (\alpha-APV, an NMDA receptor antagonist), 40 \mu M 2,3-dixoio-6-nitro-1,2,3,4-tetrahydrobenzof[1]quinoxaline-7-sulfonamide (NBQX), and 40 \mu M bicuculline. For recording of EPSPs in the absence of inhibition, the ACSF contained 40 \mu M bicuculline and, in a series of experiments, also contained 2–4 \mu M NBQX (to prevent synaptically driven oscillatory activity). To test the contribution of NMDA and mGluRs in generating local Ca\textsuperscript{2+} signals, 2-APV (100 \mu M) and methyl-4-carboxyphenylglycine (MCPG, 1 mM, a group I and II mGluR antagonist) were used through bath application. All drugs were purchased from Tocris Cookson (Bristol, United Kingdom).

Loading of olfactory nerve axons with Calcium Green-1 dextran

For Ca\textsuperscript{2+} imaging in olfactory nerve axons, mice (16 to 18 days old) were anesthetized by pentobarbital sodium (50 mg/kg, s.c.). Olfactory receptor neurons in nasal cavities were exposed to 2% Triton X-100 in physiological saline for 5 min. Subsequently, nasal cavities were injected with 8 \mu l of 4% Calcium Green-1 dextran (10 kDa, Molecular Probes, Eugene, OR) in physiological saline, and mice were recovered from anesthesia. After 2–5 days, dye-injected mice were used for slice preparation (Mutoh et al. 2005).

Ca\textsuperscript{2+} Imaging

Fluorescence of Oregon green BAPTA-1 or Calcium Green-1 dextran was excited by a two-photon laser (810 nm, Verdi, Coherent, Palo Alto, CA) using a multifocal scanner (frame rate 7 Hz) (Straub et al. 2000) or by whole field epi-illumination (488 nm; frame rate 20 Hz), with light provided by a monochromator (Polychrome IV; Till photonics, Gräfelfing) and detected by a cooled CCD camera (PCO Sensicam, PCO imaging, Kelheim) with spatial resolution of 0.226 \mu m/pixel (× 63 objective, 520x680 pixels, 2x2 binning) under the control of ImagePro software (Media Cybernetics, Silver Spring, MD). Optical filters for whole field epifluorescence consisted of a dichroic beam splitter (DCLP 505 LP; Chroma Technology, Brattleboro, VT) and an emission filter (535 ± 25 nm). Fluorescence from intracellularly loaded dye equilibrated throughout the cell within 30–40 min of commencing whole cell configuration. Changes of [Ca\textsuperscript{2+}]\textsubscript{i} were expressed as relative fluorescence changes (ΔF/F, where F is the baseline fluorescence before a stimulus and ΔF is the evoked change in fluorescence). ΔF/F was measured in areas of interest in the shaft and in the terminal tuft of the MC primary dendrite. Fluorescence values were determined by subtracting pixel values averaged over regions outside the stained cell from each pixel of the series of images (i.e., fluorescence values are “background subtracted”). The ΔF/F images were spatially low-pass filtered (Gaussian kernel with half-width of 0.5–3 \mu m). Ca\textsuperscript{2+} maps represent the average of two to five series of images (trials) unless stated otherwise. For recordings under two-photon excitation, Ca\textsuperscript{2+} images from different layers of the tufts were added to yield projection images. Responsive areas within the dendritic tuft were identified as “hot spots” if their peak amplitude exceeded the response averaged over the whole tuft (“global tuft response”) by a factor of 2. The border of these hot spots was defined by the half-maximal value of the hot spot amplitude relative to the global tuft response. Color-coded maps of ΔF/F were obtained using custom-made macros in ImagePro Plus. Color-coded images show the maps of the peak Ca\textsuperscript{2+} transient if not otherwise stated.

RESULTS

Ca\textsuperscript{2+} signals induced by bAPs in the MC primary dendrite glomerular tuft

MCs were loaded with the fluorescent Ca\textsuperscript{2+} indicator Oregon green BAPTA-1 (200 \mu M) from the patch-pipette attached to the soma. Brief intrasomatic depolarizing pulses (2 ms, 0.7–1.2 nA) were used to evoke single bAPs, and related Ca\textsuperscript{2+} transients were seen.
transients were imaged from the glomerular tuft of the primary dendrite (Fig. 1).

