Ultrafast glutamate sensors resolve high-frequency release at Schaffer collateral synapses

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Glutamatergic synapses display a rich repertoire of plasticity mechanisms on many different time scales, involving dynamic changes in the efficacy of transmitter release as well as changes in the number and function of postsynaptic glutamate receptors. The genetically encoded glutamate sensor iGluSnFR enables visualization of glutamate release from presynaptic terminals at frequencies up to \textasciitilde{}10 Hz. However, to resolve glutamate dynamics during high-frequency bursts, faster indicators are required. Here, we report the development of fast (iGlu\textsubscript{u}) and ultrafast (iGlu\textsubscript{u'}) variants with comparable brightness but increased \(K_u\) for glutamate (137 \(\mu\)M and 600 \(\mu\)M, respectively). Compared with iGluSnFR, iGlu\textsubscript{u} has a sixfold faster dissociation rate in vitro and fivefold faster kinetics in synapses. Fitting a three-state model to kinetic data, we identify the large conformational change after glutamate binding as the rate-limiting step. In rat hippocampal slice culture stimulated at 100 Hz, we find that iGlu\textsubscript{u} is sufficiently fast to resolve individual glutamate release events, revealing that glutamate is rapidly cleared from the synaptic cleft. Depression of iGlu\textsubscript{u} responses during 100-Hz trains correlates with depression of postsynaptic EPSPs, indicating that depression during high-frequency stimulation is purely presynaptic in origin. At individual boutons, the recovery from depression could be predicted from the amount of glutamate released on the second pulse (paired pulse facilitation/depression), demonstrating differential frequency-dependent filtering of spike trains at Schaffer collateral boutons.

Significance

Excitatory synapses convert presynaptic action potentials into chemical signals that are sensed by postsynaptic glutamate receptors. To eavesdrop on synaptic transmission, genetically encoded fluorescent sensors for glutamate have been developed. However, even the best available sensors lag behind the very fast glutamate dynamics in the synaptic cleft. Here, we report the development of an ultrafast genetically encoded glutamate sensor, iGlu\textsubscript{u'}, which allowed us to image glutamate clearance and synaptic depression during 100-Hz spike trains. We found that only boutons showing paired-pulse facilitation were able to rapidly recover from depression. Thus, presynaptic boutons act as frequency-specific filters to transmit select features of the spike train to specific postsynaptic cells.

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Data deposition: The plasmids for iGlu\textsubscript{u} and iGlu\textsubscript{u'} have been deposited in the Addgene database, https://www.addgene.org/75443/.

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The efficacy of synaptic transmission is not constant but changes dynamically during high-frequency activity. In terms of information processing, different forms of short-term plasticity act as specific frequency filters: Facilitating synapses are most effective during high-frequency bursts, while depressing synapses preferentially transmit isolated spikes preceded by silent periods (1). Mechanistically, a number of presynaptic and postsynaptic parameters change dynamically during high-frequency activity, e.g., the number of readily releasable vesicles, presynaptic Ca\textsuperscript{2+} dynamics, and the properties of postsynaptic receptors, which may be altered by Ca\textsuperscript{2+}-activated enzymes (2, 3).

Electrophysiological analysis of short-term plasticity, by monitoring postsynaptic responses, is complicated by the fact that neurons are often connected by more than one synapse. In addition, it is not straightforward to distinguish between presynaptic and postsynaptic plasticity mechanisms. Directly measuring glutamate concentrations inside the synaptic cleft during high-frequency activity would allow isolating the dynamics of the vesicle release machinery from potential changes in glutamate receptor properties (e.g., desensitization, phosphorylation, or lateral diffusion). Early fluorescent glutamate sensors, constructed by chemical labeling of the fused glutamate binding terminus (Fig. 1\textsuperscript{4}) inserted into the GluBP sequence, creating a large fragment iGlu\textsubscript{u} (residues 1–253) at the N terminus and a small fragment iGlu\textsubscript{u} (residues 254–279) at the C terminus (Fig. 1\textsuperscript{4}). Upon glutamate binding, GluBP is reconstituted from its two fragments, pulling the eEGFP \(\beta\) barrel together, resulting in a \textasciitilde{}fivefold fluorescence increase. iGluSnFR is targeted for extracellular expression, like previous genetically encoded glutamate sensors, by fusion with a PDGF peptide segment (10, 12).

