Firing Properties and Connectivity of Neurons in the Rat Lateral Central Nucleus of the Amygdala

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Lopez de Armentia, Mikel and Pankaj Sah. Firing properties and connectivity of neurons in the rat lateral central nucleus of the amygdala. J Neurophysiol 92: 1285–1294, 2004. First published May 5, 2004; 10.1152/jn.00211.2004. Using whole cell recordings from acute slices of the rat amygdala, we have examined the physiological properties and synaptic connectivity to neurons in the lateral sector of the central amygdala (CeA). Based on their response to depolarizing current injections, CeA neurons could be divided into three types. Adapting neurons fired action potentials at the start of the current injections at high frequency and then showed complete spike-frequency adaptation with only six to seven action potentials evoked with suprathreshold current injections. Late-firing neurons fired action potentials with a prolonged delay at threshold but then discharged continuously with larger current injections. Repetitive firers discharged at the start of the current injection at threshold and then discharged continuously with larger current injections. All three cells showed prolonged afterhyperpolarizations (AHPs) that followed trains of action potentials. The AHP was longer lasting with a larger slow component in adapting neurons. The AHP in all cell types contained a fast component that was inhibited by the SK channel blocker UCL1848. The slow component, not blocked by UCL1848, was blocked by isoprenaline and was significantly larger in adapting neurons. Blockade of SK channels increased the discharge frequency in late firers and regular-spiking neurons but had no effect on adapting neurons. Blockade of the slow AHP with isoprenaline had no effect on any cell type. All cells received a mixed glutamatergic and GABAergic input from a medial pathway. Electrical stimulation of the lateral (LA) and basolateral (BLA) nuclei evoked a large monosynaptic glutamatergic response followed by a disynaptic inhibitory postsynaptic potential. Activation of neurons in the LA and BLA by puffer application of glutamate evoked a small monosynaptic response in 13 of 55 CeA neurons. Local application of glutamate to the CeL evoked a GABAergic response in all cells. These results show that at least three types of neurons are present in the CeA that can be distinguished on their firing properties. The firing frequency of two of these cell types is determined by activation of SK channels. Cells receive a small input from the LA and BLA but may receive inputs that course through these nuclei en route to the CeA.

INTRODUCTION

The amygdaloid complex is a structure located within the medial temporal lobe that is intimately involved in emotional behavior, particularly in the generation of anxiety and conditioned fear (Davis and Whalen 2001; LeDoux 2000). Anatomically, the amygdaloid complex can be divided into >13 nuclei that have extensive local and extraamygdaloid connections (Sah et al. 2003). Sensory information from cortical and thalamic structures reaches the amygdala at the level of the lateral (LA) and basolateral (BLA) nuclei. Here information is processed locally and then transmitted, either directly and via the basal nucleus, to the central nucleus (CeA). Projections from the CeA to brain stem and hypothalamic areas mediate the behavioral, hormonal, and autonomic features of fear conditioning (Davis and Whalen 2001; LeDoux 2000).

The CeA is subdivided in four sectors: capsular, lateral, intermediate, and medial (Cassell et al. 1986). All subdivisions of the CeA receive inputs from other amygdaloid nuclei as well as from extramygdaloid sources (Krettek and Price 1978; McDonald 1998; Pitkänen 2000). Within the CeA, the capsular, lateral, and intermediate sector project to the medial sector (Jolkkonen and Pitkänen 1998); however, the medial division does not appear to provide reciprocal connections but has prominent connections to hypothalamic and brain stem regions. Consistent with its autonomic connections, electrical stimulation of the CeA in rats produces physiological fear responses with increase in heart and blood pressure, defecation, vocalization, and a potentiated startle response (Davis et al. 1994). Thus the central nucleus CeA is often considered to be an output station of the amygdaloid complex. However, given the extensive intranuclear connections within the central nucleus, local processing of information arriving at the CeA seems likely.

