Regulation of Inhibitory Synaptic Transmission by Vasoactive Intestinal Peptide (VIP) in the Mouse Suprachiasmatic Nucleus

Itri, Jason and Christopher S. Colwell. Regulation of inhibitory synaptic transmission by vasoactive intestinal peptide (VIP) in the mouse suprachiasmatic nucleus. J Neurophysiol 90: 1589–1597, 2003; 10.1152/jn.00332.2003. Circadian rhythmicity in mammals is generated by a pair of nuclei in the anterior hypothalamus known as the suprachiasmatic nuclei (SCN), whose neurons express a variety of neuropeptides that are thought to play an important role in the circadian timing system. To evaluate the influence of VIP on inhibitory synaptic transmission between SCN neurons, we used whole cell patch-clamp recording in an acute brain slice preparation of mouse SCN. Baseline spontaneous GABAergic inhibitory postsynaptic currents (IPSCs) varied significantly between regions and across phases, with a greater frequency of IPSCs observed in the dorsomedial region during the early night. Bath-applied VIP caused a significant increase in the frequency of spontaneous inhibitory postsynaptic currents (sIPSC) in a reversible and dose-dependent manner with no effect on the mean amplitude or kinetic parameters. The effect of VIP was widespread throughout the SCN and observed in both ventrolateral (VL) and dorsomedial (DM) regions. In the presence of tetrodotoxin, VIP increased the frequency of miniature IPSCs without affecting the mean magnitude or kinetic parameters. The magnitude of the enhancement by VIP was significantly larger during the day than during the night. Pretreatment with the VIP-PACAP receptor antagonist [Ac-Tyr¹, D-Phe⁶]-GHRF 1-29 or the selective VPAC₂ receptor antagonist PG 99-465 completely blocked the VIP-induced enhancement. The effect of VIP appears to be mediated by a cAMP/PKA-dependent mechanism as forskolin mimics, while the PKA antagonist H-89 blocks the observed enhancement of GABA currents. Our data suggest that VIP activates presynaptic VPAC₂ receptors to regulate inhibitory synaptic transmission within the SCN and that this effect varies from day to night.

INTRODUCTION

Daily rhythms in our behavior, most notably the sleep-wake cycle, are primarily regulated by a timekeeping structure in the hypothalamus known as the suprachiasmatic nucleus (SCN) (Gillette 1997). When SCN neurons are removed from an organism and maintained in a brain slice preparation, they continue to generate 24-h rhythms in electrical activity, peptide secretion, and gene expression (Dunlap 1999; Earnest and Sladek 1986; Prosser 1998). Previous studies suggest that the basic mechanism responsible for the generation of these rhythms is intrinsic to individual cells in the SCN (Welsh et al. 1995). Morphological studies based on peptide phenotypes and neuronal projections delineate two discrete subregions within the SCN, the ventrolateral (or core) region and the dorsomedial (or shell) region (Moore et al. 2002). Each subregion is functionally distinct and plays an important role in the translation of both photic and nonphotic stimuli into a coherent circadian rhythm that is capable of adapting to changes in the environment (Gillette 1997). Of recent interest is the physiological significance of various neuropeptides expressed in SCN neurons and co-released at active synapses with neurotransmitters such as glutamate and GABA (Moore et al. 2002; Peytevin et al. 2000). These neuropeptides are regulated in a circadian manner and are likely to transmit information that is distinct from that of classical neurotransmitters (Inouye 1996).

Vasoactive intestinal peptide (VIP)-expressing neurons found in the core region of the SCN are thought to mediate entrainment to the light-dark (LD) cycle by receiving photic information from the retina via the retino-hypothalamic tract (RHT) and geniculo-hypothalamic tract (GHT) (van Esseveldt et al. 2000). This is further supported by the observation that VIP protein and mRNA cycle diurnally in the adult rat in a LD cycle, but remain constant in prolonged darkness (DD; Shinohara et al. 1993, 1999a; Takahashi et al. 1989). Using extracellular recording in an acute brain slice preparation, Reed and coworkers (2001) demonstrated that VIP treatment during the early subjective night evoked a small phase delay and during the late subjective night evoked a large phase advance. Functionally, the microinjection of VIP into the SCN region of Syrian hamsters during the early or late subjective night produced similar phase-shifts in locomotor activity rhythms (Albers et al. 1991; Piggins et al. 1995). Short light pulses administered during the early or late subjective night also phase-shift rodent behavioral rhythms in a manner similar to VIP application, raising the possibility that VIP is an intermediate in the process of entraining the circadian system to light pulses. Additionally, administration of VIP induces mammalian period (mPer) expression in SCN neurons presumably through activation of VPAC₂ receptors, which are widely distributed throughout the SCN (Cagampang et al. 1998; Nielsen et al. 2002; Shinohara et al. 1999a). Mice overexpressing VPAC₂ receptors exhibit a shorter free-running period (Shen et al. 2000), while mice deficient in this receptor exhibit a profound disruption in both wheel-running activity and rhythmic gene...
expression (Harmar et al. 2002). Given this background, it would be surprising if VIP did not play an important modulatory role in regulating cell-to-cell communication within the SCN.

