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# Neuronal Types in the Human Anterior Ventral Thalamic Nucleus: A Golgi Study

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**Abstract** Neurons in the anterior ventral (AV) thalamic nucleus of human adults were impregnated by Golgi-Kopsch impregnation method. Results showed that at least three morphological types of neurons could be recognized in the human AV thalamic nucleus. Type I neurons were medium to large with rich dendritic arborization. Both tufted and radiating dendritic branching patterns were seen in almost every neuron of this type. Only the initial axonal segments of these cells were impregnated suggesting that these axons were heavily myelinated. Type II neurons were medium in size with poor to moderate dendritic arborization. Many of these cells possess a few dendritic grape-like appendages. Long segments (up to 300 μm) of their axons were impregnated suggesting that these axons were either unmyelinated or thinly myelinated. These axons change their direction and form loops very often. No local branches were seen for these axons suggesting that they could be projection axons. Type III neurons were small with only one or two dendrites with poor arborization. No axons for these cells were seen in this study. The three neuronal types in the human AV thalamic nucleus were compared with neuronal types already described in other thalamic nuclei of human and non-human species. The results of this study might provide a morphological basis for further electrophysiological and / or pathological studies.

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## Introduction

The anterior ventral (AV) nucleus of the thalamus is the largest of the anterior group of the thalamic nuclei. Functionally, the AV nucleus is part of the limbic system and has reciprocal connections with the mammillary body and the cingulate gyrus.

Morphological features of thalamic neurons in almost all of the thalamic nuclear groups were described. In the majority of the thalamic nuclei such as ventral posterior (VP) nucleus, lateral geniculate body (LGB), medial geniculate body (MGB), ventral anterior (VA), ventral lateral (VL), ventral medial (VM), periventricular and pulvinar, two main types of thalamic neurons namely the Golgi-type I (thalamic projection cells) and the Golgi-type II (thalamic interneurons) were described (Guillery 1966, Scheibel and Sheibel 1966; Tombol et al. 1969, Kiss and Tombol 1972, Morest 1975, Pearson and Hairen 1980; Friedlander et al. 1981; Spreafico et al. 1983; Braak and Braak 1984; Winer 1984; Yamamoto et al. 1985; Yen et al. 1985; Al-Hussain and Kultas-Ilinsky 1986; Al-Hussain 1987; Rafols et al. 1987; Al-Hussain 1992; Ma et al. 1998). The Golgi-type I neurons in these nuclei were described as medium to large cells with rich dendritic arborization while the Golgi-type II cells were described as small to medium cells with poor to moderate dendritic arborization. In two other thalamic nuclei namely the anterior ventral (AV) and mediodorsal (MD), however, only Golgi-type I neurons (projection neurons) were described with no reports of Golgi-type II neurons or interneurons (Somogyi et al. 1979; Kuroda et al. 1992; Negyessy et al. 1994). Furthermore, in the intralaminar nuclei (centromedian and parafascicular), the Golgi-type I neurons were described as cells with poor dendritic arborization while the Golgi-type II neurons were described as cells with rich dendritic arborization (Hazlett et al. 1976; Tseng and Royee 1986; Tombol et al. 1990). This make the neurons in the intralaminar nuclei completely different from their counterparts in all of the other thalamic nuclei where the Golgi-type I neurons have rich dendritic arborization while the Golgi-type II have poor dendritic arborization.

Based on the branching patterns of their dendrites, Golgi-type I neurons were classified into tufted and radiating in the motor thalamic nuclei (Tombol et al. 1969), sensory thalamic nuclei (Pearson and Hairen 1980; Spreafico et al. 1983; Winer 1984; Yen et al. 1985) and the AV nucleus (Somogyi et al. 1979). The dendrites of the first type (tufted) give rise to three or more branches while the dendrites of the second type (radiating) divide into two branches. Results in another study in the motor thalamic nuclei (Al-Hussain 1987), however, showed that these two dendritic branching patterns (tufted and radiating) were in fact present in almost every Golgi-type I neuron.