To understand information processing in the amygdala, it is important to have an understanding of the properties of neurons containing in amygdaloid nuclei as well as their connectivity. The physiological properties of neurons within the LA and BLA, and their synaptic inputs have been described in much detail (see refs in Sah et al. 2003). For the CeA, the electrophysiological properties of the neurons have been described in three species: guinea pig, rat, and cat (Dumont et al. 2002; Schiess et al. 1999). In one study using sharp microelectrodes in rat slices, two types of neuron were described that were clearly separated on their firing properties and type of afterhyperpolarization (AHP) that followed trains of action potentials (Schiess et al. 1999). In contrast, using whole cell recordings from rat, cat, and guinea pig (Dumont et al. 2002), four types of neuron were described that had varying degrees of AHP. Both cat and rat show similar electrophysiological properties in CeA neurons, whereas guinea pig CeA neurons differ from those in the cat and rat (Dumont et al. 2002). It has been suggested that these differences between guinea pigs and rats or cats could underline the distinct behavioral fear responses.
observed in those species (Dumont et al. 2002). The organization of inputs to CeA neurons have been studied in the guinea pig (Royer et al. 1999). However, while the pharmacological properties of some inputs have been examined in the rat (Delaney and Sah 2001; Lopez de Armentia and Sah 2001), little is known about the organization of these afferents. Here we investigate the electrophysiological properties and organization of synaptic inputs to neurons in the lateral sector of the central amygdala (CeL) of the rat.

METH ODS

Experiments were performed on rat brain slices in vitro. All procedures were in accordance with the Institutional Animal Care and Ethics Committee guidelines. Wistar rats (21–27 days old) were anesthetized with intraperitoneal pentobarbitone (50 mg/kg), and coronal slices (400 μm) were prepared using standard methods. After a recovery period of 30 min at 32°C, slices were maintained at room temperature in oxygenated (95% O2, 5% CO2) Ringer solution containing (in mM) 118 NaCl, 2.5 KCl, 25 NaHCO3, 1.2 NaH2PO4, 1.3 MgCl2, 2.5 CaCl2, and 10 glucose. For recordings, slices were transferred to the recording chamber and superfused with Ringer at 32–35°C.

Whole cell recordings were made from neurons in the lateral division of the central amygdala using the “blind” approach. Electrodes were filled with intracellular solution containing either (mM): 117.5 CsGlucocyte, 17.5 CsCl, 8 NaCl, 10 HEPES, 2 Mg2ATP, 0.2 NaGTP, 10 bis-(o-aminophenoxy)-N,N,N’N’-tetraacetic acid (BAPTA), and 0.1 spermine (pH 7.3, osmolarity: 290 mosM/kg) or 135 KMeSO4, 8 NaCl, 10 HEPES, 2 Mg2ATP, 0.2 NaGTP, and 0.1 spermine (pH 7.3, osmolarity: 290 mosM/kg). Access resistance was monitored throughout the experiment. In some experiments, recordings were made with sharp microelectrodes (70–100 MΩ) filtered at 5–10 kHz and digitized at 10–20 kHz (Instrutech, ITC 16, Long Island, NY). All cells described in this study had a membrane potential more negative than −50 mV. Data were recorded and analyzed using Axograph 4.8 (Axon Instruments).

Synchronized responses from the basolateral complex were evoked electrically using an array of eight stainless steel electrodes (FHC, Bowdoinham, ME). In each case, stimulation was applied through two adjacent electrodes allowing the stimulus location to be moved along the basolateral nuclei (Royer et al. 1999). A bipolar stainless steel stimulating electrode was also placed in the medial pathway, just ventral to the central nucleus. Stimuli (50 μs, 10–30 V) were applied by a constant-voltage isolated stimulator (Digitimer, DS2A, Hertfordshire, UK). In some experiments, glutamate 0.1 mM was applied locally by a pressure ejection of 5–10 ms using a Picospritzer II (Parker Instrumentation, Fairfield, NJ).