Although clearly functionally important, the effects of VIP on SCN neurons are largely unknown. Since VIP is co-expressed with GABA (Moore et al. 2002), one hypothesis is that VIP modulates inhibitory synaptic transmission within the SCN. VIP is a potent stimulator of adenylyl cyclase (AC) and is expected to stimulate cAMP and PKA via the VPAC₂ receptor (e.g., Harmer et al. 1998; Nowak and Kuba 2002). Furthermore, VIP has been shown to modulate GABAergic synaptic transmission in the hippocampus (Wang et al. 1997). Therefore it is likely that VIP acts through the cAMP/PKA cascade to regulate GABA release in neurons of the SCN. The VPAC₂ receptor is abundantly expressed throughout the SCN (Cagampang et al. 1998), suggesting that the effects of VIP may not be restricted to the shell region. In the present study, we utilized whole cell patch electrophysiological techniques to record GABA-mediated currents in SCN cells in a brain slice preparation. As a first step, spontaneous inhibitory postsynaptic currents (sIPSCs) were recorded from SCN slices from animals maintained in an LD cycle. Comparisons were made between ventrolateral (VL) and dorsomedial (DM) regions of the SCN as well as between day and night. Next, the effects of VIP on sIPSCs recorded in the VL and DM SCN at different phases were determined. Finally, the possibility that VIP’s actions are mediated by a VPAC₂ receptor and cAMP/PKA-dependent pathways was evaluated.

Methods

Animals and brain slice preparation

The UCLA Animal Research Committee approved the experimental protocols used in this study. Brain slices were prepared using standard techniques from C57 BL/6 mice between 3 and 8 wk of age. Mice were killed by decapitation; brains were dissected and placed in standard techniques from C57 BL/6 mice between 3 and 8 wk of age.

Whole cell patch-clamp electrophysiology

Methods are similar to those described previously (Colwell 2001; Michel et al. 2002). Slices were placed in a chamber (PH-1, Warner Instruments) attached to the stage of a fixed-stage upright microscope. The slice was held down with thin nylon threads glued to a platinum wire and submerged in continuously flowing, oxygenated ACSF (25°C) at 2–4 mil/min. Electrodes were pulled on a multistage puller (Sutter P-97; 1.5 nm OD borosilicate capillary glass) and resistance in the bath was typically 3–6 MΩ. The standard solution in the patch pipette contained (in mM) 112.5 K-glucuronate; 1 EGTA; 10 HEPES; 5 MgATP; 1 GTP; 0.1 leupentin; 10 phosphocreatine; 4 NaCl; 17.5 KCl; 0.5 CaCl₂; and 1 MgCl₂. The pH was adjusted to 7.25–7.3 and the osmolality was adjusted to between 290 and 300 mOsm. Whole cell recordings were obtained with an Axon Instruments 200B amplifier and monitored on-line with pCLAMP (Version 8.0, Axon Instruments). To minimize changes in off-set potentials with changing tonic conditions, the ground path used a KCl agar bridge to an Ag/AgCl ground well. Cells were approached with slight positive pressure (2–3 cm H₂O) and offset potentials were corrected. The pipette was lowered to the vicinity of the membrane, keeping positive pressure. After forming a high-resistance seal (2–10 GΩ) by applying negative pressure, a second pulse of negative pressure was used to rupture the membrane.