iGluSnFR has high glutamate affinity and a large dynamic range but reacts relatively slowly to synaptic glutamate release with a reported decay half-time \(t_{1/2}\) of 92 ms (12). Imaging iGluSnFR in cultured hippocampal neurons during 10-Hz stimulation shows summation, which, without deconvolution, might indicate that glutamate accumulates during stimulation (15). Deconvolution of the...
data suggests that glutamate is cleared between release events (15). Here, we introduce two fast iGluSnFR variants, iGlu\textsubscript{u} (for “fast”) and iGlu\textsubscript{u} (for “ultrafast”) for accurate tracking of synaptic glutamate dynamics during high-frequency transmission and identify the rate-limiting step leading to bright fluorescence upon glutamate binding. In organotypic slice cultures of rat hippocampus, iGlu\textsubscript{u} directly reports discrete synaptic glutamate release events at 100 Hz. Combining high-speed two-photon imaging and electrophysiology, we show that short-term depression of glutamate release is fully accounted for by t\textsubscript{off} of 15 ms. We show that short-term depression of glutamate release is fully accounted for by t\textsubscript{off} of 15 ms. Furthermore, we show a tight correlation between paired-pulse facilitation and rapid recovery from posttetanic depression on HEK293T cells and pyramidal neurons. Selectivity for glutamate or in the vicinity of the binding site (9). Two of the mutations lowered, and four increased, the K\textsubscript{d} for glutamate. Variants in order of increasing dissociation constant (K\textsubscript{d}) were E25A < E25R < iGluSnFR < E25D < S72T < R24K < T92A (from 19 μM to 12 mM) with Hill coefficients of 1.3–2.6 (SI Appendix, Fig. S1A and Table S1).

We selected the two variants with the fastest response kinetics, iGluSnFR E25D (termed iGlu\textsubscript{u}) and iGluSnFR S72T (termed iGlu\textsubscript{u}) (Fig. 1 A and B) for detailed biophysical characterization as isolated proteins and as membrane-bound glutamate sensors on HEK293T cells and pyramidal neurons. Selectivity for glutamate was determined against aspartate, glutamine, \textdelta-\textit{serine}, GABA, and glycine. iGlu\textsubscript{u} and iGlu\textsubscript{u} affinities for aspartate were similar to that for glutamate, as previously reported for iGluSnFR (12), but with two- to threefold lower fluorescence enhancement. The affinity for glutamate was in the millimolar range for all three probes (SI Appendix, Fig. S1B and Table S3).

### Results

**Affinity Variants of iGluSnFR by Binding Site Mutations.** We generated six iGluSnFR variants by mutating residues coordinating glutamate or in the vicinity of the binding site (9). Two of the mutations lowered, and four increased, the K\textsubscript{d} for glutamate. Variants in order of increasing dissociation constant (K\textsubscript{d}) were E25A < E25R < iGluSnFR < E25D < S72T < R24K < T92A (from 19 μM to 12 mM) with Hill coefficients of 1.3–2.6 (SI Appendix, Fig. S1A and Table S1).

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iGlu_u, whereas the apo-form showed little pH dependence, indicating a well-shielded chromophore ([SI Appendix, Fig. S1 C–E]). Brightness values for iGlu_u and iGlu_u were similar to that for iGluSnF ([SI Appendix, Table S2]). In vitro measurements gave a $K_d$ for glutamate of 33 μM for iGluSnF, similar to that previously reported (12), while iGlu_u and iGlu_u had increased $K_d$ values of 137 μM and 600 μM, respectively (Fig. 1C and [SI Appendix, Table S1]). When expressed on the membrane of HEK293T cells, $K_d$ values for glutamate were reduced to 3.1 ± 0.3 μM for iGluSnF, 26 ± 2 μM for iGlu_u and 53 ± 4 μM for iGlu_u (measured at 37 °C, Fig. 1 D and E). A similar reduction of the $K_d$ in the cellular environment compared with that in solution was reported for iGluSnF (12). The in situ fluorescence dynamic range ($F_{Glu}−F_{Glu}^0)/F_{Glu}^0$ or $ΔF/F_0$) was 1.0 ± 0.1 for both iGluSnF and iGlu_u, but 1.7-fold larger for iGlu_u.