All values are expressed as means ± SE, and statistical comparisons were done using the two-tailed paired t-test and single-factor ANOVA test. Drugs used were 6-cyano-7-nitroquinolinoxide-2,3-dione (CNQX), 2-amino-5-phosphonovalerate (APV, Tocris Cookson, Bristol, UK), bicuculline methiodide (RBI Research Chemicals, Natick, MA) kynurenic acid, picrotoxin, L-glutamate (Sigma-Aldrich, Australia), and tetrodotoxin (TTX, Alomone Laboratories, Jerusalem, Israel).

RESULTS

In coronal slices, axons bundles delimiting different nuclei of the amygdala could be identified easily using transillumination (Fig. 1). Recordings were made from the CeL, which is separated from the basolateral complex by the intermediate capsule.

FIG. 1. Trans-illuminated slice from rat brain. A: an example of acute coronal section 400 μm thick prepared for recording. The figure shows the region containing the basolateral complex and the central nucleus of the amygdala. These nuclei are delimited by bundles of axons that allow us to identify them with trans-illumination. B: the lateral and medial subdivisions of central nucleus (CeA) are outlined as well as the disposition of the 8 stimulating electrodes array in the basolateral complex (●) and the 2 stimulating electrodes in the medial pathway (●). CeL and CeM, lateral and medial sector of the central amygdala respectively; LA, lateral amygdala; BLA, basolateral amygdala.

Firing properties of CeL neurons

A total of 69 cells were recorded in whole cell configuration and were classified based on their firing properties in response to a 600-ms depolarizing current injection. Neurons were classified into three types: adapting, late firing, and regular spiking. In adapting neurons (25/69; 36%), cells fired several spikes at high frequency at the start of the current injection and showed complete spike-frequency adaptation (Fig. 2A). These neurons fired at most six or seven action potentials in response to suprathreshold current injections. In some (20/69; 29%) neurons, there was a noticeable delay between the start of the depolarizing pulse and the first action potential (AP), and these were classified as late firing (Fig. 2B). Finally, regular-spiking neurons (24/69; 35%) discharged at high frequency at the start of the current injection with no delay but fired repetitively with a small amount of spike-frequency adaptation (Fig. 2C). The passive membrane properties of the three types of cell were generally similar (Table 1), but notably late-firing neurons showed a more hyperpolarized resting membrane potential than the other groups. Adapting or regular-spiking neurons did not display a late-firing response when they were hyperpolarized by current injection (data not shown), showing that the lack of delay was in these cells is not due their more depolarized membrane potentials.
Role of Ca\(^{2+}\)-dependent K\(^+\) currents

In many neurons, trains of APs are followed by a slow AHP due to activation of Ca\(^{2+}\)-activated K\(^+\) currents. The AHP controls the excitability of the cell during trains of APs and is largely responsible for setting the firing frequency and spike-frequency adaptation (Sah 1996). APs in CeL neurons were followed by a slow AHP that lasted a variable duration between one and several seconds that was slower and larger in adapting neurons (Fig. 3). Under voltage clamp, at a holding potential of \(-50\) mV, depolarizing voltage step (100 ms) to +10 mV generated outward tail currents with fast and slow components. Consistent with the duration of the AHP, the slow

**TABLE 1.** Electrophysiological properties of CeL neurons recorded with microelectrodes and with patch pipettes in whole cell configuration

