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Presynaptic Kainate Receptor Activation Preserves Asynchronous GABA Release Despite the Reduction in Synchronous Release from Hippocampal Cholecystokinin Interneurons

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Inhibitory synaptic transmission in the hippocampus is mediated by a wide variety of different interneuron classes which are assumed to play different roles in network activity. Activation of presynaptic kainate receptors (KARs) has been shown to reduce inhibitory transmission but the interneuron class(es) at which they act is only recently beginning to emerge. Using paired recordings we show that KAR activation causes a decrease in presynaptic release from cholecystokinin (CCK)- but not parvalbumin-containing interneurons and that this decrease is observed when pyramidal cells, but not interneurons, are the postsynaptic target. We also show that although the synchronous release component is reduced, the barrage of asynchronous GABA release from CCK interneurons during sustained firing is unaffected by KAR activation. This indicates that presynaptic KARs preserve and act in concert with asynchronous release to switch CCK interneurons from a phasic inhibition mode to produce prolonged inhibition during periods of intense activity.

Introduction

Inhibitory synaptic transmission in the hippocampus is mediated by GABAergic interneurons consisting of multiple classes as defined by morphology, physiology and neurochemical markers (Klauserberger and Somogyi, 2008). Interneuron classes are hypothesized to serve different roles in hippocampal network function. One factor which shapes these roles is the differential expression of presynaptic receptors to a variety of neurotransmitters, which modulate the release of GABA. For example parvalbumin (PV)-containing, fast-spiking basket cells (PV BCs) are influenced by relatively few types of receptors when compared with a second class of, cholecystokinin (CCK)-containing basket cells (CCK BCs). As such PV BCs are thought to represent immu-

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The presynaptic kainate (KA) class of glutamate receptors have been implicated in the modulation of synaptic release of both GABA and glutamate in the hippocampus (Pinheiro and Mulle, 2008). Despite numerous studies there is no consensus on the effect of KA receptor (KAR) activation on GABA release. Application of glutamate, KA or the KAR agonist ATPA has been widely reported to increase the frequency of spontaneous IPSCs (sIPSCs) in pyramidal cells (Cossart et al., 1998; Frerking et al., 1999; Jiang et al., 2001; Semyanov and Kullmann, 2001; Fisahn et al., 2002), but this is due, at least in part, to depolarization of interneurons (Cossart et al., 1998; Frerking et al., 1999; Jiang et al., 2001) or to increased axonal excitability (Semyanov and Kullmann, 2001; Maingret et al., 2005). While several studies have reported a reduction in the amplitude of evoked IPSCs (eIPSCs) on to pyramidal cells (Clarke et al., 1997; Rodríguez-Moreno et al., 1997; Behr et al., 2002; Maingret et al., 2005) this has been attributed to indirect effects (Frerking et al., 1999; Fisahn et al., 2002). This indirect interpretation has also been disputed (Rodríguez-Moreno et al., 2000; Maingret et al., 2005) and others have seen no reduction in eIPSCs (Cossart et al., 2001). Conversely KA is reported to increase eIPSCs in interneurons (Cossart et al., 2001). All of these studies on eIPSCs have relied on extracellular stimulation of local afferents meaning that the class of interneuron mediating the IPSC under study is unknown as is the interstimulus activity of these interneurons. Indeed, one study using paired interneuron to pyramidal cell recordings suggests that KA may increase GABA release from low release probability synapses a finding that may be due to spontaneous firing causing frequency-dependent facilitation (Jiang et al., 2001). A very recent study shows that KARs mediate the depression of evoked IPSC amplitude at synapses made by CCK interneurons via an enhancement of CB1 receptor-mediated depression (Lourenço et al., 2010).
Here, using paired interneuron-pyramidal and interneuroninterneuron recordings, we show that KAR activation causes a reduction in IPSC amplitude dependent on the identity of both presynaptic and postsynaptic cells. Furthermore we show that this reduction in IPSC amplitude from CCK interneurons is due to a decrease in synchronous GABA release without any effect on asynchronous release.