While entering the whole cell mode, a repetitive test pulse of 10 mV was delivered in a passive potential range (∼−60 to −70 mV). Once the whole cell configuration was established, whole cell capacitance was calculated from voltage transients produced by a 20-mV voltage step lasting 40 ms according to standard methods (Colwell 2001; Michel et al. 2002). Whole cell capacitance and electrode resistance were neutralized. The series and input resistances were monitored throughout the experiment by checking the response to small pulses in the passive potential range. Data were not collected if series resistance was >40 MΩ or if the value changed significantly (>20%) during the course of the experiment. The standard extracellular solution used for all experiments was ACSF. When necessary, various specific blocking agents were used to isolate currents under investigation. Solution exchanges within the slice were achieved by a rapid gravity feed delivery system. In our system, the effects of bath-applied drugs began within 15 s and were typically maximal by 3–5 min.

The current required to maintain the cell’s membrane potential at −70 mV was monitored throughout the experiment. Spontaneous currents were recorded with pClamp in the gap-free mode and analyzed using MiniAnalysis software (Version 5.2.1, Synaptosoft). Events were detected using the following criteria: threshold, 5 pA; period to find local maximum, 5 ms; time before peak for baseline, 6 ms; period to search decay time, 50 ms; fraction of peak to find decay time, 0.38; period to average baseline, 2.5 ms; area threshold, 15; and detect complex peak, enabled. Events were excluded if the decay time was <6 ms (Michel et al. 2002). The same criteria were used for evaluating the frequency of miniature inhibitory postsynaptic currents (mIPSCs) in the presence of TTX. IPSC frequency was determined by counting the number of events during a 1- to 2-min time bin and reporting this number as events/s or hertz. Baseline frequency was determined 3 min after entering the whole cell configuration and treatment frequency was determined 5 min after the beginning of drug perfusion. All recordings were completed within 12 min to avoid cell death. Using these criteria in untreated cells, baseline IPSC frequency typically did not vary significantly over the 12-min time span. Neurons that demonstrated at least a 5% change in the frequency of GABA IPSCs after drug treatment were considered “responders” and were included in the appropriate treatment group.

Cell identification

After electrophysiological analysis, whole slices (350 μm) containing bicucullin-filled cells were fixed by overnight immersion in paraformaldehyde (4%) in phosphate-buffered saline (PBS). The slices were then washed with Tris-buffered saline for 1 h and processed histochemically for biocytin staining. The purpose of staining was to identify the type of cell. Neurons were initially designated as either VL or DM based on visualization with IR-DIC optics. This characterization was then verified by filling the cell with biocytin and counterstaining the slice with a Nissl stain to confirm the location of the neuron within the SCN.

Lighting conditions

Animals were maintained on a daily light-dark cycle consisting of 12 h of light followed by 12 h of dark. To evaluate diurnal variations in IPSCs and the VIP-mediated enhancement of these GABA-mediated currents, animals were killed approximately 1 h before the beginning of the phase of interest. Zeitgeber time (ZT) is used to describe the projected time of the oscillator within the SCN based on
The next experiment was designed to determine whether sIPSCs recorded in SCN neurons varied with the phase of the daily cycle. The data were collected at various phases of the animal’s daily cycle corresponding to day (ZT 4–8), early night (ZT 13–15), and late night (ZT 20–22). The sIPSC frequency in the DM SCN exhibited a daily rhythm that peaked during the early night (Fig. 3). The IPSC frequency was significantly greater in the early evening (12.0 ± 1.6 Hz, n = 16) compared with the day (7.9 ± 1.1 Hz, n = 28, P < 0.05) and the late night (7.7 ± 1.9 Hz, n = 6, P < 0.05). This diurnal rhythm was restricted to the cells in the DM region as there was no significant temporal variation in the IPSC frequency measured from the VL region (P > 0.05, Fig. 3). Similarly, no significant differences were detected in the amplitude, rise time, or decay time of sIPSCs between the three phases of the daily cycle. These data indicate that the frequency of inhibitory synaptic transmission varies with the daily cycle in SCN neurons in the DM cell population.