<table>
<thead>
<tr>
<th>Type cell</th>
<th>n</th>
<th>(V_m), mV</th>
<th>(R_m), M(\Omega)</th>
<th>(\tau), ms</th>
<th>Spike Amplitude, mV</th>
<th>Spike Duration, ms</th>
<th>Threshold, mV</th>
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</thead>
<tbody>
<tr>
<td>Whole cell (KMe)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Adapting</td>
<td>69</td>
<td>-66 ± 1.3</td>
<td>213 ± 13.4</td>
<td>29 ± 2.6</td>
<td>55 ± 1.6</td>
<td>0.89 ± 0.03</td>
<td>-32 ± 2.7</td>
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<tr>
<td>Late firing</td>
<td>25 (36)</td>
<td>-73 ± 1.4*</td>
<td>194 ± 32.1</td>
<td>23 ± 2.4</td>
<td>58 ± 2.3</td>
<td>0.99 ± 0.06</td>
<td>-33 ± 1.2</td>
</tr>
<tr>
<td>Regular spiking</td>
<td>24 (35)</td>
<td>-65 ± 1.8</td>
<td>220 ± 29.7</td>
<td>32 ± 3.3</td>
<td>54 ± 1.9</td>
<td>0.98 ± 0.03</td>
<td>-33 ± 0.7</td>
</tr>
<tr>
<td>Whole cell (KGlu)</td>
<td>18</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Late firing</td>
<td>9 (50)</td>
<td>-69 ± 1.9</td>
<td>160 ± 21.8</td>
<td>19 ± 1.7</td>
<td>88 ± 3.6</td>
<td>0.91 ± 0.06</td>
<td>-35 ± 1.3</td>
</tr>
<tr>
<td>Regular spiking</td>
<td>9 (50)</td>
<td>-68 ± 1.9</td>
<td>166 ± 20.4</td>
<td>21 ± 2.1</td>
<td>82 ± 2.9</td>
<td>0.97 ± 0.06</td>
<td>-34 ± 1.0</td>
</tr>
<tr>
<td>Microelectrodes</td>
<td>36</td>
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<td></td>
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</tr>
<tr>
<td>Adapting</td>
<td>10 (22)</td>
<td>-59 ± 2.9</td>
<td>118 ± 19.4</td>
<td>24 ± 7.0</td>
<td>52 ± 2.8</td>
<td>0.92 ± 0.21</td>
<td>-40 ± 1.9</td>
</tr>
<tr>
<td>Regular spiking</td>
<td>36 (78)</td>
<td>-60 ± 1.3</td>
<td>169 ± 11.7*</td>
<td>29 ± 2.4</td>
<td>52 ± 1.2</td>
<td>1.01 ± 0.08</td>
<td>-41 ± 1.1</td>
</tr>
</tbody>
</table>

Values are means ± SD, parentheses enclose percentages of total. \(*P < 0.05.\)

*FIG. 2.* Electrophysiological properties of three types of CeL neurons. Traces show responses recorded in current clamp to a series of 600-ms current injections (-100, 100, 300 pA) from adapting neurons (A), late-firing neurons (B), and regular-spiking neurons (C). Note that in the case of the late-firing neuron, the current pulses applied were -100, 200, and 300 pA. Bottom: the instantaneous frequency between action potentials is plotted against the spike number during the current injections illustrated above. Note that adapting neurons cease to fire after 6 or 7 action potentials while the other cell types continue to spike throughout the current injection.
component of the outward current was larger in adapting neurons. The ratio of the amplitude of the slow component (measured at 400 ms after the end of the voltage step) to that of the fast current, measured immediately after the voltage step, was 0.33 ± 0.05 (n = 12) in adapting neurons, significantly larger (P < 0.01) than that measured in late-firing (0.19 ± 0.05; n = 5) and regular-spiking (0.12 ± 0.02; n = 10) neurons.

As the AHP is generally due to activation of calcium-dependent potassium currents, we next tested the calcium sensitivity of the AHP. In all cell types, application of tetrodotoxin blocked AP generation and revealed the presence of a depolarizing hump at the beginning of the current injection (Fig. 4). This depolarizing hump was abolished when voltage-dependent calcium channels were blocked with cadmium (250 μM) showing that all cell types express voltage-gated calcium currents. Blockade of calcium currents with cadmium (250 μM, n = 9; Fig. 4) or loading cells with the calcium chelator BAPTA (10 mM; n = 3) abolished the slow AHP showing that it was due to activation of calcium activated potassium conductances.

