Distribution of vasopressin and vasoactive intestinal polypeptide (VIP) fibers in the human hypothalamus with special emphasis on suprachiasmatic nucleus efferent projections
Dai, J.; Swaab, D.F.; Buijs, R.M.

Published in:
The journal of comparative neurology

DOI:
10.1002/(SICI)1096-9861(19970714)383:4<397::AID-CNE1>3.0.CO;2-Y

Link to publication

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: http://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.

UvA-DARE is a service provided by the library of the University of Amsterdam (http://dare.uva.nl)
Distribution of Vasopressin and Vasoactive Intestinal Polypeptide (VIP) Fibers in the Human Hypothalamus With Special Emphasis on Suprachiasmatic Nucleus Efferent Projections

JIAPEI DAI, DICK F. SWAAB, AND RUUD M. BUIJS
Graduate School Neurosciences Amsterdam, Netherlands Institute for Brain Research, 1105 AZ Amsterdam ZO, The Netherlands

ABSTRACT

The human suprachiasmatic nucleus (SCN) is located in the basal part of the anterior hypothalamus and is considered as the biological clock that generates circadian rhythms and synchronizes the daily activity pattern with the environmental light-dark cycle. However, the mechanisms and pathways by which the SCN transmits its information to the other brain areas are unknown. Therefore, in the present study, we investigated the efferent projections of the SCN by the immunocytochemical staining of two major peptidergic SCN neurotransmitters: vasopressin (VP) and vasoactive intestinal polypeptide (VIP). It confirmed that these peptides are present in different subdivisions of the SCN. The results of this investigation show that VP and VIP fibers arising from the SCN were detected to branch extensively and hence seem to innervate the SCN itself and the central and medial part of the anteromedial hypothalamic area (AVH), the area below the paraventricular nucleus (sub-PVN), the ventral part of the paraventricular nucleus (PVN), and the dorsomedial nucleus of the hypothalamus (DMH). There appeared to be substantial congruity between the presumptive human SCN projections and those as observed by tracing in rat or hamster. Regarding the anatomical organization of the human SCN projections, the main projection areas appeared to be the AVH, the sub-PVN, the ventral part of the PVN, and the DMH. The observation that VIP and in particular VP fibers pass between the SCN and the PVN suggests that the human SCN and the PVN may have a direct anatomical connection. In addition, VP and VIP fibers were detected in several other hypothalamic areas that are not known to have clear direct connections to the SCN. The possible origin of these VP and VIP fibers is discussed. J. Comp. Neurol. 383:397–414, 1997. © 1997 Wiley-Liss, Inc.

Indexing terms: paraventricular nucleus; sub-paraventricular zone; dorsomedial nucleus of hypothalamus; anteromedial hypothalamic area; CRH

The suprachiasmatic nucleus (SCN) is responsible for maintaining circadian rhythms in sleep, wakefulness, hormone levels, body temperature, and blood pressure in mammals (Rusak and Zucker, 1979). To understand how the SCN communicates its circadian information to the rest of the brain, knowledge of the organization of SCN projections is essential. Studies using immunocytochemical staining for SCN neurotransmitters (Sofroniew and Weindl, 1978; Buijs et al., 1978; Buijs, 1978; Card et al., 1981; Card and Moore, 1984; Smale et al., 1991), SCN lesions (Hoorneman and Buijs, 1982), retrograde transport of horseradish peroxidase (HRP), fluorescent dyes (Stephan et al., 1981; Watts and Swanson, 1987), anterograde transport of 3H-labeled amino acids (Swanson and Cowan, 1975; Berk and Finkelstein, 1981; Stephan et al., 1981), and, more recently, Phaseolus vulgaris-leucoagglutinin (PHA-L) tracing (Watts et al., 1987; Buijs et al., 1993; Kalsbeek et al., 1993; Orpen and Steiner, 1994; Morin et
al., 1994) have identified the SCN projection areas in rodents. This identification has provided insight into which hypothalamic areas in the rodent brain may serve to integrate the circadian signal. In the rat and hamster, the subparaventricular zone and dorsomedial nucleus of the hypothalamus (DMH) were identified as major projection areas. Only a limited number of direct projections to the paraventricular nucleus (PVN) where neurosecretory neurons are located were found, suggesting that the SCN may influence PVN functions mainly by means of multisynaptic connections (Watts and Swanson, 1987; Buijs et al., 1993).