Some quantitative features such as diameter of dendrites of different orders, number of branching points and analysis of dendritic branching patterns of both Golgi-type I and Golgi-type II neurons were reported only in the motor thalamic nuclei (Al-Hussain 1987).

To the best of our knowledge, the neurons in the AV thalamic nucleus were described only in the cat (Somogyi et al. 1979). In the last study (Golgi and HRP study), three types of projection neurons were described without reporting of Golgi-type II (interneurons) in the AV nucleus. The objectives of this study were: (1) to describe morphological and quantitative features of Golgi-type I neurons in the AV nucleus of the human (2) to attempt to find Golgi-type II neurons in the AV thalamic nucleus (3) to compare the neurons in the human AV nucleus with their counterparts previously described in the cat AV nucleus and other thalamic nuclei of both human and non-human species.

## Materials and Methods

This study was based on studying the AV thalamic nucleus of six human brains which were kept in 10% neutral buffered formalin (NBF) for several years. The brains were taken from adult (aged 35–50 years) individuals with no history of neurological diseases.

Specimens (3–5 mm thick) were cut in frontal plane and processed according to the Golgi-Kopsch impregnation method described by Fox et al. (1951). In all experiments, after Golgi silvering the tissue blocks were embedded in paraffin shells as described by Millhouse (1981). Coronal sections (100 μm thick) were cut and put immediately into absolute ethanol for 2 h and cleared by xylene for 5 min. Sections then were mounted and coverslipped with permount. Selected impregnated neurons were examined (drawn, photographed and measured) by using a Nikon light microscope equipped with drawing tube (camera lucida), photographing system and oculometer. The AV nucleus was identified by using the atlas for stereotaxy of the human brain by Schaltenbrand et al. (1977).

## Results

Neurons in the human AV thalamic nucleus were classified according to: (1) soma size (2) complexity of dendritic arborization, (3) dendritic spines and/or appendages and (4) axons. Using these criteria, three main types of neurons referred to as type I, type II and type III were found in this human study.
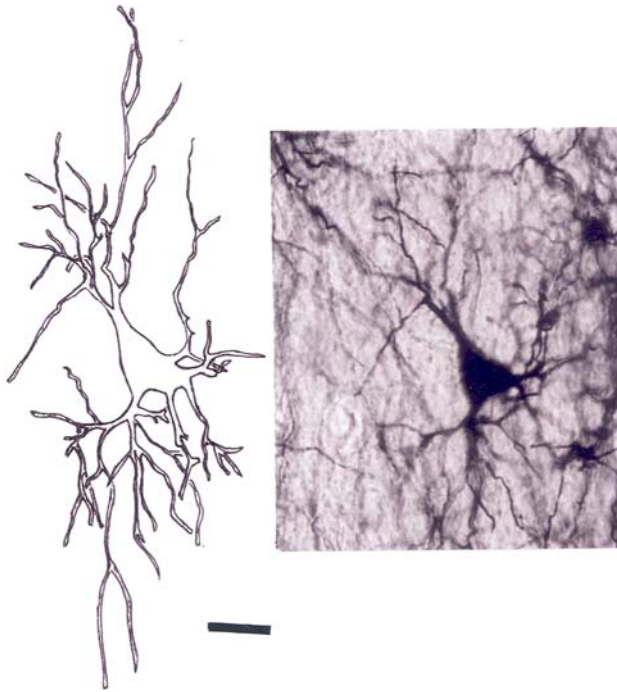
### Type I Neurons

These neurons (Fig. 1) have cell bodies of medium to large size with an average mean diameter of 22.8 μm (SD = 2.8, $N$ = 80). They varied in shape: multipolar, triangular or ovoid with no somatic spines or appendages. These cells have from 4 to 10 primary dendrites with dense dendritic tree as indicated by the large number of branching points and free dendritic tips (Table 1). Dendritic protrusions, hair-like appendages and spines were seen but they were uncommon. Both radiating and tufted dendritic branching patterns were found in almost every neuron. The radiating branching pattern was more common than the tufted branching pattern especially in the distal dendrites (Table 2). The results also showed a wide range of variability of the widths (diameters) of the dendrites of the same order with overlap of diameters not only between primary and secondary dendrites but also between primary and tertiary dendrites as well (Histogram 1: Fig. 2).