Two types of slow calcium-activated potassium currents, $I_{AHP}$ and $sI_{AHP}$, contribute to the slow AHP that follows APs (Sah and Faber 2002). SK channels are responsible for $I_{AHP}$, which has rapid rise and decay kinetics and is blocked by the selective blockers apamin and UCL1848 (Sah and Faber 2002; Shah and Haylett 2000). In contrast, $sI_{AHP}$ has significantly slower kinetics, is insensitive to SK channel blockers, but is modulated by a range of neurotransmitters. As these currents play a significant role in neuronal firing properties, we tested for the presence of these two conductances and their roles in determining the firing properties of CeL neurons. In response to a 100-ms depolarizing voltage step from a holding potential of −50 mV, the fast component of the outward tail current was selectively blocked by UCL1848 (100 nM; Fig. 5). The decay time constant of the $I_{AHP}$ current, measured as the UCL1848-sensitive component of the current by digital subtraction was 169 ± 35 ms in late-firing neurons (n = 5), 175 ± 69 ms in regular-spiking neurons (n = 4), and 126 ± 18 ms in adapting neurons (n = 4). The similarity in the decay time constants of $I_{AHP}$ indicates that the calcium-buffering capacity of these neurons is similar (Sah 1992). The slow component of the tail current had a slow rising phase and decayed much slower and was similar in the three cells with an average time constant of 1.6 ± 0.2 s (n = 8; Fig. 5B). These kinetic features are consistent with the underlying currents being $I_{AHP}$ and $sI_{AHP}$. As expected for $sI_{AHP}$ currents, the slow component was selectively blocked by the beta catecholamine receptor agonist isoprenaline (n = 3; Fig. 5) or muscarine (n = 3; not shown). Consistent with the roles of these currents in mediating the two components of the AHP, the fast, rapidly rising component of the AHP was selectively blocked by UCL1848, whereas the slow component was selectively blocked by isoprenaline (Fig. 5). The absence of any effect of isoprenaline on the AHP in nonadapting neurons (Fig. 5D) is consistent with virtual absence of the slow current in these cells.

We next tested the role of the two AHPs in the firing properties of CeL neurons. Blockade of $I_{AHP}$ with UCL 1848 (100 nM) increased the discharge frequency and the number of APs triggered by depolarizing current pulses both in late-firing neurons (n = 5) and regular-spiking neurons (n = 5; Fig. 6). In the presence of UCL 1848, the number of APs evoked by a twice threshold current injection changed from 7.6 ± 1.5 to 12.5 ± 3.1 spikes in late-firing neurons (n = 6; Fig. 6B) and from 11.0 ± 2.1 to 17.7 ± 4.2 in regular-spiking neurons cells (n = 4; Fig. 6C). In contrast, blockade of SK channels had no effect on the firing properties of adapting CeL neurons. The number of APs evoked by a twice threshold current injection
was 3.7 ± 1.2 in control Ringer and 3.5 ± 0.5 in the presence of UCL 1848 (n = 4; Fig. 6A). As shown in the preceding text, the sI_AHP current in adapting neurons is larger than that present in the other two cell types. This current is thought to be a major determinant of spike-frequency adaptation in a number of neurons (Sah 1996). However, no specific blockers of this current are currently available. The sI_AHP current is the target for modulation by a range of transmitter systems (Sah 1996). Application of isoprenaline and muscarine, which blocked the slow AHP, also caused other actions in CeL neurons; this precluded us using this as a test for the role of the slow current. However, when recordings were made with electrodes filled with a Kgluconate-based internal solution (n = 18), when the amplitude of sI_AHP is much reduced (Zhang et al. 1994) or when cells were loaded with high concentrations of BAPTA (n = 4), no adapting cells were found. Thus the adaptation seen in these cells likely results from the presence of the sI_AHP current.