Under whole field fluorescence excitation, somatically triggered APs robustly produced a rise in [Ca\(^{2+}\)]\(_i\), in dendritic shafts and tuft terminals, indicating that these APs equally invaded all of the terminal branches in the tuft (Fig. 1, A–C). The relatively homogeneous distribution of the Ca\(^{2+}\) signal was not due to the saturation of the Ca\(^{2+}\) indicator because increasing numbers of bAPs raised the peak amplitude of the Ca\(^{2+}\) transient in the dendritic tuft near-linearly (n = 3, Fig. 1D–E). The rise in [Ca\(^{2+}\)]\(_i\) was clearly larger in thinner terminal branches of the tuft as compared with the more proximal dendritic regions (Fig. 1, B and C). This clear gradient of increasing Ca\(^{2+}\) transients from the primary dendrite toward the fine tuft branches was seen in all cells examined (n = 12). We measured Ca\(^{2+}\) transients in different portions of dendritic tufts (including dendritic shaft, first order branch and second order branch) in n = 7 cells with clear morphological details. We found significantly larger Ca\(^{2+}\) transients with higher order dendritic compartments (peak amplitude [ΔF/F]: dendritic shaft: 6.5 ± 0.7%, first order branch: 10.2 ± 0.8%; second order branch: 12.9 ± 0.8%, mean ± SE, P < 0.0002, One-way analysis of variance [ANOVA], post hoc Tukey test). Because the diameter of dendrites decreases toward more distal dendritic branches of the MC primary tuft (Kasowski et al. 1999), the simplest explanation for the observed gradient is the difference in surface-to-volume ratio; larger surface-to-volume ratio of thinner dendrites would be expected to result in a larger increase in [Ca\(^{2+}\)]\(_i\).

An alternative explanation for the gradient could be that auto-excitation of tuft branches or inhibitory mechanisms at more proximal sites are involved (Aroniadou-Anderjaska et al. 1999; Carlson et al. 2000; Chen et al. 2000; Didier et al. 2001; Isaacson 1999; Lowe 2002; Salin et al. 2001). These mechanisms may produce inhomogeneities in the bAP-Ca\(^{2+}\) maps that cannot be resolved by whole field fluorescence excitation (Debarbieux et al. 2003).

To clarify this point, we performed an additional series of measurements using two-photon laser scanning excitation to improve spatial resolution. The two-photon system employed uses full frame integration; therefore it gives an accurate measure of the Ca\(^{2+}\) signal over the integration period (100 ms) (Straub et al. 2000). The advantage of two-photon excitation, as employed here, lies in the high spatial resolution, and the complementary whole field fluorescence recording allowed a high temporal resolution. In the experiments employing...
two-photon excitation, both excitatory and inhibitory synaptic transmissions were blocked by 40 μM NBQX, 50 μM t-APV, and 40 μM bicuculline. The results obtained under these conditions were consistent with those obtained with whole field imaging in control ACSF: bAPs invaded all parts of the MC dendritic tuft, and with synaptic transmission blocked, Ca$^{2+}$ transients still increased in amplitude with the decrease in dendritic diameter (Fig. 1, F–J). We therefore measured and compared Ca$^{2+}$ transients from different locations. Data from n = 4 cells were pooled in Fig. 1J. The peak amplitude ΔF/F values were 4.2 ± 1.3% at the base of the dendritic tuft; 6.4 ± 1% at first order branch, and 12 ± 1% at second order branch (mean ± SE; P = 0.0005, one-way ANOVA, post hoc Tukey test). We concluded that larger Ca$^{2+}$ transients in more distal branches were based on differences in the surface-to-volume ratio and were not due to auto-excitation or dendrodendritic interactions.