Also, the human SCN forms an essential component in the adaptation to environmental changes and is able to generate circadian rhythms. It was found that day-night behavioral rhythms are disturbed when the SCN is affected, as is the case in Alzheimer’s disease (Swaab et al., 1985). Although insight into SCN projections was extended from rodent to primate, e.g., macaque monkey (Moore, 1993), so far, nothing is known about human SCN projections. In the present study, the putative projections of the SCN were examined by immunocytochemical staining for SCN neurotransmitters in the human hypothalamus.

The human SCN is composed of a small heterogeneous group of parvicellular neurons (Sofroniew and Weindl, 1984; Buijs et al., 1993) located in the basal part of the anterior hypothalamus containing a number of neuroactive compounds, e.g., vasopressin (VP), vasoactive intestinal polypeptide (VIP), neuropeptide-Y (NPY), somatostatin (SOM), peptide histidine methionine (PHM, which is homologous to the peptide histidine isoleucine [PHI] in rat), gastrin-releasing peptide (GRP), neotensin (NT), and galanin (Dierickx and Vandeseande, 1977; Sofroniew and Weindl, 1980; Itoh et al., 1983; Stapa et al., 1984; Swaab et al., 1985; Mai et al., 1987; Cassone et al., 1988; Gai et al., 1990; Walter et al., 1990; Moore, 1992; Zhou et al., 1995a). Studies of the intrinsic organization of the human SCN have demonstrated that, as in the rodent (Vandeseande et al., 1975; Card et al., 1981; Cassone et al., 1988; Mikkelsen et al., 1991; Kalsbeek and Buijs, 1992), the human SCN is also segregated into anatomical subdivisions in which the different neurotransmitters are preferentially located (Stapa et al., 1984; Mai et al., 1991; Moore, 1992). To examine which SCN neurotransmitter is suitable for determining SCN projections, a number of SCN neuropeptides, i.e., VP, VIP, SOM, PHM, GRP, NT, and galanin were studied. It was found, however, that most neuropeptide staining could not be used for this purpose due to the massive presence of the same peptides derived from other sources. Only VP and VIP staining revealed clear projections from the SCN without a too disturbing interference of staining of the same peptides from other sources. Consequently, the course of efferent SCN VP and VIP fibers and the site of innervation of their terminals in the human hypothalamus will be described in the present study.

### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AVH</td>
<td>anteroven tral hypothalam ic are a</td>
</tr>
<tr>
<td>BST</td>
<td>bed nucleus of the stria terminals</td>
</tr>
<tr>
<td>CRH</td>
<td>corticotrophin-releasing hormone</td>
</tr>
<tr>
<td>CSF</td>
<td>cerebrospinal fluid</td>
</tr>
<tr>
<td>DMH</td>
<td>dorsomedial nucleus of the hypothalamus</td>
</tr>
<tr>
<td>FO</td>
<td>fornix</td>
</tr>
<tr>
<td>INF</td>
<td>infundibular nucleus</td>
</tr>
<tr>
<td>MB</td>
<td>mamillary body</td>
</tr>
<tr>
<td>NBM</td>
<td>nucleus basalis of Meynert</td>
</tr>
<tr>
<td>NTL</td>
<td>lateral tuberal nucleus</td>
</tr>
<tr>
<td>OC</td>
<td>optic chiasm</td>
</tr>
<tr>
<td>OT</td>
<td>optic tract</td>
</tr>
<tr>
<td>POA</td>
<td>preoptic area</td>
</tr>
<tr>
<td>PVN</td>
<td>paraventricular nucleus</td>
</tr>
<tr>
<td>PH</td>
<td>posterior hypothala mic nucleus</td>
</tr>
<tr>
<td>PHI</td>
<td>peptide histidine isoleucine</td>
</tr>
<tr>
<td>PEN</td>
<td>periventricular nucleus</td>
</tr>
<tr>
<td>PHA-L</td>
<td>phaeohogalus vulgaris leucocagglutinin</td>
</tr>
<tr>
<td>SCN</td>
<td>supraopti c nucleus</td>
</tr>
<tr>
<td>SDN</td>
<td>sexual dysfunction nucleus of preoptic area</td>
</tr>
<tr>
<td>SON</td>
<td>supraoptic nucleus</td>
</tr>
<tr>
<td>sub-PVN</td>
<td>the area below paraventricular nucleus</td>
</tr>
<tr>
<td>TBS</td>
<td>Tris-bufferede saline</td>
</tr>
<tr>
<td>TMN</td>
<td>tuberomamillary nucleus</td>
</tr>
<tr>
<td>VMN</td>
<td>ventromedial nucleus</td>
</tr>
<tr>
<td>VP</td>
<td>vasopressin</td>
</tr>
<tr>
<td>VIP</td>
<td>vasoactive intestinal polypeptide</td>
</tr>
<tr>
<td>3V</td>
<td>third ventricle</td>
</tr>
</tbody>
</table>