Only initial axonal segments arising from the cell bodies of these cells were impregnated suggesting that these axons were myelinated.

### Type II Neurons

The most frequently impregnated neurons in this study (Figs. 3 and 4) have multipolar, triangular or ovoid cell bodies with an average mean diameter of 19 μm (SD = 2.5, $N$ = 100). Three to six primary dendrites originate from the cell bodies. The number of branching points and free dendritic tips of these dendrites were less than those of type I neurons (Table 1). Dendrites of these cells have a few grape-like appendages including

**Fig. 1** Camera lucida drawing and photomicrograph of type I neuron. Scale for drawing = 30 μm

**Table 1** The mean of branching points (BP) per neuron and the mean of the free dendritic tips (FDT) per neuron of both Golgi-type I and Golgi-type II neurons

|                     | Mean BP                      | Mean FDT                      |
|---------------------|------------------------------|-------------------------------|
| Golgi-type I cells  | 19.2 ($n = 24$)<br>(SD = 2.299) | 25.96 ($n = 42$)<br>(SD = 7.25) |
| Golgi-type II cells | 8.69 ($n = 32$)<br>(SD = 3.75) | 11.84 ($n = 32$)<br>(SD = 5.63) |

**Table 2** Radiating and tufted branching patterns in dendrites of different orders of Golgi-type I and Golgi-type II cells

| Golgi-type I cells ($n = 24$ cells) | | | | Golgi-type II cells ($n = 32$ cells) | | | |
|---|---|---|---|---|---|---|---|
| Dendritic order | Radiating (R) | Tufted (T) | R:T Ratio | Dendritic order | Radiating (R) | Tufted (T) | R:T Ratio |
| 1st ($n = 94$) | 79 | 15 | 5.3 | 1st ($n = 69$) | 68 | 1 | 68 |
| 2nd ($n = 126$) | 113 | 13 | 8.7 | 2nd ($n = 77$) | 72 | 5 | 14.4 |
| 3rd ($n = 111$) | 104 | 7 | 14.9 | 3rd ($n = 64$) | 61 | 3 | 20.3 |
| 4th ($n = 60$) | 57 | 3 | 19 | 4th ($n = 37$) | 35 | 2 | 17.5 |
| 5th ($n = 19$) | 19 | 0 | – | 5th ($n = 14$) | 14 | 0 | – |
| Total | 372 | 38 | 9.8 | Total | 250 | 11 | 22.7 |

*R = radiating branching pattern, T = tufted branching pattern
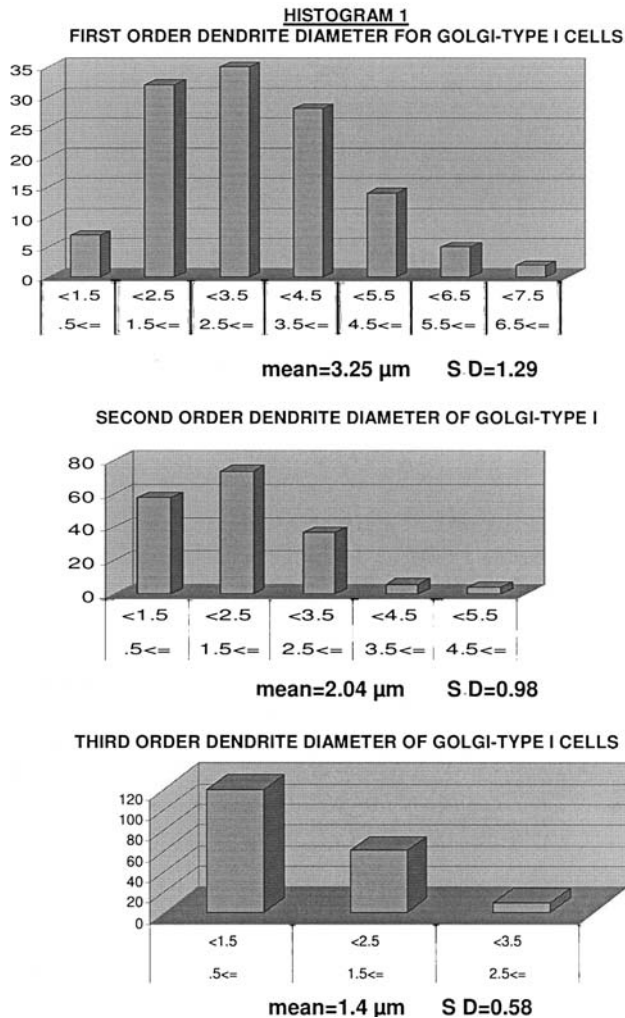
**Fig. 2** Histogram 1: Distribution of mean diameters of first order, second order and third order dendrites of Golgi-type I neurons