**Spontaneous IPSCs frequency varied between day and night in the SCN**

In this study, we used the whole cell voltage-clamp technique to record sIPSCs from neurons in the SCN (Fig. 1). IPSCs were widespread in the SCN and could be detected from every neuron recorded (n = 187). Overall, the mean frequency and the mean amplitude of sIPSCs recorded at a holding potential of −70 mV were 5.9 ± 0.6 events/s (mean ± SE, n = 107) and −14.3 ± 0.8 pA, respectively. The time to rise and the time to decay (latency of the inward current peak from the baseline) were 2.4 ± 0.1 and 14.2 ± 0.5 ms, respectively. The IPSCs exhibited a reversal potential between −40 and −50 mV (n = 8), a range consistent with the calculated chloride equilibrium potential (E_Cl) of −45.6 mV at 25°C. The reversal potential for IPSCs, and presumably E_Cl, stabilized within 3 min of entering the whole cell configuration and remained constant for the duration of the experiment (n = 8). Because the reversal potential for chloride was more positive than the holding potential used to measure GABA currents, all recordings show IPSCs as inward currents. All sIPSCs were completely abolished with the GABA_A antagonist bicuculline (25 μM, 8 of 8 neurons tested), indicating that they are mediated by GABA_A receptors. In contrast, the sIPSCs were unaffected by the AMPA/kainate (KA) GluR antagonist 6-cyano-7-nitroquinoxaline-2,3-dione (CNQX, 20 μM, 8 of 8 neurons tested).

Neurons were initially designated as either VL or DM based on their location within the SCN visualized with infrared differential interference contrast (IR-DIC) optics and with the help of landmarks such as the third ventricle and optic chiasm (Fig. 2). This localization was then verified by filling the cell with biocytin and counterstaining the slice with a Nissl stain to confirm that the neuron was in the VL (6 of 6 neurons examined) or DM (6 of 6 neurons examined) region. Overall, the frequency of sIPSCs in the VL region (3.9 ± 0.6 Hz, n = 44) differed significantly from IPSCs measured in the DM region (8.1 ± 1.0 Hz, n = 41, P < 0.01). No significant differences were detected in the amplitude, rise time, or decay time of sIPSCs between the VL and DM SCN regions. Thus sIPSCs are a general feature of cells within the SCN but are less frequent in the retinal recipient VL region.

**Statistics**

Between group differences were evaluated using t-test or Mann-Whitney rank sum tests when appropriate. Values were considered significant if P < 0.05. All tests were performed using SigmaStat or SigmaPlot (SPSS, Chicago, IL). In the text, values are shown as mean ± SE. Each group of data is collected from more than or equal to three animals, with n representing the number of cells recorded.

**RESULTS**

**sIPSCs recorded in VL and DM SCN**

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The next experiment was designed to determine whether sIPSCs recorded in SCN neurons varied with the phase of the daily cycle. The data were collected at various phases of the animal’s daily cycle corresponding to day (ZT 4–8), early night (ZT 13–15), and late night (ZT 20–22). The sIPSC frequency in the DM SCN exhibited a daily rhythm that peaked during the early night (Fig. 3). The IPSC frequency was significantly greater in the early evening (12.0 ± 1.6 Hz, n = 16) compared with the day (7.9 ± 1.1 Hz, n = 28, P < 0.05) and the late night (7.7 ± 1.9 Hz, n = 6, P < 0.05). This diurnal rhythm was restricted to the cells in the DM region as there was no significant temporal variation in the IPSC frequency measured from the VL region (P > 0.05, Fig. 3). Similarly, no significant differences were detected in the amplitude, rise time, or decay time of sIPSCs between the three phases of the daily cycle. These data indicate that the frequency of inhibitory synaptic transmission varies with the daily cycle in SCN neurons in the DM cell population.

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Application of the neuropeptide VIP enhanced inhibitory synaptic transmission

The application of VIP was found to increase the sIPSC frequency but not other properties of sIPSCs recorded in SCN neurons (Fig. 4). For example, during the day, VIP (100 nM) increased the sIPSC frequency by 36 ± 2% above baseline \((n = 14, P < 0.01)\). This effect of VIP was widespread in the SCN and, overall, about two-thirds of SCN neurons tested (37/58 cells) responded to VIP with an increase in sIPSC frequency.