### MATERIALS AND METHODS

#### Brain material

For the present study, the brains of eight subjects were obtained from the Netherlands Brain Bank (NBB; coordinator Dr. R. Ravid). The required permission for brain autopsy was obtained either from the patients themselves or from partners or relatives. Autopsy was performed according to the protocols of the NBB, which includes measurement of pH of the cerebrospinal fluid to estimate aonal state (Hardy et al., 1985; Ravid et al., 1992). Neuropathology was performed on all subjects in a systematic way by Dr. W. Kamphorst (Free University, Amsterdam, The Netherlands) or Prof. F. C. Stam (NBB). Details of age, postmortem delay, brain weight, clinical diagnosis, and cause of death of the subjects are given in Table 1.

None of the controls or patients had died of raised intracranial pressure.

#### Tissue treatment

The hypothalamus was dissected at autopsy and immersed in a fixative containing 4% paraformaldehyde in...
0.1 M phosphate buffer (pH 7.4). To facilitate the penetration of the fixative, an additional treatment was applied to the tissue within 4 hours. The tissue was put in a small container with the same fixative, placed in a beaker filled with ice cubes and water, and put in the microwave at low setting (80 W) for 15 minutes (Buijse et al., 1993). Then the tissue was kept in the same fresh fixative at room temperature for 8–10 days. After fixation, the tissue was stored in 30% sucrose-phosphate buffer (pH 7.4) for 2–3 days. Sections, 25 to 35 µm, were cut on an cryostatin in the frontal (Fig. 1, seven cases) or sagittal plane (one case, NBBn 95-096) and collected in a series of vials in sequential order. Subsequently, free-floating sections were rinsed in Tris-buffered saline (TBS, pH 7.4) at 4°C (2 days to 2 weeks) until immunocytochemical staining was performed.

Immunocytochemistry

Immunocytochemical staining for VP, VIP was performed with the ABC (avidin-biotin complex) ELITE detection method (Vector Laboratories, Burlingame, CA) and consisted of the following steps at room temperature unless stated otherwise: (1) pretreatment with 100% methanol (10 minutes) and 3% H₂O₂ in 0.05 M Tris, 0.9% NaCl (TBS; 10 minutes); (2) rinse in TBS (3 × 10 minutes); (3) incubation with the first antibody (1 hour at room temperature, and overnight at 4°C; incubation buffer consisted of 0.05 M Tris, 0.9% NaCl, 0.25% gelatin, and 0.5% Triton X-100, pH 7.6). The first antibodies were (a) rabbit VP antiserum (Truus, 29-01-89, Netherlands Institute for Brain Research [NIBR]), 1:1000-4000 and (b) rabbit VIP antiserum (Viper, 18-09-86, NIBR), 1:2000-6000; (4) rinse in TBS (3 × 10 minutes); (5) incubation with biotinylated goat anti-rabbit IgG (H + L, Vector) 1:400 (1.5 hours); (6) rinse in TBS (3 × 10 minutes); (7) incubation with ABC (Vector), 1:800 (1.5 hours); (8) rinse in TBS (3 × 10 minutes); (9) 0.05% 3,3'-diaminobenzidine tetrachloride (DAB) plus 0.2% nickel-ammonium sulphate, activated with 0.001% H₂O₂ (10–15 minutes); (10) rinse in TBS (2 × 10 minutes).

The sections were mounted on chrome alum-coated glass slides, air-dried, dehydrated in graded ethanol series, and mounted in Entellan (Merck, Darmstadt, Germany).

