Axon Collaterals of Meynert Cells Diverge Over Large Portions of Area V1 in the Macaque Monkey

KATHLEEN S. ROCKLAND1,2* AND TINA KNUTSON2
1Laboratory for Cortical Organization and Systematics, RIKEN Brain Science Institute, Wako-shi, Saitama 351-0198, Japan
2Department of Neurology, College of Medicine, University of Iowa, Iowa City, Iowa 52242

ABSTRACT

Patchy intrinsic connections, originating mainly from horizontal collaterals of pyramidal neurons, have been demonstrated in area V1 and many other cortical areas. In this article, we identify a network of intrinsic connections concentrated in layer 6 of area V1. These are visualized by extracellular injections of anterograde tracers in V1, which label small clusters of large terminal boutons in layer 6, in conjunction with thick axon segments. These segments can be traced back to infragranular Meynert cells (n = 10), which are retrogradely labeled from the injections. By using serial section analysis, we identified the following features of this distinctive system of Meynert cell collaterals: (1) terminal clusters are relatively small (<100 μm); (2) each cluster has a small number of rather large boutons (up to 3.0 μm); (3) there is typically a termination-free zone in the immediate vicinity (0.5–2.0 mm) of the cell body; (4) a single neuron has multiple branches that can extend up to 8.0 mm from the soma; and (5) the collaterals are concentrated in layer 6. These features are different from those of horizontal intrinsic connections in the supragranular layers of area V1. They are consistent with fast dynamics and a possible role in wide-field motion processing, such as has been associated with Meynert cells from other studies. J. Comp. Neurol. 441:134–147, 2001. © 2001 Wiley-Liss, Inc.

Indexing terms: area V2; directional selectivity; horizontal connections; layer 6; motion pathway

The solitary cells of Meynert are a morphologically specialized class of large cells, like Betz cells in the motor cortex (reviewed in Chan-Palay et al. 1974; Payne and Peters, 1989). They project to both area MT/V5 and the superior colliculus (Lund et al., 1975; Spatz, 1975; Shipp and Zeki, 1989) via collaterals (Fries et al., 1985; Weisenhorn et al., 1995). In part because of this pattern of connectivity, it is thought that Meynert cells may be involved in the motion detection system (e.g., Livingstone, 1998). This is also suggested by the results of antidromic stimulation of MT/V5 (Movshon and Newsome, 1996). One study in cat visual cortex describes a Meynert neuron with a very large binocularly driven standard complex receptive field (Gabbot et al., 1987). This neuron, which was identified as a corticocorticocortical neuron, had extensive intracortical axon collaterals that would be well suited, as noted by these authors, to facilitate response properties of other infragranular neurons across a wide region in space. Because Meynert cells are widely scattered (Chan-Palay et al., 1974; Winfield et al., 1981; Peters and Sethares, 1993) however, they have been relatively difficult to investigate, and many of their properties remain poorly understood.