Ca$^{2+}$ signals induced by activation of ON synapses

The subthreshold EPSPs were evoked by stimulating bundles of ON axons that innervate the glomerular tuft of the dye-filled MC. Optical and electrical recordings of the evoked EPSP were interleaved with recordings of bAPs under either whole field illumination (Fig. 2) or two-photon excitation (Fig. 3). Synaptic stimulation induced Ca$^{2+}$ maps that were distinct in several respects from those induced by bAP. First, Ca$^{2+}$ transients associated with subthreshold EPSPs were pronounced in the tuft, whereas changes in the primary dendrite proximal to the tuft were either small or absent (Fig. 2, B–E). Second, synaptically induced Ca$^{2+}$ transients were clearly localized to one or several hot spots (Fig. 2, C and D; n = 12). The localization of Ca$^{2+}$ hot spots was robust throughout single trials, with only small variation in peak amplitudes (Fig. 2, C1–C3).

Two-photon microscopy revealed that these hot spots correspond spatially to short portions of terminal dendritic branches (Fig. 3). To account for possible errors in recorded Ca$^{2+}$ maps that may have resulted from a biased normalization of the fluorescence signals to resting fluorescence levels, we also normalized the data by dividing the EPSP-Ca$^{2+}$ maps by corresponding bAP-Ca$^{2+}$ maps (ΔF$_{\text{syn}}$/ΔF$_{\text{b-AP}}$; Fig. 3G). These ratio maps closely resembled the ΔF$_{\text{syn}}$/F maps, indicating that the observed hot spots did not result from inhomogeneities in dye concentration or from errors in background subtraction.

For cells recorded under whole-field illumination (n = 8), quantitative analysis was applied to compare the Ca$^{2+}$ signals over the hot spot regions with the average response over the entire tuft (“global responses”). We defined “hot spot(s)” as the region(s) in the EPSP-Ca$^{2+}$ map where the ΔF/F values exceeded the global response by a factor of two. Eight out of twelve cells exhibited one to three clearly defined hot spots according to this definition. The border of hot spots was defined by a threshold value calculated as half-maximal amplitude within the hot spot region relative to the global response. The average size for hot spots was 7.8 ± 0.7 μm in diameter (mean ± SE, n = 15 hot spots from n = 8 cells). The Ca$^{2+}$ signals averaged over the whole tuft and over hot spots as well as the ratio between these values were calculated for bAP and EPSP-induced signals in each cell. The average signals (ΔF/F; mean ± SE, n = 8) were 8.16 ± 2.26% (bAP at hot spot), 6.53 ± 1.55% (bAP over the whole tuft; P > 0.08, compared with bAP at hot spot), 5.14 ± 0.60% (EPSP at hot spot), and 1.35 ± 0.22% (EPSP over the whole tuft; P < 0.0005, compared with EPSP at hot spot). The mean ratio between the EPSP-induced signals over the hot spots and the signals measured over the whole tuft was 4.8 ± 1.2 (SE) and is significantly larger than the corresponding value for the bAPs (1.2 ± 0.1, mean ± SE; P < 0.02, paired t-test).

To better understand the input-output relationship between ON axons and MC terminal tufts, we estimated the spread of activated fibers in our slice preparation by imaging Ca$^{2+}$ signals in the presynaptic terminals of ON axons. Ca$^{2+}$ staining in the ON axons was achieved by nose injection of Calcium Green-1 dextran 2–5 days before slice physiology and imaging (n = 5). Figure 3 shows examples of presynaptic Ca$^{2+}$ signals that were obtained by the same protocol used to image postsynaptic responses. These examples indicate activation of a subset of dye-loaded ON fibers with relatively low stimulation intensity (Fig. 4, A2 and B1), and under higher stimulation intensity, a more widespread activation of ON fibers with subregions that exhibit larger than average signals (Fig. 4, A3 and B2). The subset of activated ON fibers depended on the positioning of the stimulation electrode, as illustrated by the extreme case, in...
which the stimulation electrode was placed onto the lower border of a glomerulus (Fig. 4B3). The presynaptic Ca$^{2+}$ signals were graded with stimulation intensities (Fig. 4, A2–B2) and thus represented compound responses, as does the ON-EPSP. This result suggests that postsynaptic hot spots may be recruited at locations where the density of activated synapses is high.

Localized Ca$^{2+}$ signals induced by activation of ON synapses are mediated by NMDA receptors

The localized Ca$^{2+}$ changes in the MC dendritic tuft could be due to Ca$^{2+}$ influx through NMDA receptors or voltage-gated Ca$^{2+}$ channels, or may reflect the release of Ca$^{2+}$ from internal stores following activation of group I mGluRs. To test the involvement of NMDA receptors, we compared EPSP-induced Ca$^{2+}$ transients under control conditions and after bath application of 100 μM of the NMDA receptor antagonist D-APV.