terminal appendages at dendritic tips. Both radiating and tufted branching patterns were seen for dendrites of these neurons but with much less tufted dendrites comparing to the type I neurons (Table 2). Overlap of diameters was found not only between primary and secondary dendrites but also between primary and tertiary dendrites as well with wide range of variability of the widths of the dendrites of the same order (Histogram 2: Fig. 5).

Long parts (up to 300 μm) of axons of these cells were impregnated suggesting that these axons were unmyelinated or thinly myelinated. These axons change their direction very often and form loops. No local branches were seen for these axons.
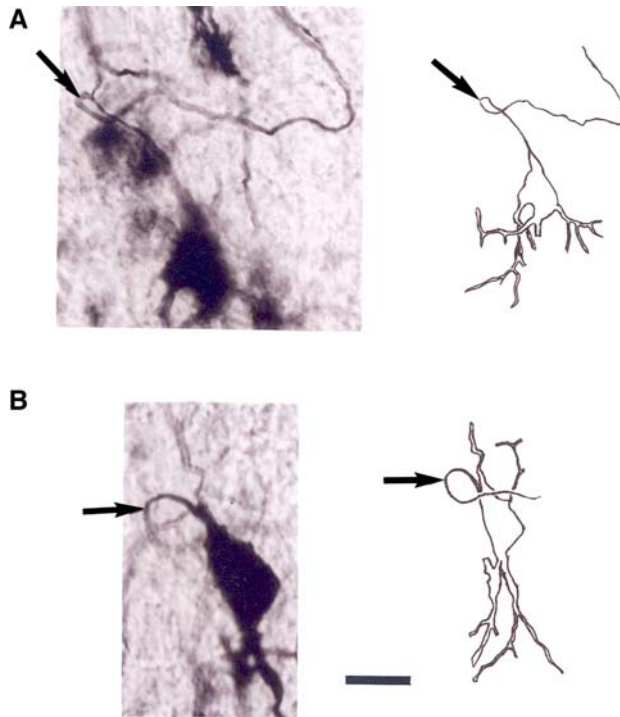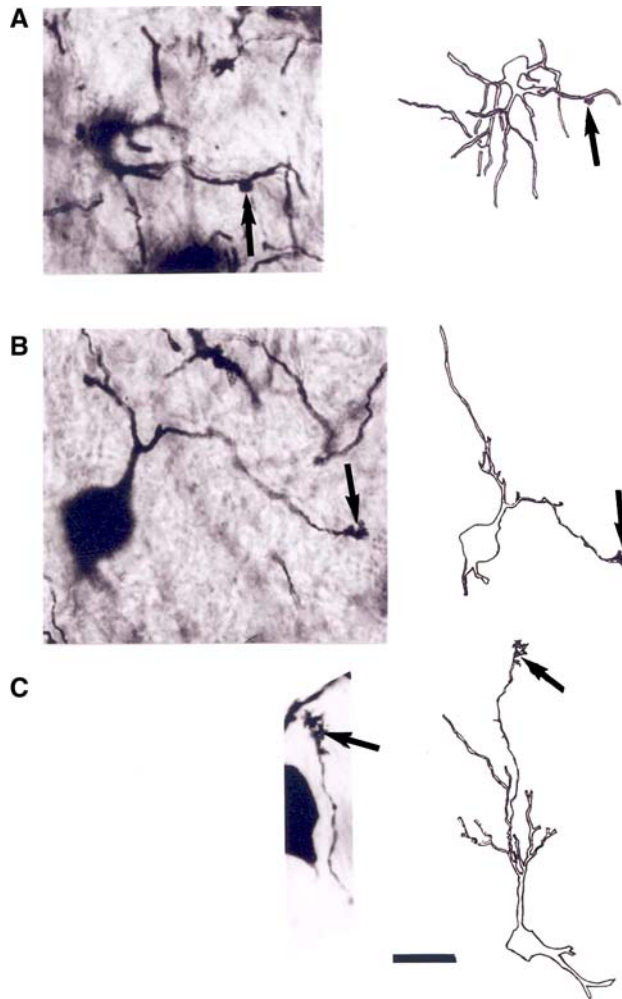
**Fig. 3** Camera lucida drawings and photomicrographs of two type II neurons (**A** and **B**) with axonal loops (arrows). Scale for drawing = 30 μm