Kinetic Measurements of iGluSnF Variants in Vitro and In Situ. Based on their large $K_d$ values, we expected iGlu_u and iGlu_u to have faster glutamate release kinetics than iGluSnF. Fluorescence measurements in a stopped-flow instrument indeed revealed faster off rates for the new variants: using the nonfluorescent high-affinity GluBP 600n (10) in excess (0.67 mM) to trap reuptake, we were able to improve iGluSnF kinetics by a factor of 6.3. To image glutamate dynamics in the synaptic cleft, we expressed the newly generated iGluSnF variants in CA3 pyramidal cells in organotypic slice culture of rat hippocampus. Fluorescence was monitored at single Schaffer collateral terminals in CA1 by spiral scanning (Fig. 1 F and J) while action potentials (APs) were triggered by brief (2 ms) depolarizing current injections into the soma of the transfected CA3 neuron. A zoomed-in iGlu_u example trace sampled at 1 kHz, the resolution used in all quantitative experiments with this indicator, is shown (Fig. 1K). The iGluSnF response started 4.5 ± 1.6 ms (mean ± SD) before the somatic action potential, consistent with a short propagation delay between CA3 and CA1. Consistent with the stochastic nature of glutamate release, individual boutons showed different release probabilities (median $p_r = 0.56$, range 0.05–1.0). For kinetic analysis, boutons with high release probability and good separation between release failures and successes were selected ([SI Appendix, Fig. S2]). The measured fluorescence decay time constants ($τ_{off}$) were 13.8 ± 3.8 ms for iGluSnF, 5.2 ± 2.0 ms for iGlu_u and 2.6 ± 1.0 ms for iGlu_u (Fig. 1 L and [SI Appendix, Fig. S3]). Thus, compared with iGluSnF, synaptic responses detected by iGlu_u were revealed to be faster by a factor of 5.3. Interestingly, blocking glutamate uptake with $	ext{δ}-$threo-beta-benzoxylaspartate (DL-TBOA, 40 μM) did not slow down the decay of iGlu_u fluorescence ([SI Appendix, Fig. S4]), suggesting that after spare activation of Schaffer collateral synapses, glutamate is rapidly cleared from the synaptic cleft by diffusion, not by active transport. The situation may be different in highly active neuropil (12, 16).

Synaptic Glutamate Dynamics During High-Frequency Stimulation. With decay kinetics of 1–2 ms, iGlu_u and iGlu_u are promising tools for direct tracking of synaptic glutamate during high-frequency stimulation. The response of iGluSnF, iGlu_u and iGlu_u to paired-pulse stimulation (Fig. 2 and [SI Appendix, Fig. S3]) and to trains of 10 APs at 50, 67, and 100 Hz ([SI Appendix, Fig. S5]) was tested. While the responses of iGluSnF and iGlu_u suggested build-up of glutamate during high-frequency stimulation, iGlu_u responses revealed that even at 100-Hz stimulation, glutamate was completely cleared from the synaptic cleft between APs (Fig. 2F and [SI Appendix, Fig. S5]). Interestingly, the amplitudes of synaptic fluorescence signals ($ΔF/F_0$) were similar for all three indicators, suggesting that the on rate, not the overall affinity, determined the number of glutamate-bound indicator molecules in the synaptic cleft.