RESULTS

We analyzed the hypothalamus in serial sections from the lamina terminals to the level of the mamillary body (MB). Counterstaining with haematoxylin-eosin or thionine was performed in some sections for orientation. In these sections, anatomical structures such as PVN, supraoptic nucleus (SON), periventricular nucleus (PEN), sexually dimorphic nucleus (SDN) of preoptic area, lateral tuberal nucleus (NTL), and tuberomamillary nucleus (TMN) were clearly visible. Little variation was found in the pattern of innervation of VP or VIP fibers between the studied subjects. One representative case (NBBn 96-010) who did not die of a neurological or psychiatric disease will be described in detail, with reference to others where relevant. A series of drawings (Fig. 2 A–V) were made from consecutive sections of the hypothalamus of this subject to illustrate the distribution of VP and VIP staining.

VP and VIP neurons in the SCN

Neurons with immunoreactivity for VIP or VP were located in topographically distinct regions of the SCN with some overlap (Fig. 3A,B). VP cells were present in the dorsal and medial part of the SCN throughout its anterior-posterior extent (Figs. 3B, 4B). In addition, a much smaller group of VP cell bodies was present in the ventral part of the SCN, particularly at the anterior level. VIP neurons were concentrated in the ventral part of this nucleus (Fig. 3A). Some densely packed VIP neurons were also detected in the centromedial part of the SCN (Fig. 4A), and these VIP neurons were usually surrounded by VP neurons (Figs. 2C,D, 4A,B). In most cases, only a few VIP cells were evident in the dorsal part of the SCN. Some VIP positive neurons were observed in the SCN immediately adjacent to the optic chiasm (OC), whereas a few VIP positive neurons were found to be embedded in the OC (Fig. 3A).

Projections and distribution of VP and VIP immunoreactive fibers

The chiasmatic region. VIP positive fibers from the ventral and central part of the SCN leave the SCN and run anteriorly, dorsally, and posterodorsally. The anteriorly directed VIP fibers reach the anterior part of the medial preoptic area (POA). A small number of VIP and some VP fibers innervate diffusely in these areas. The dorsally running VIP fibers from the SCN are very dense. Most of these VIP fibers reach the central and medial part of the anteroverentral hypothalamic area (AVH) at anterior SCN level (Figs. 2C, 5A,C) and tend to innervate the medial part of the AVH at posterior SCN level (Figs. 2E, G, 4A,C). In frontal sections, VIP fibers in this pathway were seen to branch and give rise to terminal boutons, and to continue...
Fig. 2. A series of line drawings arranged from rostral to caudal (A-V) to illustrate schematically the location of vasoactive intestinal polypeptide (VIP) and vasopressin (VP) cell bodies and fibers in a human hypothalamus (NBBn 96-010). The dots correspond to the position and density of the cell bodies. Short lines (in J, L, N) illustrate the area through which the fibers of VP magnocellular cell bodies pass and their axonal morphology also can be seen in Figure 6B. For explanation of abbreviations, see Abbreviations list.
Figure 2 (Continued.)
Figure 2 (Continued.)
Figure 2 (Continued.)
dorsally to form an extensive plexus (Fig. 5A,C). Some dorsal-running VIP fibers pass through the area between the SCN and PVN and reach the ventral part of the PVN (Fig. 4A,C). A moderate number of VIP fibers were seen in the ventral part of PVN, but only a few VIP fibers were found in the dorsal part of the PVN, and even fewer in the periventricular part of the PVN. Dense VIP terminals were also observed in the SCN itself. Most of these branching fibers are concentrated in the dorsal and posterior part of the SCN (Fig. 4A). The VIP terminals located in the posterodorsal part of the SCN seem to overlap with VP neurons in consecutive sections (Fig. 4A,B). Some VIP fibers are present in the midline part of the OC, running along the ventricle. More posteriorly, a dense network of VIP fibers was detected in the area located between the posterior SCN and the anterior VMH, ventral to the PVN. We define this area as sub-PVN. VIP fibers in the sub-PVN form an extensive plexus along the ventral border of the PVN, and a few VIP fibers appear to enter the PVN from the sub-PVN (Figs. 2I, 6A,C). Some VIP fibers were seen in the lateral part of the AVH, which is close to the ventromedial part of the SON, but almost no VIP fibers were detected in the SON except for a few VIP positive magnocellular neurons and fibers scattered in the SON in one case (NBBn 94-124). In addition, the central part of the bed nucleus of the stria terminalis (BSTc) is very densely innervated by VIP fibers of unknown but probably diverse origin.