**Synaptic inputs to CeL neurons**

**CONNECTIONS FROM THE MEDIAL PATHWAY.** We have shown previously that stimulation of fibers medial and ventral to the CeL evokes a robust input to CeL neurons (Delaney and Sah 2001; Lopez de Armentia and Sah 2003). This pathway is thought to contain afferents originating in the lateral parabrachial area (Bernard et al. 1993; Neugebauer et al. 2003). Electrical stimulation of the medial pathway elicited a biphasic response in all CeL neurons. When recordings were made in current clamp, stimulation of this pathway generated an excitatory postsynaptic potential (EPSP) followed by an inhibitory postsynaptic potential (IPSP; Fig. 7A1). Under voltage-clamp at depolarized membrane potentials, stimulation evoked a fast inward current followed by a slower outward current (Fig. 7A2). Application of the nonspecific glutamatergic blocker kynurenic acid (3 mM) abolished the fast inward current followed by a slower outward current (Fig. 7A2). The outward current was little affected by kynurenic acid but could be blocked by the GABA_A antagonist picrotoxin (100 μM, n = 10; Fig. 7A2). Thus inputs arriving into the CeL through the medial pathway contain both glutamatergic and GABAergic afferents.

**Connections from the BLA complex**

Electrical activation within the BLA complex also elicited a biphasic response in CeL neurons (Fig. 7B). Application of the nonspecific glutamate receptor antagonist kynurenic acid (3 mM) blocked both the excitatory and inhibitory components of the response (n = 17), showing that the inhibitory response in this pathway is polysynaptic in nature. Stimulation from all regions from the dorsal part of the lateral amygdala to the basal nucleus (Fig. 1) evoked a similar response in CeL neurons. We were unable to detect any significant differences in the amplitudes of the evoked synaptic response as the stimulus was moved ventrally thought the basolateral complex. An example from one cell is illustrated in Fig. 7C that shows responses in one cell in response to stimulation from the most dorsal and most ventral pair of electrodes (Fig. 1). Neurons in the CeL are well known to receive feedforward inhibition from the inter-
calculated cell masses that are located on the border of the basolateral complex and the central nucleus (Delaney and Sah 2001; Royer et al. 1999). Consistent with this, when stimulation electrodes were moved to the intermediated capsule, an inhibitory postsynaptic current (IPSC) could be consistently observed when responses were not observed in control Ringer, applied glutamate led to a depolarization and generation of APs that were curtailed due to activation of the IPSP. Blockade of GABAergic inhibition with picrotoxin increased the number of APs evoked (Fig. 8B). These results indicate that neurons in the lateral and basolateral amygdala project to CeL and that the BLA complex is under a strong inhibition by local interneurons. In most cells, the response to puffer application of glutamate was small. Indeed the response was little larger than the size of the spontaneous miniature synaptic potentials recorded in the same neurons (Fig. 8C). At a holding potential of −70 mV, the average amplitude of the spontaneous miniature synaptic current was 17 ± 2 pA, whereas the response to puffer application of glutamate in the basolateral complex was 42 ± 8 pA (n = 13). This result indicates that at least in a coronal section, projection neurons in the basolateral complex make contacts with CeL neurons that have at most two or three release sites. Depolarization of the postsynaptic cell revealed a slow component to the synaptic current consistent with the presence of dual component glutamatergic synapses at these inputs (Lopez de Armentia and Sah 2003). It was notable that in some cells, responses could be obtained in a single cell from several sites within the basolateral complex indicating that there is some convergence of inputs to CeL neurons.

Puffer application of glutamate in the medial sector did not produce any responses in CeL neurons (n = 5) while application of glutamate within the CeL consistently activated GABAergic responses in CeL neurons (n = 15; Fig. 8E). These results are consistent with the lack of projections from the medial to the lateral sector (Jolkkonen and Pitka 1998) and suggest that there are extensive local connection within the largely GABAergic neurons of the lateral division (Sun and Cassell 1993).