Excitatory postsynaptic potentials (EPSPs) in CA1 become strongly depressed during high-frequency stimulation (17). We were interested whether EPSP depression during 100-Hz stimulation could be fully accounted for by depression of glutamate release from presynaptic boutons. In paired recordings from connected CA3-CA1 pyramidal cells, we triggered APs in the CA3 cell by brief current injections while monitoring postsynaptic potentials (EPSPs) in the CA1 cell. The protocol consisted of a short high-frequency burst (10 APs at 100 Hz) followed by a single AP 500 ms after the burst to probe recovery of synaptic function (18). We repeated the protocol up to 100 times at 0.1 Hz and averaged the recorded traces (Fig. 3 A–C). As expected, connected CA3-CA1 pyramidal cell pairs showed strong depression during the high-frequency train. The response to the recovery test pulse (#11) was not significantly different from the first EPSP in the train, indicating full recovery of synaptic function. To investigate depression and recovery of glutamate release, we evaluated iGlu_u signals during identical stimulation (Fig. 3 D and E). Due to the extremely fast kinetics of the indicator, deconvolution of the fluorescence time course was not necessary: We read the peak amplitudes during the 100-Hz train directly from the averaged fluorescence time course.
(average of 10 independent trials sampled at 1 kHz), Glutamate release decreased during the train with a time course that matched EPSP depression (Fig. 3D). This result points to a purely presynaptic origin of depression, which is consistent with AMPA receptors rapidly recovering from desensitization after each release event (recovery = 5 ms; ref. 19). However, glutamate release 500 ms after the tetanus was still significantly depressed (two-tailed Student’s test, P value: 0.0034) while AMPA receptor currents were not. This discrepancy suggests that the response of AMPA receptors to eftiot glutamate was in fact potentiated 500 ms after the high-frequency train, compensating for the reduced output of Schaffer collateral boutons.

Paired-Pulse Facilitation Correlates with Rapid Recovery from Depression. The rapid kinetics of iGluF allowed us to analyze frequency filtering at individual boutons. On the second AP, boutons showed a wide range of facilitated (3 of 12 boutons) or depressed responses (9 of 12 boutons, Fig. 3F). The response to the 10th AP was strongly depressed in all boutons (16% of response amplitude to first AP), with no correlation between the second and the 10th response (R² = 0.005, Fig. 3F and G). Interestingly, a highly significant correlation was observed between the response to the second AP and the recovery response 500 ms after the high-frequency train (R² = 0.715, Fig. 3H and I). In contrast, we found no correlation between the amount of bleaching in individual experiments (F1ΔF0[pre-11th pulse]/F1ΔF0[1st pulse]) and the amplitude of the recovery response ((ΔF/Δt)11th pulse/(ΔF/Δt)1st pulse), indicating that poor recovery was not caused by excessive bleaching or dilution of indicator molecules (Fig. 3J). Thus, synapses that showed pronounced paired-pulse facilitation were also able to recover rapidly from depression, both of which is indicative of a low utilization of presynaptic resources (18). Such boutons are optimized for the transmission of high-frequency activity (spike bursts). In contrast, boutons that showed paired-pulse depression were still depressed 500 ms after the high-frequency train. These boutons act as low-pass filters: They preferentially transmit isolated APs preceded by a silent period.

Response Kinetics of iGluSnFR and Variants iGluA and iGluF Are Based on the Rate of Structural Change. Finally, we investigated the response mechanism of iGluSnFR and its fast variants using fluorescence stopped flow with millisecond time resolution. In association kinetic experiments (20 °C), the fluorescence response rates (kobs) showed hyperbolic glutamate concentration dependence, approaching saturating rates of 643 s⁻¹ and 1.240 s⁻¹ for iGluSnFR and iGluF, respectively (Fig. 4A–D). For iGluF, in contrast, kobs was found to be concentration-independent at 604 s⁻¹ (Fig. 4E and F). We considered two different reaction pathways to explain our kinetic data (Fig. 4G). iGluSnFR is represented as a complex of the large fragment of the GluBP domain (GluBP-1-253, iGluA), N-terminally flanking cpEGFP and of the C-terminally fused small GluBP fragment (GluBP-254-279, iGluF). The term iGluA ~ iGluA indicates that the large GluBP fragment iGluA, and the small fragment iGluF, are within one molecule, albeit separated by the interjecting cpEGFP. In SI Appendix, Scheme 1, the binding of glutamate to iGluF in iGluA ~ iGluA is the primary step (no change in fluorescence). Glutamate binding is followed by a conformational change induced by the reattachment of iGluA to GluA-bound iGluF, resulting in the highly fluorescent GluA.iGluA* complex (rate-limiting step). According to SI Appendix, Scheme 1, the hyperbolic dependence of the observed rate kobs on the glutamate concentration [Glu] has the intercept of the y axis at k2 (SI Appendix, Kinetic Theory and Eq. 7). At low [Glu], the initial slope line gives k1.kF. At high [Glu], kobs tends to k₂ + k₃. Although kobs for iGluF, appears essentially concentration independent, its kinetics is consistent with SI Appendix, Scheme 1, with k₃ + k₄ having a similar value to k₂ (SI Appendix, Table S5).