VIP positive fibers from the SCN leave the dorsal part of the SCN and run mainly dorsally and posterodorsally. Most dorsal-running VP fibers pass through the area between the SCN and the ventral part of the PVN but are also seen to reach the ventral part of the PVN (Figs. 4B,D, 5B,D), and enter the central and medial part of the AVH. VP innervation in this area is present in the same region as VIP innervation, but it is less dense and located more medially. Although many VP fibers were observed to enter the ventral part of the PVN (Figs. 4B,D, 5B,D), it was impossible to make an unequivocal judgment whether the observed VP fibers in the ventral part of the PVN were indeed derived from the SCN, because many VP cell bodies and their processes exist in this area. A relatively high density of VP fibers was also detected in the sub-PVN (Fig. 6B,D), but the pattern of innervation was slightly different from the VIP innervation. The location of VP fibers in the sub-PVN was more medially than that of VIP fibers. VP fibers were also present in the SCN itself, but in much smaller amounts than VIP fibers. In addition, VP fibers or terminals can also be seen in the anteroventral part of the PEN and the midline part of the OC.

The tuberal region. VP and VIP fibers innervate the entire DMH (Figs. 7A–D, 8A–D), but the density increases clearly in the posterior part (Fig. 2Q–V). It was found that VP fibers course dorsally along the ependyma and reach the DMH at the level of the anterior part of the nucleus. The VP fibers in the medial part of the DMH were denser than those in the lateral part of the DMH. VIP positive fibers were very abundant in the DMH, from the anterior to the posterior part (Figs. 7A,C, 8A,C). The highest density of fibers was observed in the posterior part of the DMH (Fig. 8A,C). The sagittal sections were particularly helpful to follow the VP and VIP fibers from the SCN in anterior-posterior direction. In these sections, VIP fibers from the SCN were indeed seen to reach the ventral part of
the DMH directly. A small difference between VP and VIP innervation in the DMH was detected. VIP positive fibers seem to be denser than the VP fibers. In some cases VIP fibers tend to innervate the ventrolateral part of the DMH, or to show an inferolateral direction innervation, whereas VP fibers are mainly located in the medial part of the DMH close to the ventricle. In addition, VIP fibers can also be seen in the posterior part of the BST, infundibular nucleus (INF), some areas of the TMN and the NTL. Nevertheless, VP fibers are very sparse in these areas.