D-APV did not affect the initial fast phase of the ON-EPSP that is mediated by AMPA receptors but did block the slow EPSP component ($n = 11$, Fig. 5A, Carlson et al. 2000; Ennis et al. 1996; Trombley and Westbrook 1990). Single bAPs that consistently generated larger Ca$^{2+}$ signals than subthreshold EPSPs (Fig. 2) did not induce any detectable D-APV-sensitive potential (Fig. 5A3).

The ON-EPSP-associated Ca$^{2+}$ signal, however, was either completely blocked or greatly attenuated by D-APV ($n = 8$, Fig. 5B and 6A and C). To take into account an increased dye concentration with subsequent increase in Ca$^{2+}$ buffering and decrease in fluorescence transients (Ma and Lowe 2004) during
the time period required to wash in d-APV, we interleaved recordings of EPSPs with recordings of bAPs. The peak amplitude and the decay time of bAP-induced Ca\textsuperscript{2+} transients were only slightly reduced and prolonged after wash in d-APV (Fig. 5C and 6A). The bAP-induced Ca\textsuperscript{2+} signals slowed even further after d-APV was washed out, whereas the EPSP-induced Ca\textsuperscript{2+} signals recovered, at least partially (n = 3, Fig. 5B). Comparison of the resulting synaptically induced signals before and after wash in d-APV (3.78 ± 0.374%, mean ± SE before d-APV, vs. 0.77 ± 0.194% after d-APV; P < 0.0005, n = 8, paired t-test) with bAP-induced signals before and after wash in d-APV (13.03 ± 1.66% before d-APV, vs. 11.04 ± 2.20% after d-APV; P > 0.13, n = 8, paired t-test) confirmed that the drug specifically reduced ON-EPSP–related Ca\textsuperscript{2+} signals (Fig. 6A). To take into account a decrease over time in the measured Ca\textsuperscript{2+} transients, we compared the ratio of synaptically induced Ca\textsuperscript{2+} transients after and before d-APV (0.21 ± 0.04, mean ± SE) to that of bAP-induced signals (0.72 ± 0.07; P < 0.0001, t-test; Fig. 6C).

MCs of the main olfactory bulb express high levels of the group I mGluR1 (Heinbockel et al. 2004; Sahara et al. 2001; Shigemoto et al. 1992; Van den Pol 1995), and probably also low levels of mGluR5 (Sahara et al. 2001). These receptors can mediate a release of Ca\textsuperscript{2+} from internal stores (Coutinho and...
Knöpfel 2002), and it is therefore possible that they contribute to the synaptically induced transients. To test the possible role of group I mGluR1 in synaptically evoked Ca\(^{2+}\) transients, we used MCPG, a group I and II mGluR antagonist (1 mM). We compared the ratios of synaptically induced Ca\(^{2+}\) signals to those of bAP-induced signals in the presence of the mGluR antagonist, as described above for the experiments with the NMDA receptor antagonist D-APV. MCPG did not affect the peak amplitude of ON-EPSPs, but slightly (statistically not significantly) reduced the initial part of the EPSP (Fig. 6B; Ratio of \(\Delta F/\Delta F^0\) values after and before adding MCPG: 0.93 ± 0.07, mean ± SE, \(P > 0.17\) compared with control, t-test, \(n = 6\)).