Materials and Methods

Slice preparation. Hippocampal slices (300 μm thick) were prepared from mice aged postnatal day 12 (P12)–P22. All animals were anesthetized with isoflurane before decapitation according to National Institutes of Health animal welfare guidelines. C57BL/6 mice or mice expressing GFP under the promoter for GAD67 (Brager et al., 2003; Daw et al., 2009) or PV (B13 line) (Goldberg et al., 2008) were used as indicated. Brains were rapidly dissected out and placed in cold modified artificial CSF (aCSF) (see below) containing 0.5 mM CaCl2/4.5 mM MgSO4 or partial sucrose aCSF containing the following (in mM): 80 NaCl, 3.5 KCl, 1.25 H2PO4, 25 NaHCO3, 4.5 MgSO4, 0.5 CaCl2, 10 glucose, and 90 sucrose equilibrated with 95% O2/5% CO2. Cells were hemisected and transverse sections were cut with a Leica VT1000S microtome. Slices were incubated at 35°C for 30 min and at least a further 30 min at room temperature (~22°C) in the dissection solution before recording.

Whole-cell recordings. Slices were transferred to a recording chamber and perfused with aCSF containing 125 mM NaCl, 3.5 mM KCl, 1.25 mM H2PO4, 25 mM NaHCO3, 1.5 mM MgSO4, 2.5 mM CaCl2 (or as indicated) and 20 mM glucose, equilibrated with 95% O2/5% CO2 and maintained at 33–35°C. Cells were visualized using a 40× objective and IR-DIC video microscopy (Zeiss Axiozkop 2 FS Plus). Fluorescence of GCP-containing cells was excited by a Lambda LS light source (Sutter Instruments) and visualized online using Spot Basic imaging software and RT KE camera (both Diagnostic Instruments Inc.). Whole-cell recordings were made using a Multiclamp 700A amplifier (Molecular Devices). Recording electrodes (3–5 MΩ) were filled with a solution containing 130 mM KCl, 8.5 mM NaCl, 4 mM MgATP, 0.3 mM Na GTP, 5 mM HEPES and 0.5 mM EGTA adjusted to pH 7.3 using KOH and 290 mM using sucrose. Biocytin (2 mg/ml) was added on the day of recording. Uncompensated series resistance (8–25 MΩ for interneurons, 5–20 MΩ for pyramidal cells/granule cells) was monitored in postsynaptic cells via a –5 mV voltage step and recordings stopped after changes >30%. Firing patterns were investigated by giving a series of incrementing 500 ms duration current steps from –70 mV of between 20 and 150 pA step sizes starting from a negative step of double the step amplitude until at least double action potential threshold amplitude. During drug application synaptic transmission was monitored by producing pairs of action potentials in the presynaptic cell at 50 Hz every 10 s by giving 2 ms 1–2 nA current steps. Presynaptic trains before and after drug application consisted of 25 presynaptic action potentials at 50 Hz from –70 mV while holding the postsynaptic cell at –70 mV in voltage clamp. Ten trains were delivered at 0.1 Hz. Trains were not delivered during KA application as postsynaptic responses to trains were often not stable if delivered after a prolonged period of time. Data were acquired at 10 kHz using Pclamp 9.2 (Molecular Devices) and filtered at 4 kHz.

Data analysis. Points in amplitude vs time plots represent the peak amplitude derived from an average of 6 consecutive traces. Values stated in text are the peak amplitude derived from an average of 24 traces either immediately before or 6–10 min after drug application. Averaging was performed to increase the signal-to-noise ratio particularly for small amplitude IPSCs. Success rate is 1 failure rate; we used this parameter to allow calculation of percentage change when baseline failure rate r = 0.