We compared the effect of VIP on sIPSCs between the DM and VL regions of the SCN, but found that there were no significant differences between these regions during day, early night, or late night. Therefore the data from both regions were pooled for the remainder of the experiments evaluating the effect of VIP on sIPSCs. The effect of VIP on SCN neurons was concentration dependent with a maximal effect observed at or above 100 nM and a half-maximal response at 42 nM (Fig. 5). The magnitude of VIP-mediated enhancement of sIPSC frequency was phase-dependent (Fig. 6). During the day, application of VIP (100 nM) increased the frequency of sIPSCs by 36 ± 2\% \((n = 14)\). In contrast, the same VIP treatment increased the frequency of sIPSCs 16 ± 2\% during the early night \((n = 12)\) and by 13 ± 2\% \((n = 11)\) during the late night. The effect of VIP on sIPSC frequency was significantly greater \((P < 0.01)\) in the day than in either the early or the late night. The percentage of cells responding to 100 nM VIP did not change from day to night (60–65\% in either phase). The effect of VIP was long-lasting and did not wash out after 30 min drug-free ACSF \((n = 6)\).
VIP enhanced IPSC frequency through a presynaptic mechanism

To determine if a presynaptic mechanism was responsible for VIP’s ability to enhance sIPSCs throughout the SCN, we performed similar whole cell patch-clamp recordings of SCN neurons in the presence of the Na+/H1 channel blocker TTX. In the presence of TTX (0.5 μM), VIP administered during the day significantly increased the frequency but not amplitude of miniature IPSCs (mIPSCs) 21 ± 3% above baseline (n = 13; Fig. 6). Additionally, VIP administered during the early night increased the frequency but not amplitude of mIPSCs 10 ± 3% above baseline (n = 12), reflecting the same phase-dependent relationship noted above in the absence of TTX (P < 0.01). Cumulative distributions of sIPSC and mIPSC amplitudes and inter-event intervals also confirm that VIP enhances GABA release by a presynaptic mechanism (Fig. 7). The inter-event interval curve is shifted to the left with no change in the cumulative amplitude curve for 4/5 SCN neurons in TTX and 4/6 SCN neurons in the absence of TTX, indicating that the time interval between each event is shorter after VIP administration. The remaining three neurons showed a shift to the left in both the inter-event interval and the cumulative amplitude plots, indicating that the amplitude of IPSCs were smaller after VIP administration and suggesting that a subset of VIP-responsive neurons display both presynaptic and postsynaptic changes when treated with VIP.

VIP enhanced IPSC frequency through mechanisms dependent on VPAC2 receptors and adenylyl cyclase signaling

The next set of experiments was designed to characterize the receptor and associated signaling pathway mediating VIP’s enhancement of inhibitory synaptic transmission. First, we found that enhancement of GABA release was selective for VIP in that the related peptide PHI (100 nM: 0.2 ± 2%, n = 6) had no significant effect on sIPSC frequency. Treatment with the peptide PACAP (100 nM), however, resulted in a 15 ± 3% increase in sIPSC frequency (6/10 cells) during the day. We expected PACAP to have a similar effect on GABAergic sIPSCs because it has been previously reported that PACAP binds and activates the VPAC2 receptor at approximately the same concentration as VIP (Laburthe and Couvineau 2002). Next, we found that treatment with the VPAC receptor antagonist [Tyr1,D-Phe2]GHRF(1-29) (100 nM) by itself reduced sIPSC frequency (11% decrease, n = 9) as well as completely prevented any stimulatory effect of VIP (50 nM) on sIPSC frequency during the day (0 ± 3%, n = 8; Fig. 8). Similarly, in the presence of the selective VPAC2 antagonist PG 99-465, VIP (50 nM) had no significant effect on IPSC frequency (3 ± 3%, n = 6). Since the VPAC2 receptor can be positively coupled to the cAMP/PKA cascade, we sought to determine the involvement of this signaling pathway. Pretreatment of the slices with H-89 (20 μM), an inhibitor of PKA,
resulted in no significant enhancement exhibited a daily rhythm with significant differences between the IPSCs recorded from the two regions.

**DISCUSSION**

In the present study, whole cell patch-clamp techniques were used to measure sIPSCs from SCN neurons. While these currents were widespread in the SCN, the sIPSC frequency was consistently higher in the DM subdivision when compared with the VL subdivision of the SCN. The sIPSC frequency also varied with the daily cycle and exhibited a peak in the early night (ZT 13–15). In contrast, the sIPSC amplitude, rise time, or decay time did not vary between the SCN regions or with the daily cycle. Application of the neuropeptide VIP increased the sIPSC frequency but not other properties of the sIPSCs recorded in the SCN. This enhancement was seen in about two-thirds of the SCN neurons examined and was similar in both DM and VL SCN regions. The magnitude of the VIP enhancement exhibited a daily rhythm with significantly larger effects observed during the day. This effect of VIP on IPSC frequency, as well as the daily variation in the magnitude of the response, was observed in the presence of TTX. Furthermore, VIP’s actions were blocked by antagonists for VPAC receptors as well as the PKA inhibitor H-89. Forskolin, an AC activator, mimicked the stimulatory action of VIP and pretreatment with forskolin precluded further stimulation by VIP. These results indicate that VIP enhances IPSC frequency through presynaptic activation of VPAC_2 receptors and positive coupling to AC cascade. Overall, these observations also raise the possibility that VIP may play an important role in regulating inhibitory synaptic transmission throughout the SCN.