\(Ca^{2+}\) signals induced by activation of ON synapses are graded

The ON stimulation-induced local \(Ca^{2+}\) signals may represent all-or-none “\(Ca^{2+}\) spikes” (Urban and Castro 2005) or may be graded with recruitment of increasing numbers of ORN axons. To investigate this issue, we determined the minimal ON stimulation intensity needed to evoke an AP in the patch-clamped MC and then measured the responses evoked by fractions of this reference intensity. Compound EPSP amplitude varied with stimulation intensity, as did the evoked \(Ca^{2+}\) signals (Fig. 7). The peak amplitude of the EPSP and the initial portion of the slower EPSP component (EPSP area, between 50 and 200 ms after ON stimulation) varied in near-linear relation to stimulation intensity (Fig. 7C). However, larger minimal stimulation intensities are required to evoke the \(Ca^{2+}\) transients and the later NMDA receptor-mediated EPSP component (EPSP area, between 200 and 500 ms after ON stimulation; Fig. 7C, \(n = 5\) cells). To test the effect of larger stimulation intensities without AP firing in the recorded cell, we performed the next set of experiments with pipettes containing the Na channel blocker QX-314 (10 mM). Higher stimulation intensities induced large stimulus-locked EPSPs and a fast rise in \(Ca^{2+}\), followed by unsynchronized synaptic events and a further increase in \(Ca^{2+}\) (Fig. 8, \(n = 3\) cells). A prolonged or delayed rise in \(Ca^{2+}\) and unsynchronized synaptic events were also seen in cells with standard pipettes (see Fig. 7B) and were efficiently depressed by D-APV (see Fig. 5, A and B).

**DISCUSSION**

Our results showed that ON stimulation, subthreshold for spike initiation in the recorded MC, induced localized \(Ca^{2+}\) responses that required the activation of NMDA receptors in the MC dendritic glomerular tuft. \(Ca^{2+}\) transients evoked by bAPs spread throughout the dendritic tuft, with amplitudes that increased with the decrease of the diameters of the terminal dendrites. In contrast to bAP-associated \(Ca^{2+}\) transients, synaptically induced \(Ca^{2+}\) transients exhibited clear hot spots, were longer lasting, and were associated with prolonged electrical activity.

\(Ca^{2+}\) signals induced by bAP in the glomerular tuft

\(Ca^{2+}\) signals evoked by bAPs in the MC glomerular dendritic tuft have attracted much attention because terminal dendritic branches in the tuft behave both as postsynaptic structures that receive olfactory receptor cell terminals and as presynaptic structures that release transmitter (Bischofberger and Jonas 1997; Murphy et al. 2005; Rall et al. 1966). It has been shown previously by indirect measurements using \(Ca^{2+}\) imaging (Charpak et al. 2001; Debarbieux et al. 2003), as well as by direct measurement using voltage imaging (Djurisic et al. 2005).
that bAPs propagate in a nondecremental manner into the dendritic tuft of MCs. Our results are in agreement with previous reports showing that single bAPs trigger significant Ca\(^{2+}\) transients in the distal branches of the dendritic tuft. We did not, however, find failures of bAPs in triggering Ca\(^{2+}\) signals in selected dendritic tuft branches as reported in earlier in vivo measurements (Debarbieux et al. 2003). This discrepancy might be due to differences in intraglomerular inhibitory processes between in vitro, slice preparation, and in vivo recording from an anesthetized animal. Also in contrast to one earlier report showing that the amplitude of Ca\(^{2+}\) transients did not depend on the diameter of the dendrite (Debarbieux et al. 2003), our current results clearly demonstrated Ca\(^{2+}\) signals that were consistently larger in thinner dendrites, in agreement with concurrent observations made in the accessory olfactory bulb (Ma and Lowe 2004; Urban and Castro 2005). The reason for this discrepancy between the in vitro and in vivo data is not clear. Our results also demonstrated that bAP-induced Ca\(^{2+}\) transients were not influenced by autoexcitation (Figs. 1 and 5C) or GABAergic local inhibition (Fig. 1). We also found no direct evidence for NMDA receptor-dependent autoexcitation.
in the voltage trace following a single bAP (Aroniadou-Anderjaska et al. 1999; Issaon 1999; Salin et al. 2001).

**Ca\(^{2+}\) signals induced by ON-EPSPs in the glomerular tuft**

In contrast to the widespread Ca\(^{2+}\) signals induced by bAPs, dendritic Ca\(^{2+}\) signals following subthreshold ON stimulation were pronounced in the tuft, whereas changes in the primary dendrite proximal to the tuft were either small or absent. Also, these synaptically induced Ca\(^{2+}\) transients were clearly localized to one or several hot spots.