In the alternative pathway (SI Appendix, Scheme 2), the reattachment of iGluA to iGluF occurs without prior binding of glutamate. Therefore, iGluA ~ iGluA with the GluBP fragments separated and complete GluBP domain (iGluA*) are in equilibrium. The conformational change that represents the reattachment of the two GluBP fragments is expected to generate a fluorescent state of cpEGFP. However, the equilibrium is likely to be strongly shifted to the separated, nonfluorescent state (iGluA ~ iGluF). Assuming that this equilibrium is fast and glutamate binding stabilizes the fluorescent state, at low [Glu], a linear dependence of kobs on [Glu] is predicted with a slope
of $K_{u}(1 + K_3)$ and an intercept of the $y$ axis at $k_{-2}$ (SI Appendix, Kinetic Theory and Eq. 15). Although at low [Glu] monoexponential fluorescence changes are expected, as [Glu] increases, the concentration of iGlu$^*$ cannot be assumed to be at steady state and slow isomerization will limit $k_{obs}$ in a similar pattern to that for SI Appendix, Scheme 1. Thus, at high [Glu], even if iGlu$^*$ and Glu.iGlu$^*$ have equal relative fluorescence intensities, biphasic fluorescence changes would be expected for the association reactions. As all of the reactions studied here for the three variants had a single exponential appearance, we can exclude SI Appendix, Scheme 2 as a possible reaction pathway. In conclusion, SI Appendix, Scheme 1 provides an excellent fit to our measurements (SI Appendix, Table S5), pointing to “Venus fly-trap” closure by glutamate binding as a required first step for the conformational change that increases iGluSnFR fluorescence.

**Discussion**

The development of iGluSnFR was a breakthrough in fluorescent glutamate sensors toward investigating neurotransmission in living organisms (20). Here, we describe how to overcome one of the key limitations of iGluSnFR, its slow response kinetics, and use the ultrafast variant iGlu$_u$ to investigate synaptic transmission and frequency filtering at individual Schaffer collateral boutons. For all tested variants, synaptic off kinetics was slower by a factor of 2.5–3.8 compared with temperature-matched in vitro measurements on isolated protein. This is consistent with the much higher affinities of HEK293T cell-expressed glutamate sensors compared with soluble protein. These systematic differences, also noted in the original characterization of iGluSnFR (12), may be attributed to the tethering of the molecule to a membrane anchor, slowing down conformational changes compared with free-floating sensor molecules. Nevertheless, the relative differences in affinity and kinetics of the new versions compared with iGluSnFR were preserved in vitro and in situ. The on and off rates of iGlu$_u$ are greater (two- and five- to sixfold, respectively) compared with iGluSnFR. Interestingly, iGlu$_u$ was a faster reporter in the hippocampal slice than iGlu, although the latter has a faster limiting rate. iGlu$_u$ may be put at an advantage over iGlu by its concentration-independent response kinetics. It must be noted that the kinetics of iGluSnFR-type indicators are ultimately limited by the structural change that reconstitutes the fluorescent complex, similar to calcium-sensing GCaMPs. The constraints of the mechanism with regard to the onset of fluorescence suggest that it cannot be engineered to resolve submillisecond glutamate dynamics. To achieve microsecond response times, it might be necessary to develop hybrid glutamate indicators using synthetic dyes.