**Spontaneous IPSCs are widespread within the SCN**

Anatomical studies support the distinction of at least two subdivisions within the SCN (Abrahamson and Moore 2001). The core or VL subdivision of the SCN receives photic input from the retina and intergeniculate leaflet as well as nonphotic input from the raphe. Neurons in this region express GABA as well as several peptides including VIP and gastrin releasing peptide. The shell or DM subdivision does not appear to receive direct retinal innervation, but rather obtains input from core SCN neurons as well as other brain regions (Moga and Moore 1997). These neurons express GABA as well as several peptides including, most notably, arginine vasopressin (AVP). The efferent projections of the two subdivisions are also distinct and generally include projections to the hypothalamus, thalamus, and cortical regions (Leak and Moore 2001). Although peptide expression was not characterized in these cells, video microscopy was used to visually place neurons within the two general subdivisions of the SCN. Regardless of region or phase, we detected inhibitory currents in every neuron recorded in the SCN (n = 187). We observed a significant regional difference in that the DM subdivision received a higher frequency of inhibitory currents regardless of the phase. There were no other significant differences between the IPSCs recorded from the two regions.
The slice preparation used in the present study does not allow us to define the source of GABA input onto the cells from which we are recording. It is widely accepted that most SCN neurons are GABAergic and are likely to use this transmitter to communicate with other neurons within and beyond the SCN (Abrahamson and Moore 2001; Castel and Morris 2000). Electrophysiological analysis indicates that SCN neurons receive a high frequency of GABA_A-mediated postsynaptic currents (De Jeu and Pennartz 2002; Jiang et al. 1997; Kim and Dudek 1992) that at least partly originate within the SCN itself (Strecker et al. 1997). Other sources of GABAergic input include the arcuate nucleus, supraoptic nucleus, and the intergeniculate leaflet (e.g., Morin and Blanchard 2001; Saeb-Parsy et al. 2000). Based in part on the observation that photic stimulation inhibits electrical discharge of some SCN neurons, the hypothesis has been raised that GABA may even be released directly from retinal ganglion cells innervating the SCN (Jiao and Rusak 2003). Certainly our data are consistent with earlier work suggesting that SCN neurons are under tonic GABAergic control. Moreover, our data demonstrate that the frequency of GABA release onto SCN neurons varies with a diurnal rhythm that peaks during the early night. While not the focus of the current study, the presence of a rhythm in IPSC frequency may have important implications for SCN function.

Effects of VIP on IPSCs in the SCN

While many core SCN neurons express VIP, the physiological roles of this peptide in the SCN are not well defined. Previous studies have shown that VIP and VIP mRNA levels are regulated by lighting conditions, suggesting that VIP release is dependent on photic input and peaks during the night (Shinohara et al. 1999a,b). Physiologically, extracellular recordings of the firing rate of SCN neurons in a brain slice indicate that VIP administration can cause phase shifts of the circadian rhythm of electrical activity (Reed et al. 2001). Since VIP is co-expressed with GABA, we hypothesized that VIP modulates inhibitory synaptic transmission within the SCN. Furthermore, a recent study by Reed and coworkers (2002) showed that VIP predominantly elicited suppressions in SCN cellular activity, some of which were modulated by bicuculcline, implicating the involvement of GABAergic mechanisms. Our present results demonstrate that VIP can profoundly enhance GABAergic IPSCs throughout the SCN during both day and night. In addition, we observed a significantly greater effect of VIP during the day compared with early and late night. We do not know if this rhythm is self-sustained nor did we identify the mechanisms responsible for the rhythm. For example, it is possible that we observed a reduced effect of VIP during the night because endogenous levels of VIP were already increased, occluding further enhancement of GABAergic IPSCs with exogenous VIP application during this phase. It may also be possible that VIP receptors (VPAC_2) are less sensitive to VIP during the night.