DISCUSSION

With respect to the distribution of VIP and VP neurons in the human SCN, our present results are in agreement with previous observations (Stopa et al., 1984; Swaab et al., 1985; Mai et al., 1991). Up until now, the putative projections of VP and VIP fibers originating from the SCN have not been described in detail in the human hypothalamus. It will be clear that, based only on the present immunocytochemical staining for VP and VIP, no definitive conclusions can be drawn with respect to their site of origin. However, the use of the combination of frontal and sagittal sections makes it possible to follow VP and VIP fibers over some distance and draw some conclusions with reasonable certainty about the origin of VP and VIP fibers in the hypothalamus. The detailed knowledge on SCN projections by means of PHA-L tracing and VP and VIP immunocytochemistry in the rat and hamster brain helped us to evaluate the present data (Buijs et al., 1978; Buijs, 1978; Sofroniew and Wendl, 1978; Stephan et al., 1981; Watts et al., 1987; Mikkelsen and Molier, 1988; Buijs et al., 1993; Kalsbeek et al., 1993; Orpen and Steiner, 1994; Mikkelsen and Vrang, 1994; Morin et al., 1994). The present study shows that many VIP fibers branch extensively and presumably from terminals in the following areas: (1) the central and medial part of the AVH, (2) the SCN, (3) the sub-PV, (4) the DMH, and (5) the BSTc. Many VP fibers do likewise in same areas as VIP fibers with some variability in the density with the exception of the large thick fibers from the magnocellular system which show a typical projection pattern. Branching of VIP fibers in the SCN are present throughout the entire extent of the nucleus but are most prevalent in its dorsal and posterior portions. It is difficult to determine where these presumptive VIP terminals in the SCN come from. The possibilities are that they originate from the ipsilateral and contralateral SCN. There are far fewer VP fibers in the SCN compared with VIP fibers. VIP and VP fibers were found to run along the dorsal surface of the OC but not in the optic tract (OT), suggesting that commissural fibers running between the left and right SCN exist (Swaab et al., 1985).
Fig. 4. Caudal level of the SCN, showing distribution of VIP and VP cell bodies and fibers. C and D are the magnification of the area of the AVH (arrow and arrowhead) in A and B, respectively. VIP and VP fibers and terminals are visible in the ventral part of PVN (arrowheads). 3V, third ventricle. For abbreviations, see list. Scale bar = 200 µm for A, B, 500 µm for C, D.
Fig. 5. Illustrating innervation of VIP (A, C) and VP (B, D) fibers in the anterior hypothalamic areas. A: Many VIP fibers from the SCN project directly to the central part of the anteroventral hypothalamic area (AVH) and form an extensive plexus just lateral and ventral of the paraventricular nucleus (PVN). Some VIP neurons are visible in the ventral part of the PVN. B: VP fibers from the SCN project to the medial part of the AVH. Many fibers seem to project into the ventral part of the PVN. C and D are the magnification of the area (arrow and arrowhead) in A and B, respectively. 3V, third ventricle. For abbreviations, see list. Scale bar = 200 µm for A,B, 500 µm for C,D.
Fig. 6. Distribution of dense VIP and VP fibers in the sub-PVN. **C** is a high magnification of a part of the ventral PVN in **A**; VIP fibers are visible in this area (arrow). Many VP fibers along the ventral border of the PVN are shown in **B**, and are presented in more detail in the high magnification (**D**). Some of them seem to pass into the PVN. For abbreviations, see list. Scale bar = 200 µm for A, B, 500 µm for C, D.
Fig. 7. Distribution of VIP (A, C) and VP (B, D) fibers in the medial (Fig. 7) and posterior (Fig. 8) level of the dorsomedial nucleus of the hypothalamus (DMH) in consecutive sections. VIP fibers are denser than VP fibers. C and D are the magnifications of A and B, respectively. 3V, third ventricle. Asterisk, blood vessel. Scale bar = 200 μm for A, B, 500 μm for C, D.
Fig. 8. Distribution of VIP (A, C) and VP (B, D) fibers at the level of the posterior part of the dorsomedial nucleus of the hypothalamus (DMH) in consecutive section. VIP fibers are denser than VP fibers. C and D are the magnifications of A and B, respectively. Arrows in A and C, and arrowheads in B and D point to the same area. 3V, third ventricle. Scale bars – 200 µm for A, B, 500 µm for C, D.
Animal tracing studies showed that indeed one side of the SCN can project to another one (Stephan et al., 1981; Buijs et al., 1994). The human SCN may thus also have contralateral VP and VIP projections that can synchronize the two SCN. The intense VIP immunocytochemical staining fibers and terminals in the human BSTc have been described in the previous studies (Walter et al., 1991; Zhou et al., 1995b). Very sparsely labeled fibers were found in the BST from the animal SCN tracing studies. We did not get any indication for fibers running from the human SCN to the BSTc. In addition, no VP fibers that can match with the density of VIP fibers are present in this nucleus. Therefore, it is probable that VIP fibers in the human BSTc are derived from other brain regions, such as the amygdala, rather than from the SCN.

Four areas contain a combination of VP and VIP fibers are most probably SCN terminal fields. The first area is the central and medial part of the AVH. In frontal and sagittal sections throughout the SCN, it was shown that many VP and VIP positive fibers leave the SCN and directly reach this area. The fibers in this pathway branch and give rise to terminal boutons to form an extensive plexus. All these observations strongly suggest that the SCN has direct efferent projections to this area. This innervation pattern is similar to that found in primates (Cassone et al., 1988; Moore, 1993). In addition, compared with rat and hamster hypothalamic topographical organization, the present evidence suggests that the human central and medial part of the AVH may be homologous with the rat or hamster medial preoptic nucleus (MPN) (Simerly and Swanson, 1986). It has been demonstrated in rodents that the MPN receives inputs from widely distributed areas in both the forebrain and the brainstem, and sends its efferent projections to other brain regions (Re- nau, 1979; Berk and Finkelstein, 1981; Simerly and Swanson, 1986). This area has been implicated in the regulation of sleep, thirst, reproductive behavior, sexual behavior, and body temperature (Larsson, 1979; Simerly and Swanson, 1986). Whether the human AVH has similar functions is unknown. The human SDN, also called the intermediate nucleus, is located in the central part of the AVH between the SON and the PVN at the same anteroposterior level as the SCN (Swaab and Fliers, 1985; Hofman and Swaab, 1988; Braak and Braak, 1992). Some VP and VIP fibers and terminals innervate the SDN, suggesting that the SCN may influence SDN function possibly related to the innervation of VP fibers which come from the SDN in the ventral part of the PVN. This difficulty is due to the large number of VP neurons and their processes in this nucleus. There are possibly direct projections from the SCN to the PVN in the present observation, suggesting that the SCN and the PVN may have direct anatomical connections. The periventricular part of the PVN is a narrow structure along the third ventricle. The clear features is that this area contains medium-sized and small nerve cells, and immunocytochemical staining for SOM shows many positive neurons. Almost no VIP fibers are present in this area, suggesting that VIP fibers in the SCN may have no projections to this area. However, it is not known whether the presently observed VP fibers represent a direct projections from VP neurons of the SCN. The functional role of this area also needs to be investigated.