Synaptic iGlu$_u$ imaging revealed complete clearance of glutamate between release events even at 100-Hz stimulation frequency. The first attempts to estimate the time course of synaptic glutamate transients were based on the decay of NMDA receptor responses in primary cell culture: Kinetic analysis of the displacement of a competitive NMDA receptor antagonist suggested glutamate clearance with $\tau = 1.2$ ms (21). More recent studies using computational modeling and fluorescence anisotropy imaging in tissue suggest that it is closer to 100 $\mu$s (22, 23). Thus, due to the intrinsic kinetic limits of the iGluSnFR mechanism, even iGlu$_u$ cannot resolve the true dynamics of free glutamate in the synaptic cleft. Moreover, our spatiotemporal resolution is limited by scanning, although in most experiments, the spiral scan line intersected the release site two or more times and, thus, effectively increased temporal sampling of cleft glutamate by the same factor (e.g., from 1 to 2 kHz). In our analysis, we binned all measurements (pixels) of a scan line into a single time point (1 ms), potentially under-sampling the sharp peak of iGlu$^*$ signals (SI Appendix, Fig. S6). For experiments where the peak amplitude of iGlu$_u$ signals is of critical importance, temporal sampling could be improved by assigning a time value to every pixel of the spiral scan line before analysis (SI Appendix, Fig. S2). What we can say with confidence is that accumulation of glutamate in the synaptic cleft does not contribute to short-term plasticity at Schaffer collateral synapses.

Glutamate release showed strong depression during 100-Hz firing, in line with the expected depletion of release-ready vesicles. As we controlled the generation of every action potential by firing, in line with the expected depletion of release-ready vesicles. As we controlled the generation of every action potential by firing, in line with the expected depletion of release-ready vesicles. As we controlled the generation of every action potential by firing, in line with the expected depletion of release-ready vesicles. As we controlled the generation of every action potential by firing, in line with the expected depletion of release-ready vesicles. As we controlled the generation of every action potential by firing, in line with the expected depletion of release-ready vesicles.
responses were fully recovered 500 ms after the train while the iGluR response was still significantly depressed. The most parsimonious explanation is a long-lasting depression of glutamate release. There are alternative scenarios that could explain smaller iGluR responses on the 11th pulse, e.g., indicator molecules retrieved into endosomal structures during endocytosis, or accumulation of indicator in a (hypothetical) desensitized state. In these scenarios, facilitating boutons, which experience more exocytosis and endocytosis and iGluR activation during the train, would be expected to show smaller responses at the 11th pulse. However, we found a strong correlation in the opposite direction (Fig. 3F), making these scenarios less likely.

As response amplitudes (40–120% ΔF/F0) were typically less than half of that of the maximal change in fluorescence we determined for the three indicators (SI Appendix, Table S3), we did not correct for the nonlinearity of the iGluSnFR variants (Fig. 1C). To determine the absolute (or “peak”) glutamate concentration in the synaptic cleft, however, indicator saturation and undersampling would have to be taken into account.

The full recovery of the AMPA response points to an unexpected increase in sensitivity of the postsynaptic compartment to glutamate. By association with different auxiliary proteins and other scaffold-related mechanisms, the density and open probability of postsynaptic glutamate receptors can quickly change (24, 25). In hippocampal slice cultures, posttetanic potentiation is well established and requires the activity of protein kinase C (26). Thus, it is possible that elevated Ca2+ levels in the spine during our high-frequency protocol enhanced AMPA receptor currents by a number of mechanisms, compensating for the reduced glutamate release 500 ms after the tetanus.

The surprisingly tight correlation between paired-pulse facilitation and rapid recovery from depression at individual boutons provides direct evidence that differential use of presynaptic sources determines the neural code between pyramidal cells (1, 18). Using Schaffer collateral synapses as an example, we show that iGluR is a useful tool for a mechanistic analysis of high-frequency synaptic transmission, interrogating presynaptic function independently of postsynaptic transmitter receptors.

Methods

We provide a detailed description of the methods, data analysis, and kinetic modeling in SI Appendix.