Mechanisms of VIP modulation and related peptides

While the mechanisms underlying the diurnal modulation of VIP response are not yet understood, our results have clarified the mechanisms through which VIP is acting to regulate inhibitory synaptic transmission within the SCN. First, VIP enhanced mIPSC frequency in the presence of TTX. Each miniature synaptic current is thought to result from the spontaneous fusion of an individual synaptic vesicle with the presynaptic membrane subsequently resulting in quantal release of transmitter molecules. Changes in the frequency at which this process occurs are normally associated with alterations in the presynaptic release process, while changes in the amplitude of the currents reflect postsynaptic changes in receptor sensitivity or ionic driving force. So the finding that VIP changed the mIPSC frequency certainly indicates a presynaptic mechanism. However, there were a few cells that also exhibited a change in IPSC amplitude. This observation, coupled with the previous work demonstrating that VIP can regulate potassium channels in cells in other brain regions, suggest that VIP may have multiple actions on SCN neurons (Haug and Storm 2000).

Second, the effects of VIP are likely to be mediated by VPAC_2 receptors. Both VPAC and selective VPAC antagonists were found to prevent VIP-mediated enhancement of IPSC frequency. Previous studies have established that the VPAC subtype of receptor is expressed in the SCN (Cagam-pang et al. 1998; Shinohara et al. 1999a) and mediates the VIP-induced suppression of the frequency of action potentials recorded in SCN neurons (Cutler et al. 2003). Several studies using in situ hybridization have failed to find expression of VPAC receptors in the SCN and it is generally accepted that the VPAC receptor is absent in the mammalian SCN (Ajpur et al. 2002; Cagam-pang et al. 1998; Usdin et al. 1994). In other preparations, the VPAC receptor is positively coupled to AC and is expected to act via stimulation of cAMP and PKA (Harmar et al. 1998). Furthermore, in other systems, there is evidence that GABA currents are positively regulated by this second messenger cascade (e.g., Poisbeau et al. 1999; Shindou et al. 2002). In the present study, we demonstrate that forskolin mimics while H-89 prevents sIPSC enhancement by VIP. In summary, our data suggest that VIP acts through VPAC receptors to stimulate the cAMP/PKA cascade and presynaptically enhance GABA release in the SCN.

Albers et al. (1991) previously demonstrated that coadministration of VIP, PHI, and gastrin-releasing peptide (GRP) within the SCN mimicked the phase-delays effects of light-on circadian control following in vivo microinjection. The observed phase-delaying effect on behavior and cellular activity was much greater than that observed with the administration of VIP, PHI, or GRP alone or coadministration of any two of these peptides. These data suggest that although the related peptides serve a common purpose, each one may have a distinct function in the circadian timing system. We bath-applied PHI (100 nM) in SCN slices to determine if the peptide was capable of binding to the VPAC receptor and modulating GABA currents in a manner similar to VIP, but found that it had no effect on the frequency of IPSCs. The apparent ineffectiveness of PHI to modulate GABA currents is consistent with a recent study identifying a unique receptor for PHI, which is expressed in the pituitary and binds neither VIP nor PACAP (Tse et al. 2002).

Functional importance

Our data indicate that VIP can broadly regulate GABA-mediated synaptic input to SCN neurons. Through this mech-
anism, VIP could function to modulate the photic input to the SCN as well as coupling between neurons in the SCN. Previous studies have shown that injection of GABA agonists into the SCN can modulate light- and NMDA-induced phase shifts (Gillespie et al. 1997; Mintz et al. 2002) as well as fos-induction (Gillespie et al. 1999). These data suggest that GABAergic tone in the SCN can modulate light-induced phase shifts perhaps by direct regulation of the amplitude of glutamate-evoked responses in retino-recipient SCN neurons. Second, most SCN neurons are GABAergic and are likely to use this transmitter to communicate with other neurons in the SCN. Previous studies suggest that GABAergic mechanisms appear to have the capability to synchronize SCN cell populations in culture conditions (Liu and Reppert 2000; Shirakawa et al. 2000). Therefore by modulating the frequency of GABA release, VIP could function to alter the degree of synchronization between SCN cell populations. This suggestion is supported by the finding that VIP, but not glutamate, can cause phase shifts of the rhythms in vasopressin release from cultured SCN neurons (Watanabe et al. 2000). Although VIP may have multiple actions within the SCN cell population, our data suggest that neuropeptides in the VIP family play a central role in the mammalian circadian timing system.

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