Type III Neurons

The least frequently impregnated neurons in this study (Fig. 6) differ from type I and type II neurons in terms of cell body size and features of dendritic trees. Type III neurons were small neurons with an average mean diameter of 13.8 μm (SD = 1.2, $N = 18$). They have only one primary dendrite (unipolar) or two primary dendrites (bipolar). These dendrites have poor arborization with no protrusions, spines or appendages. No axons for these neurons were seen in this study.

**Discussion**

This study was based on the Golgi-Kopsch method of silver impregnation applied on the AV thalamic nucleus of the human adults. Three types of neurons were described and compared with their counterparts in the cat AV nucleus (Somogyi et al. 1979) and other thalamic nuclei (Guillery 1966; Scheibel and Sheibel 1966; Tombol et al. 1969; Kiss and Tombol 1972; Morest 1975; Hazlett et al. 1976; Pearson and Hairen 1980; Friedlander et al. 1981; Spreafico et al. 1983; Braak and Braak 1984; Winer 1984; Yamamoto et al. 1985; Yen et al. 1985; Al-Hussain and Kultas-Ilinsky 1986; Tseng and Royee 1986; Al-Hussain 1987; Rafols et al. 1987; Tombol et al. 1990; Al-Hussain 1992). The human type I neurons were similar to the type I (tufted) and type II (radiating) projection neurons

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**Fig. 4** Camera lucida drawings and photomicrographs of three type II neurons (**A**, **B** and **C**) with grape-like appendages (arrows). Scale for drawing = 30 μm

described by Somogyi et al. (1979) in the cat AV. These neurons have rich dendritic arborization similar to their counterparts in the majority of the thalamic nuclei. However, both tufted and radiating dendritic branching patterns were found in almost every type I neuron in this study and therefore it was not possible to subclassify these neurons into tufted and radiating subtypes as reported in some studies of some thalamic nuclei such as the AV nucleus, the motor thalamic nuclei and the sensory thalamic nuclei (Somogyi et al. 1979; Kiss and Tombol 1972; Pearson and Hairen 1980; Spreafico et al. 1983; Winer 1984; Yen et al. 1985). The results of this study came in agreement with similar results reported in the motor thalamic nuclei in both human (Al-Hussain 1995) and cat (Al-Hussain 1987) where both radiating and tufted dendritic branching patterns were found in almost every type I neuron. It has been suggested that the
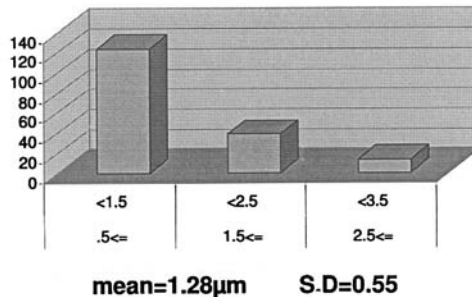
**HISTOGRAM 2**
**FIRST ORDER DENDRITE DIAMETER OF GOLGI-TYPE II CELLS**