To determine synchronous and asynchronous GABA release, trains were deconvolved as follows using IgorPro (WaveMetrics). An artificial mIPSC was created using the rise to peak of a recorded unitary IPSC and a single exponential decay to baseline calculated from a fit of the IPSC to remove noise. Separate artificial mIPSCs were created for each pair analyzed based on the kinetics of the IPSCs recorded in that pair. This mIPSC was then scaled to give a peak of 20 pA. This value was chosen as close as the smallest events detected after the train in most cells. Baseline was subtracted from postsynaptic waveforms and 20 repetitions of binomial (Gaussian) smoothing were applied. Fourier transforms of the mIPSC and individual trains were calculated. The Fourier transform of the mIPSC was then divided, point by point, in to the Fourier transform of the train. The quotient of this division was returned to the time domain via the inverse Fourier transform to produce the release rate histogram (Diamond and Jahr, 1995). Synchronous release was calculated from the area under the release rate histogram for the 5 ms following the onset of the presynaptic current step while asynchronous release was the area of the following 15 ms (see Fig. 5A, inset) and, when calculating asynchronous release for the entire burst, for the period following the last step until the end of the trace. Asynchronous release after the end of the train was included only for data referring to the entire train. This method almost certainly underestimates the degree of asynchronous release (e.g., one third of truly random release would be regarded as synchronous) but does so equally across all cells and allows for jitter in spike timing and in the delay to the onset of the synchronous IPSC. Both modes of release were calculated from an average of 10 release rate histograms each calculated from a single postsynaptic waveform. Synchronicity ratio (SR) was simply synchronous release/asynchronous release from the start of the train to the end of the sweep (Daw et al., 2009).

All values of statistical significance are results of two-tailed t tests, a value of <0.05 was considered significant. All statistics are shown ± SEM and illustrated in graphs as mean value with error bars representing SEM.

Anatomical reconstruction. After biocytin filling during whole-cell recordings, slices were fixed with 4% paraformaldehyde and stored at 4°C then permeabilized with 0.3% Triton X-100 and incubated with Alexa Fluor 555 or Alexa Fluor 633-conjugate streptavidin. Resectioned slices were mounted on gelatin-coated slides using Mowiol mounting medium. Cells were visualized using epifluorescence microscopy (Olympus AX70) and images for representative examples were obtained with a Leica TCS SP2 RS Confocal Microscope. Frames of maximum projection images were created from stacks (2 μm steps) and stitched together in Adobe Photoshop.

Results

We investigated whether the effect of KAR activation on inhibitory synaptic transmission in the hippocampus depends on the identity of presynaptic and postsynaptic cells by making whole-cell recordings from synaptically connected interneuron-interneuron or interneuron-pyramidal cell/granule cell pairs in the CA1, CA3 and dentate gyrus regions of the hippocampus [collectively referred to as principal cells (PCs)]. CCK interneuron recordings were made from GFP-positive cells in a mouse line expressing EGFP under a GAD-65 promoter (Brager et al., 2003). We have previously characterized GFP-positive cells recorded from the pyramidal layer and inner third of stratum radiatum in this mouse line (Daw et al., 2009). We found that cells which produced a barrage of asynchronous IPSCs in response to long trains of action potentials also displayed depolarization-induced suppression of inhibition, which is specific to CCK interneurons (Katona et al., 1999; Wilson et al., 2001; Foldy et al., 2007), and were positive for CCK mRNA when tested with single cell rTPCR. Two other groups have previously shown this highly asynchronous GABA release to be a phenomenon specific to CCK interneurons of both the dentate and CA regions of the hippocampus (Hefft and Jonas, 2005; Karson et al., 2009). We used deconvolution analysis (see methods) to determine the SR during trains of 25 action potentials at 50 Hz for each neuron pair calculated as total synchronous GABA release/total asynchronous release. We included only those synaptic connections which displayed an SR < 0.3 (Daw et al., 2009) in the CCK-interneuron set. Morphology of interneurons demonstrating asynchronous release was recovered for 42/52 presynaptic cells and were consistent with the CCK-positive cell classes we reported in our previous study (Daw et al., 2009) (supplemental Figs. S1–S3,
Presynaptic KAR activation decreases IPSC amplitude in PCs when CCK but not PV interneurons are presynaptic. A, Example CCK interneuron to PC pair. Top shows presynaptic cell response to 500 ms current step at double threshold amplitude (160 pA). Bottom shows an average of 24 paired pulse traces before (left, black) and after (right, gray) 1 μM KA application taken at time points indicated in A. Top trace, presynaptic cell; bottom trace, postsynaptic cell. This applies to all paired pulse traces in this and later figures. B, Peak first IPSC amplitude vs time plot for example shown in A. Each point represents the peak amplitude of an average of 6 traces. This applies to all amplitude vs time plots in this and later figures. C, Average data for all experiments as shown in A and B, n = 8. D, Plot of change in IPSC amplitude after 1 μM KA application vs change in CV (black) and failures (gray). E, Example PV interneuron to PC pair. Top shows presynaptic cell response to 500 ms current step at double threshold amplitude (1200 pA). F, Amplitude vs time plot for all PV interneuron to PC pairs, n = 6. For this and subsequent figures cell types in pairs are labeled as follows: CCK, CCK interneuron; PV, PV interneuron; PC, principal cell (pyramidal/granule).