The fourth area is the DMH. In previous studies with conventional staining it was suggested that the DMH is poorly differentiated from the surrounding hypothalamic area in the human hypothalamus (Braak and Braak, 1992). Until now, no immunocytochemical staining for neuropeptideric transmitters or histochemical staining for classical neurotransmitters has been found to mark specifically DMH neurons. However, in the present study, the DMH borders, with the exception of the ventral part that borders the VMH, could be easily recognized in the Nissl stained sections. At the anterior level of the DMH, the paraventriculo-hyopophyseal tract (containing VP fibers) passes through the lateral part of the hypothalamus and projects to the pituitary; the tract forms the anterolateral border of the DMH (Figs. 2L,N, 6B). At the posterior level, the lateral border connects with the TMN, which is characterized by the presence of neurons containing a large cell body with lipofuscin granules. The medial border of the DMH is the third ventricle. The anterodorsal part of the DMH often borders with the medial side of the fornix (FO) and the ventrolateral border of the PVN (Fig. 2N,P) and merges gradually with the posterior hypothalamic nucleus (PH) at the posterosdorsal part of the DMH (Fig. 2R). It is usually difficult to distinguish the ventral border of the DMH from the VMH with conventional Nissl staining, although in some cases the medium-sized nerve cell's of the DMH are markedly richer in lipofuscin deposits than the neurons of the VMH. During our search for
immunocytochemical markers for the DMH, a dense network of SOM fibers was found to innervate the VMH from the anterior to the posterior part. Using SOM immunocytochemical staining we could thus indirectly distinguish the ventral border of the DMH from the VMH. VP and VIP fibers show extensive branching and densely innervate the DMH from the anterior to the posterior part. In the present study, although some direct projections from the SCN to the DMH were detected in sagittal sections, it is not known with certainty whether all the VP and VIP fibers that terminate in the DMH come from the SCN. On the other hand, the fact that in animal experiments VP and VIP fibers in the DMH are derived from the SCN (Hoorneman and Buijs, 1982; Kalsbeek et al., 1993; Buijs et al., 1993) reinforces the idea that this may also be the case in human.

The present study illustrates the projections of the SCN in the human hypothalamus by the immunocytochemical staining of SCN neurotransmitters and provides a picture of which areas might receive an input from the SCN. Our results showed that these areas (such as the central and medial part of the AVH, the sub-PVN, and the DMH) may receive SCN projections. The results match those of the animal studies using immunocytochemical staining for SCN neurotransmitters and tracing technique, suggesting that hypothalamic topographical organization might be comparable for many species. In addition, the remarkable finding that there clearly are VIP and in particular VP fibers running between the SCN and the ventral part of the PVN in the human, suggests that the SCN may be responsible for the expression of circadian rhythms in hormone secretion (e.g., ACTH and corticosterone secretion) by direct pathways. In addition, the projections to the medial part of the AVH, sub-PVN and DMH may allow an indirect influence on PVN neurons by means of multisynaptic pathways. We also demonstrated in the human as in the rat (Buijs et al., 1993) a different pattern of innervation for VP and VIP in the AVH, sub-PV and DMH. It appears that the VP fibers and terminals tend to innervate more medially than VIP in these three areas. The possibility exists thus that VIP and VP neurons in the SCN may affect different neurons, which further supports the idea that VIP and VP neurons in the SCN may be responsible for different functions in expressing biological rhythms.

**ACKNOWLEDGMENTS**

We are grateful to A. Holtrop, M. Koereman, J. Wouda, and S. Pindak for their help in collecting and documenting brain material, G. van der Meulen for the photographs, and W.T.P. Verweij for secretarial help. The brain material was obtained from the Netherlands Brain Bank (Coordinator R. Ravid). This study was supported by Netherlands Institute for Brain Research grant 94-11.

**LITERATURE CITED**