**DISCUSSION**

In this study, using whole cell recordings in acute brain slices, we have examined the physiological properties and synaptic connectivity of neurons in the lateral division of the rat central amygdala. We find that these neurons can be separated into at least three types that can be distinguished on their firing properties. In response to sustained depolarizing current injection, one class of cell (adapting neurons) fires only a few APs and then shows complete spike-frequency adaptation. A second class of cell, regular firing neurons, fires a train of APs during the current injection. This train shows some spike-frequency adaptation at the start of the AP train but continues to spike during the current injection. The third type of cell (late firer) is similar to regular-spiking neurons except for the finding that hyperpolarizing these neurons leads to a noticeable delay before the first AP.

There have been two previous studies examining the electrophysiological properties of CeL neurons (Dumont et al. 2002; Martina et al. 1999; Schiess et al. 1999). In the first
study, using sharp microelectrode recordings from rat CeA neurons (Schiess et al. 1999), two cell types (called type A and B) were described. The properties of these neurons are compatible to those described here as repetitive firers and adapting cells, respectively. Type B cells formed 37% of the cell population, close to our estimate of 36% for adapting neurons. Late-firing neurons described by us were not described in the Schiess study. However, in response to suprathreshold current injections, these cells behave similarly to repetitive firers and together (late + repetitive firers) constitute 63% of the total cell population, similar to the 63% described for type A cells by Schiess et al. (1999). In another set of experiments, we made intracellular recordings with sharp microelectrodes from 46 CeL neurons (Table 1). Only two types of cell were encountered when recording in this modality: adapting and regular spiking. Ten (22%) exhibited full adaptation, whereas the other 36 neurons (78%) were similar to the repetitive firers. No single or late-firing neurons were found with intracellular microelectrodes. These values are very similar to those reported by Schiess et al. and indicate that the differences in firing properties arise from the different recording modes in the two studies.

More recently, whole cell recordings have been made from both lateral and medial sectors of the CeA from rat, cat, and guinea pig (Dumont et al. 2002; Martina et al. 1999). In this study, three main cell types were described and called low-threshold bursters, regular-spiking, and late-firing neurons. The late-firing and regular-spiking neurons are similar to those described by us. However, no adapting neurons were described. Furthermore for the CeL in the rat, regular-spiking neurons formed 65% of the cell population while the late firers accounted for only 9%. In our study, we estimated late firers to form 29% of the total population, significantly different from the 9% described by Dumont et al. (2000). What accounts for these differences in firing properties? Dumont et al. made whole cell recordings using potassium-gluconate-based internal solutions. In contrast in the current study, we have used potassium-methylsulphate-based internal solutions. The difference in cell properties in the two studies likely stems from this difference in internals solutions. This effect of gluconate in

FIG. 6. SK channels activation determines the firing frequency of neurons. Responses of an adapting (A), late-firing (B), and regular-spiking (C) neuron to 600-ms current injection (375 pA) in control conditions. Blockade of SK channels with 100 nM UCL1848 increased the number of AP and their firing frequency in regular-spiking neurons (B and C) but did not affect the firing properties of adapting neurons (A). The change in discharge frequency is plotted as the instantaneous frequency against spike number (bottom).
The firing properties of neurons are determined in large by the complement of ion channels that they express (Hille 1992). In particular, slow calcium-activated potassium currents are key determinants of the repetitive firing properties (Sah and Faber 2002). We find that CeL neurons express both types of slow calcium-activated potassium currents. The apamin and UCL1848-sensitive $I_{\text{AHP}}$ current is present in all three cell types and makes a major contribution to setting the spiking frequency of repetitive firers and late firers. However, while clearly present in adapting cells, this current appears to have little impact on the firing properties. While the $I_{\text{AHP}}$ current is present in all three cell types, its amplitude is much larger in fully adapting neurons. The $I_{\text{AHP}}$ current has been proposed to be the major determinant of spike-frequency adaptation (Sah 1996). The lack of fully adapting neurons under conditions where the slow AHP was much reduced is consistent with the presence of a larger $I_{\text{AHP}}$ current in adapting neurons. Late-firing neurons are similar to repetitive firers in that they do not show marked spike-frequency adaptation. These neurons have a more hyperpolarized resting membrane potential. The slow ramp to AP initiation has been previously been described and has been shown to be due to activation of the slowly inactivating, voltage-dependent potassium current $I_D$ (Martina et al. 1999). In agreement with this, as shown by Martina et al. (1999), low concentrations of 4-AP (30 μM) that block $I_D$ (Storm 1988) was able to block the delayed response (data not shown).