IPSCs on to pyramidal cells mediated by CCK- but not PV-containing interneurons are inhibited by KA

IPSC amplitude was monitored in postsynaptic PCs held in voltage clamp at −70 mV (GABA_A-mediated IPSC is an inward current due to symmetrical Cl− concentration) while pairs of action potentials were evoked at 50 Hz in the presynaptic cells by depolarizing current steps every 10 s. After a 4 min baseline period 1 μM KA was bath applied together with 50 μM GYKI 53655 to prevent activation of AMPA receptors. When CCK interneurons were presynaptic, IPSC amplitude was significantly reduced by 1 μM KA (IPSC amplitude 6–10 min after 1 μM KA application = 63 ± 15% baseline, p < 0.05, n = 8, Figs. 1A−C, 2C). Coefficient of variation (CV) and failure analysis demonstrate that this reduction is due to a decrease in presynaptic release as the change in IPSC amplitude is strongly negatively correlated with changes in both parameters (CV: R² = 0.77, p for slope fit = 0.005, failures: R² = 0.75, p for slope fit = 0.01, Fig. 1D). The reduction in IPSC amplitude produced by 1 μM KA is a specific result of KAR activation as no effect was seen when 1 μM KA was applied together with both the AMPA-selective antagonist GYKI 53655 and the AMPA/KA antagonist CNQX (50 μM, IPSC = 103 ± 26% baseline, p = 0.86, n = 6, Fig. 2C). In contrast when PV interneurons were presynaptic KA had no effect on IPSC amplitude (IPSC = 101 ± 25% baseline, p = 0.97, n = 6, Fig. 1E,F), CV (124 ± 20% baseline, n = 6, p = 0.3) or success rate (101 ± 1% baseline, n = 6, p = 0.2).

Kainate depresses IPSCs at low concentration at GluK1 receptors

At CA3 mossy fibers application of KA in the low micromolar range results in a depression of EPSCs, but conversely, lower concentrations cause an increase in EPSC amplitude (Schmitz et al., 2001). To test whether this bimodal effect of KA also exists at CCK interneuron synapses we applied 200 nM KA during recordings of CCK interneuron to PC pairs. Additionally to separate the effect of KAR activation from that of AMPA receptor inhibition we applied KA after prior application of GYKI 53655. In contrast to mossy fiber synapses this low concentration of KA resulted in a depression of CCK interneuron-mediated IPSCs indistinguishable to that caused by 1 μM KA (IPSC = 59 ± 5% baseline, p vs baseline <0.05, p vs 1 μM KA = 0.8, n = 7) (Fig. 2A, C; supplemental Fig. S1, available at www.jneurosci.org as supplemental material).
In a number of systems presynaptic actions of KAR activation have been ascribed to GluK1-containing receptors (Clarke et al., 1997; Vignes et al., 1998; Fisahn et al., 2002; Lourenc¸o et al., 2010). To test whether this subtype was also responsible for the inhibition of CCK interneuron-mediated IPSCs we applied 200 nM KA in the presence of GYKI 53655 and the specific GluK1 antagonist UBP302 (10 μM). Inhibition of GluK1 abolished the depression of IPSC amplitude showing that KA acts via GluK1-containing receptors.