mean=3μm          S.D=1.24
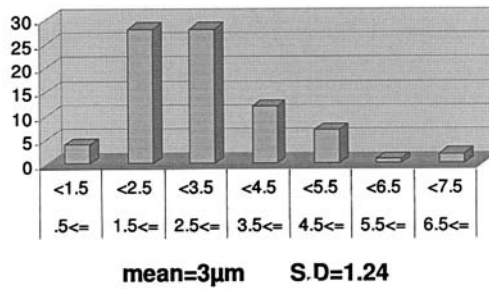
**SECOND ORDER DENDRITE DIAMETER OF GOLGI-TYPE II CELLS**



mean=1.92μm          S.D=0.68
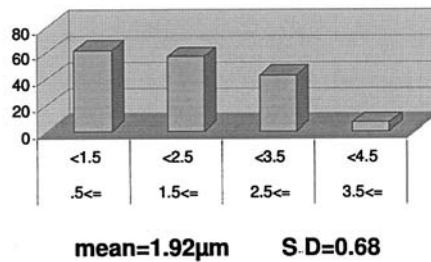
**THIRD ORDER DENDRITE DIAMETER OF GOLGI-TYPE II CELLS**



mean=1.28μm          S.D=0.55

**Fig. 5** Histogram 2: Distribution of mean diameters of first order, second order and third order dendrites of Golgi-type II neurons

dendritic branching pattern can play an important role in determining the electrical properties of a dendritic tree (Hillman 1979). Therefore, it can be assumed that, at least in the AV and the motor thalamic nuclei, most of the Golgi-type I neurons may have dendrites with different electrical properties.

The Golgi-type II neurons which were not reported in the cat AV nucleus (Somogyi et al. 1979) were found in the human AV (this study). The type II neurons found in this human study have very characteristic morphological feature which was not reported before in any of the thalamic nuclei. This characteristic morphological feature is the formation of loops and changing of directions made by most of the impregnated axons of these neurons. Since that it was the first time to impregnate axons of Golgi-type II
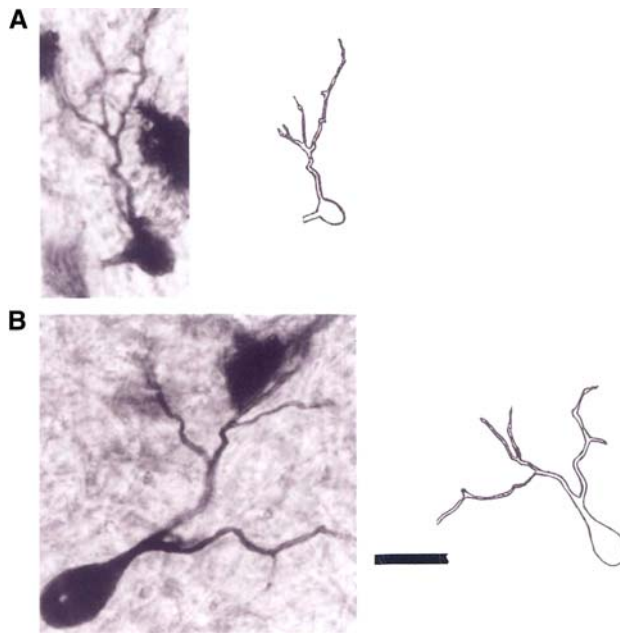
**Fig. 6** Camera lucida drawings and photomicrographs of two type III neurons (**A** and **B**). Scale for drawing = 30 μm