The central amygdala receives amygdaloid as well as extraamygdaloid projections. We find that all neurons in the lateral division of the CeA receive mixed excitatory/inhibitory inputs from the medial pathway, perhaps containing inputs from the parabrachial nucleus (Bernard et al. 1993; Neugebauer et al. 2003). This is a robust input in all cells and has been proposed to mediate the inputs containing pain related information. However, stimulation in this region also consistently evoked a monosynaptic GABAergic inhibitory input to these cells. The source of this input is not clear but may represent inputs from the bed nucleus of the stria terminalis (Dong et al. 2001).
Electrical stimulation in the basolateral complex evoked excitatory responses in all CeL neurons. As the stimulus was moved dorsally from the LA to the basal nucleus equally strong inputs could be evoked in CeL neurons, suggesting that neurons in the lateral and basolateral amygdala project to the CeL. Similar findings have been reported for CeL neurons in the guinea pig (Royer et al. 1999) and is consistent with tract tracing studies that show projections from these areas to the CeL (Paré et al. 1995; Pitkänen et al. 1995; Smith and Pare 1994). However, direct excitation of pyramidal neurons in the basolateral complex with glutamate was less effective than electrical stimulation, and the responses to glutamatergic activation of basolateral neurons were generally small. Thus it seems likely that innervation of CeL neurons by neurons in the basolateral complex is relatively weak. This result is consistent with the finding that stimulation of the lateral amygdala leads to spread of excitation into the basal regions but not the central amygdala (Wang et al. 2001). It was notable that activation of the neurons in the basolateral complex was much more robust when inhibition was blocked showing that local inhibition is very strong within these nuclei (Lang and Pare 1997). This difference between electrical stimulation and direct activation of neurons in basolateral nuclei suggests that there are fibers of passage coursing though the lateral, basolateral, and basal nuclei that innervate neurons in the lateral division of CeA. Indeed in preliminary experiments, we have found that puffer application of glutamate to the adjacent perirhinal or entorhinal cortex can also evoke excitatory responses in CeL neurons. The axons of these cells are likely to course through the basolateral complex on their way to the CeA and be excited by electrical stimulation in the basolateral complex (Fig. 1). As shown previously (Royer et al. 1999), stimulation in the basolateral complex evoked a disynaptic IPSP in CeL neurons and is thought to be due to excitation of the intercalated cells that lie between the basolateral and central nuclei (Delaney and Sah 2001; Royer et al. 1999).

The CeL receives extensive projections from cortical, brain stem, and thalamic regions (McDonald 1998; Pitkänen 2000). Although the intraamygdaloid projections are relatively sparse, neurons within the lateral division do receive a large inhibitory projection from the intercalated cell masses (Delaney and Sah 2001; Paré and Smith 1993), which in turn receive excitatory inputs from the lateral, basolateral and basal nucleus (Royer et al. 1999). Studies on fear conditioning have concentrated at changes in glutamatergic inputs in the lateral amygdala (Davis and Whalen 2001; LeDoux 2000). The extensive convergence of inputs into the central amygdala coupled to the fact that the physiological measures in fear conditioning are initiated by outputs of this nucleus suggests that changes in synaptic transmission within the central nucleus is another potential site for regulation of fear conditioning.

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References