Reduction in IPSC amplitude is not via an indirect activation of GABAB or CB1 receptors. The reduction in evoked IPSC amplitude in hippocampal pyramidal cells caused by KAR activation has been attributed to an indirect result of the increase in sIPSCs due to both activation of presynaptic GABAB receptors and to a reduction in postsynaptic input resistance (Frerking et al., 1999; Fisahn et al., 2002). Consistent with previous reports in the presence of KA we observed an increase in sIPSC frequency in PCs. However this increase was transient and had returned to baseline frequency 6–10 min following 1 μM KA application, at which time the reduction in IPSC amplitude was not due to indirect effects of an increase in sIPSCs or GABAB or CB1 receptor activation.

Reduction in IPSC amplitude is not via an indirect activation of GABA_9 or CB1 receptors. The reduction in evoked IPSC amplitude in hippocampal pyramidal cells caused by KAR activation has been attributed to an indirect result of the increase in sIPSCs due to both activation of presynaptic GABA_9 receptors and to a reduction in postsynaptic input resistance (Frerking et al., 1999; Fisahn et al., 2002). Consistent with previous reports in the presence of KA we observed an increase in sIPSC frequency in PCs. However this increase was transient and had returned to baseline frequency 6–10 min following 1 μM KA application, at which time the reduction in IPSC amplitude was not due to indirect effects of an increase in sIPSCs or GABAB or CB1 receptor activation.

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A recent study has described a mechanism by which KA activation reduces CCK interneuron-mediated IPSCs by facilitating the effect of CB1 receptor activation such that when CB1 receptors are blocked pharmacologically, KA-induced depression no longer reduces IPSC amplitude (Lourenço et al., 2010). As part of this mechanism, CB1 receptor activation requires mGluR-mediated release of the endogenous CB1 agonist 2-AG. In our study it is unclear how mGluRs would be activated but it is possible that CB1 receptors as a result of spontaneously released GABA are unlikely to affect the observed uIPSC amplitude. Although we have shown that KA causes a reduction in IPSC amplitude onto PCs at both high and low concentrations it is possible that 1 μM lies in the middle of a bimodal effect of KA at CCK interneuron to interneuron synapses. To test this we applied 200 nM kainate to CCK interneuron pairs. As for 1 μM, 200 nM had no effect on uIPSC amplitude (IPSC 126 ± 26% baseline, n = 3, p = 0.4,
KA specifically inhibits synchronous GABA release

We have found that application of KA causes a reduction in the peak amplitude of IPSCs produced by CCK interneurons in PCs. This is primarily a measure of synchronous GABA release, however CCK interneurons potentially mediate much of their inhibitory action via asynchronous release (Hefft and Jonas, 2005; Daw et al., 2009). To test whether asynchronous release onto PCs is also inhibited by KA application we delivered 10 trains of 25 presynaptic action potentials at 50 Hz before and after 10 min in the presence of 1 μM KA. We used deconvolution analysis (see methods) to calculate the amount of GABA released in 20 ms time windows corresponding to each action potential and throughout the whole train. KA (1 μM) caused a reduction in overall synchronous release throughout the train that was greater than that seen for asynchronous release (synchronous release = 67 ± 21% baseline, asynchronous release = 91 ± 27% baseline, p < 0.05, n = 6, Fig. 5A–D). This effect was most apparent during the first 5 action potentials of the train when synchronous release is greatest in control conditions (synchronous release first 5 action potential = 60 ± 20% baseline, asynchronous release = 110 ± 29% baseline p < 0.05, Fig. 5A–C). This resulted in an SR that was lower throughout the train in the presence of 1 μM KA (baseline SR = 1.9 ± 0.4, 1 μM KA SR = 1.4 ± 0.3, p < 0.01, n = 6, Fig. 5A,B,D), which was again most pronounced early in the train (baseline SR first 5 action potentials = 8.1 ± 1.8, 1 μM KA SR = 4.0 ± 1.1, p < 0.05, n = 6, Fig. 5A,B,D). This decrease in synchronicity is a specific effect of KAR activation and not a general feature of reduced release probability as we have previously shown than SR increases when release probability is reduced in low extracellular Ca²⁺ (Daw et al., 2009).