The EPSP-associated dendritic Ca\(^{2+}\) transients could theoretically be caused by mobilization of Ca\(^{2+}\) from internal stores. Our experiments excluded the role of mGluRs because the mGluR antagonist MCPG did not significantly affect the Ca\(^{2+}\) transient associated with the ON-EPSP. The mGluR antagonist had also only a minor effect on the ON-EPSP itself, consistent with a previous report (De Saint and Westbrook 2005). The Ca\(^{2+}\) signals were, however, either blocked completely or greatly attenuated by the NMDA receptor antagonist d-APV. Another potential entry pathway is via voltage-gated Ca\(^{2+}\) channels that are activated by the NMDA receptor-mediated depolarization. Because the peak amplitude of the ON stimulation-induced EPSP was not dependent on NMDA receptors, it is unlikely that voltage-gated Ca\(^{2+}\) channels are the major source for the NMDA receptor-dependent Ca\(^{2+}\) transients. The source of the d-APV-insensitive residual component of the Ca\(^{2+}\) signal following ON stimulation (approximately 25% of the control response), however, has not been clarified. It is, therefore possible that a part of the Ca\(^{2+}\) signal is mediated by low-threshold voltage-gated Ca\(^{2+}\) current, as suggested by previous experiments of Charpak et al. 2001. However, on the basis of indirect evidence, these authors concluded that Ca\(^{2+}\) signals are completely independent of NMDA receptor activation, which is markedly different from our results.

NMDA receptors may be activated directly by glutamate released from the ON, and by glutamate released from MC dendrites following an initial activation of dendritic glutamate release by the ON input. Our data provide evidence for additional dendritically released glutamate. Thus Ca\(^{2+}\) signals and slower synaptic components increase supralinearly with stimulation intensity, while the EPSP peak amplitudes (which is a measure of recruited ON fibers) increase more linearly with stimulation intensity (Fig. 7C). Moreover, ON stimulation was often followed by barrages of unsynchronized synaptic events and a prolonged rising phase of the Ca\(^{2+}\) transient. Indeed, the slow NMDA receptor-dependent component has previously been attributed to recurrent, intraglomerular dendrodendritic interactions (Carlson et al. 2000).

The most likely scenario for glomerular integration of ORN inputs is that dendrodendritic mutual excitation of dendrites of neighboring MCs can become self-supportive after an initial ON input. The hot spots in our Ca\(^{2+}\) maps would then reflect regenerative glutamate release in chemical glomerular compartments, as proposed by Schoppa and Westbrook (2001). The mechanisms for termination of this regenerative mutual excitation of dendritic tufts is unclear but may involve depletion of releasable dendritic glutamate, Ca\(^{2+}\) activated outward currents, or GABAergic inhibition. It should be noted that natural stimulation most likely would activate ORN axon terminals that are more homogenously distributed over the glomeruli than was the case under our experimental focal stimulation conditions. It is therefore likely that the local hot spots of slow NMDA receptor-dependent process studied here will fuse to a more homogenous pattern under natural conditions. In the absence of hot spots, the dendrodendritic interactions that are reflected by the hot spots seen with focal ON activation will, however, still contribute to the coupling of MCs. This scenario is in agreement with previous proposals that glutamate released from MC dendrites is regenerative and contributes to synchronization of glomerular responses to ON activity (Christie et al. 2005; Issacson 1999; Schoappa and Westbrook 2001).

**Functional implications**

The elaborated MC dendritic tufts and multifaceted dendrodendritic interactions are suggestive of specific dendritic information processing (as opposed to simply relaying ON inputs) in olfactory glomeruli. All signaling mechanisms that are known to occur at the level of the olfactory glomeruli can be attributed to one specific computational outcome, namely, to increase sensitivity for the specific class of ORNs that provide input to that given glomerulus. Increase in sensitivity is achieved by sampling of and averaging over all ORN inputs (Van Drongelen et al. 1978). This process requires coupling of MCs so that the average ORN inputs can be represented by the population of MCs that are associated with one given glomerulus. In addition to sampling and averaging, dendrodendritic interaction can boost the ON inputs by regenerative mutual excitation. In this picture, inhibitory mechanism is required to dampen sensitivity for strong ON inputs. Faster interaction such as gap-junction coupling (Christie et al. 2005) may synchronize spike timing of MCs. This synchronization of spiking may further enhance sensitivity via stochastic resonance, or may provide information that is encoded by OB network oscillations or the MC target cells in the olfactory cortex.

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**References**