neurons that change direction and have loops in the thalamus, it is possible that, this feature is characteristic feature for the axons of human thalamic type II neurons. The impregnation of long segments of the axons of these cells without local branches suggest that these neurons with Golgi-type II feature namely the relativly poor dendritic arborization may in fact send their axons outside the thalamus. In fact, these cells look similar to the type III projection neurons that seem to have relatively poor dendritic arborization (see figue 2f, Somogyi etal. 1979). Also, Golgi-type II neurons that send their axons outside the thalamus were reported in the mediodorsal (MD) nucleus (Babmindra et al. 1977). The type II neurons in the human AV nucleus were found to have grape-like dendritic appendages not only at the dendritic shafts but also at dendritic tips. In the sensory thalamic nuclei, large number of spines and grape-like appendages were described for the dendrites of Golgi-type II neurons including their branching points and dendritic tips (Guillery 1966; Morest 1975; Pearson and Hairen 1980; Friedlander et al. 1981) while in the motor thalamic nuclei few spines and grape-like appendages were found along the shafts of Golgi-type II dendrites but never at their dendritic tips (Al-Hussain 1987; Al-Hussain 1992). Whether the location of these appendages along the dendritic trees of the type II neurons make a significant difference was not clear. The grape-like appendages were found to be part of complex synaptic structures called glomeruli where they act as postsynaptic to afferent fibres and presynaptic to dendrites of Golgi-type I neurons (Morest 1975; Al-Hussain 1987). These appendages were connected to the main stem of the type II dendrites via a thin stalk. It is known that the thin necks of spines in other types of neurons represent sites of increased resistance to current spread. The events occurring at the heads of spines are to

a large extent isolated from the rest of the dendrite and vice versa (Diamond et al. 1969; Chan-Palay and Palay 1970). By analogy, one can suggest that a similar autonomy exists in glomeruli, in the sense that depolarization of dendritic appendages of Golgi-type II caused by afferents in glomeruli would hardly spread to the rest of the Golgi-type II dendritic tree or soma, and a similar minimal influence on glomeruli can be expected from currents generated in other parts of Golgi-type II cells. Thus, the role of the specializations (spines and appendages) of Golgi-type II can only be in relationship to the afferents and dendrites of Golgi-type I. Since the dendrodendritic contacts formed by Golgi-type II appendages on Golgi-type I were symmetrical and large in number (Al-Hussain 1987), they could effectively hyperpolarize large areas of the Golgi-type I dendritic membrane and thus modulate the excitatory input to the dendrites of the Golgi-type I neurons arriving via the afferents. What happens exactly at these sites (glomeruli) is not really clear. Finally, Type II cells in the human AV nucleus have poor to moderate dendritic arborization similar to their counterparts already described in the specific motor and sensory thalamic nuclei (Guillery 1966; Scheibel and Sheibel 1966; Tombol et al. 1969; Kiss and Tombol 1972; Morest 1975; Pearson and Hairen 1980; Friedlander et al. 1981; Spreafico et al. 1983; Braak and Braak 1984; Winer 1984; Yamamoto et al. 1985; Yen et al. 1985; Al-Hussain and Kultas-Ilinsky 1986; Al-Hussain 1987; Rafols et al. 1987; Al-Hussain 1992; Ma et al. 1998) and differ from the Golgi-type II neurons in the intralaminar nuclei which have rich dendritic arborization (Tombol et al. 1990).

The type III neurons found in this study were similar to the Golgi-type III cells described in the human VL thalamic nucleus (Al-Hussain 1992). The type III cells in these human thalamic nuclei were very small with only one or two primary dendrites which rarely branch and have no spines or appendages. No similar neurons were described in non-human thalamic nuclei. Whether these very small unipolar and bipolar neurons were specific for human was difficult to determine and need further Golgi studies.

An interesting quantitative result from this study concerns the wide overlap of the widths of primary, secondary and tertiary dendrites of both type I and type II neurons in the human AV thalamic nucleus which came in agreement with similar results reported in the cat motor thalamic nuclei (Al-Hussain 1987). Therefore, this criterion namely the diameter of dendrites which was used in some ultrastructural studies in the thalamus (Morest 1970; Rinvik and Grofova 1974a; Morest 1975) to identify the order of the dendrites at the EM level was not reliable at least in the AV and motor thalamic nuclei.

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