Discussion

We have shown that the depressing effect of KAR activation on IPSCs in the hippocampus is dependent on the identity of both the presynaptic and postsynaptic cell type. In PCs IPSCs mediated by CCK interneurons are strongly depressed by KAR activation whereas those mediated by PV interneurons are unaffected. In interneurons IPSCs mediated by either presynaptic cell class are also unaffected. Furthermore we have shown that the depression is restricted to synchronous GABA release. Asynchronous GABA release, a prominent mode of synaptic transmission by CCK interneurons, is unaffected by KA application.

A decrease in IPSC amplitude in response to KAR activation has been shown by a number of groups but these studies focused on IPSCs evoked by extracellular stimulation (Clarke et al., 1997; Rodriguez-Moreno et al., 1997; Frerking et al., 1999; Behr et al., 2002; Fisahn et al., 2002; Maingret et al., 2005). There are two main disadvantages to this form of stimulation. First there are numerous different interneuron classes in the hippocampus (Klausberger and Somogyi, 2008) and extracellular stimulation activates axons from many cell classes at the same time. As a result the source of IPSCs is unknown and it is not possible to identify any cell-type-specific effects. Second, KA directly depolarizes interneurons causing spontaneous firing (Cossart et al., 1998; Fisahn et al., 2002) so that release probability at stimulated synapses will be affected by previous, spontaneous, activity. This phenomenon may also explain the result of one previous study using paired recordings which, unlike our study, did not prevent spontaneous presynaptic firing by injecting hyperpolarizing current (Jiang et al., 2001). As would be expected IPSCs mediated by synapses showing low release probability in baseline conditions, and therefore likely to show frequency-dependent facilitation, were increased in amplitude when KA application caused spontaneous firing. This study also made no attempt to identify the interneuron classes involved.

The ability, in our study, to segregate IPSCs based on presynaptic cell class and to prevent spontaneous firing probably also explains why we were able to see a decrease in IPSC amplitude which was not dependent on the increase in sIPSCs or GABAAR receptor activation (Frerking et al., 1999). Thus, we both conclusively demonstrated the inhibitory effect of KAR activation on IPSCs in the
hippocampus and have shown that this effect is dependent on the identity of both presynaptic and postsynaptic cell type.

In our recordings of interneuron to interneuron synapses we observed no effect of KAR activation whether PV or CCK interneurons were presynaptic. Synapses made by CCK interneurons on to interneurons produce small and highly variable amplitude uIPSCs (Daw et al., 2009) which accounts for the large variability seen in this dataset and as such we cannot entirely rule out that the small, nonsignificant increase, in IPSC amplitude is consistent with a facilitatory effect of KA on interneuron IPSCs (Mulle et al., 2000; Cossart et al., 2001). Alternatively these changes may occur at synapses made by other classes of interneuron which were not studied here.

Very recently another study, which also used paired recordings, reached similar conclusions regarding the identity of interneurons mediating the KA-induced reduction in evoked IPSCs (Lourenço et al., 2010). This study used synthetically released glutamate to activate KARs and elegantly showed that the depressive action of KAs is due to an enhancement of the effect of a CB1 receptor action produced by mGluR-dependent release of endocannabinoids. Contrary to this finding we find that the effect of KAR activation remains in the presence of a CB1 antagonist. This was expected as in our experimental design there is likely no KAR activation remains in the presence of a CB1 antagonist. This study used synaptically released glutamate, reached similar conclusions regarding the identity of interneurons mediating the KA-induced reduction in evoked IPSCs, or occurred at synapses made by other classes of interneuron which were not studied here.

During periods of intense local activity, such as the kindling paradigm, synchronous GABA release determines the network excitability. However, it has been shown that asynchronous GABA release is also important in regulating network activity (Klausberger et al., 1999; Cossart et al., 1998). In our recordings of interneuron to interneuron synapses we observed no effect of KAR activation whether PV or CCK interneurons were presynaptic. Synapses made by CCK interneurons on to interneurons produce small and highly variable amplitude uIPSCs (Daw et al., 2009) which accounts for the large variability seen in this dataset and as such we cannot entirely rule out that the small, nonsignificant increase, in IPSC amplitude is consistent with a facilitatory effect of KA on interneuron IPSCs (Mulle et al., 2000; Cossart et al., 2001). Alternatively these changes may occur at synapses made by other classes of interneuron which were not studied here.

References