After extracellular injections of anterograde tracers in area V1, we have consistently observed small clusters of large boutons in layer 6. These occur in conjunction with thick axon segments and large, retrogradely filled Meynert neurons (Fig. 1). There are several potential sources for these clusters (see Discussion), but we have shown, by using serial section reconstruction, that they originate from Meynert cells in the deeper layers. Moreover, this appears to be a distinct system of intrinsic connections with the following features: (1) terminal clusters are rel-
Fig. 1. Photomicrographs illustrating label in layer 6 resulting from an injection of BDA in area V1. A: Three isolated terminal clusters (arrows), 5.0 mm ventral to the injection site. The middle arbor (vertical oblique arrow) is shown at higher magnification in C. B: Typical long axonal segment, 10 mm ventral to the injection site, with three terminal clusters (arrows). Two of these are shown at higher magnification in D and F. E: Three retrogradely labeled large neurons (arrows) at the border of layers 5 and 6. This field is from near the injection site, and there is densely labeled neuropil in layers 5A and 6. The edge of the injection is 2.0 mm to the right of the image. Scale bars = 200 μm in A,B,E, 100 μm in D,F, 25 μm in C.
Results are based on injections of biotinylated dextran amine (BDA) in four monkeys (4.0–6.6 kg; Macaca mulatta) and biocytin in one animal (4.5 kg, M. mulatta). Animals were tranquilized with ketamine (11 mg/kg) and maintained under deep anesthesia with Nembutal (25 mg/kg, i.v.). All surgery was performed on deeply anesthetized animals under sterile conditions, according to institutional and federal guidelines, as specified in approved Animal Care and Use Forms (University of Iowa and RIKEN Brain Science Institute). Area V1 was localized relative to the occipital pole and, subsequent to craniotomy and durotomy, in relation to the lunate sulcus. Injections were placed dorsal to the ectocalcarine sulcus in three animals and more ventral, in the upper visual quadrants were placed dorsal to the ectocalcarine sulcus in one. Two to four pressure injections (1.5–4.0 mm in diameter), which involved all six layers but did not invade the white matter. Biocytin was delivered iontophoretically (7 μA in a 7-second on/off cycle) at two sites.

Animals were given postsurgical doses of antibiotics and analgesics, allowed to recover, and survived 18–29 days (or 2 days in the case of biocytin). They were then reanesthetized with nembutal (75 mg/kg) and perfused transcardially, in sequence, with 0.5 liters of 0.9% saline and 0.5% sodium nitrite, 2–4 liters of 4% paraformaldehyde, and chilled 0.1 M PB with 10%, 20%, and 30% sucrose (0.5 liters each). Brains were cut serially in the coronal or horizontal planes by frozen microtomy (at 50 μm), and processed histologically in avidin-biotin complex (Vector Labs, Burlingame, CA, elite ABC kits), as described previously (Rockland and Knutson, 2000).

In our experience, BDA is primarily transported in the anterograde direction, but sporadic retrograde labeling often occurs, particularly around injection sites. At greater distances, the amount of retrograde transport varies with different connections and, even when it occurs, seems to label fewer neurons than would be labeled by Fast Blue (FB) or HRP.

Brains were scanned for global projections within V1, and labeled elements were chosen for serial reconstruction. In some instances (n = 10), reconstruction began at the cell body. More frequently, we selected axon segments identifiable as “Meynert-like” (small clusters of large boutons, originating from large-caliber axons, as shown in Figure 1). Reconstruction was carried out by means of a camera lucida microscope attachment at 100×, 200×, and/or 400× magnifications (1,000× oil was used for complex fields). Area V1 was easily identified, even in non-counterstained tissue, by its distinctive lamination pattern. Layer 6 was easily identified as being more cell dense than either the overlying layer 5 or the subjacent white matter. As further verification, some sections were counterstained with Nissl after completion of the axon analysis.

Additional material available for observation included 3 macaque brains with injections of PHA-L in area V1 and 3 squirrel monkey brains with BDA injections in V1. These also showed the conjunction of large boutons, thick axon segments, and filled Meynert neurons in layer 6 but were not used for axon reconstruction. In one other monkey, two pressure injections (0.75 μl each) of FB (4% in PBS) were made in area V1 in order to confirm the distribution of retrogradely labeled Meynert cells. Eighteen days postoperative, this animal was reanesthetized and perfused as described above. The tissue was sectioned at 50 μm and sections mounted immediately onto subbed slides for observation.

Photomicrographs were taken with an Olympus DP50 digital camera mounted on an Olympus BX60 microscope at a resolution of 72 dpi. Images were resized to approximately 1,000 dpi, then figures were constructed in Adobe Photoshop 5.5 and printed on a Codonics NP-1660M dye sublimation printer.

RESULTS

In the vicinity of the injection sites, there was dense labeling in the supragranular layers (layers 3 and 4B), which, in accord with previous studies (Rockland and Lund, 1983; McGuire et al., 1991; Malach et al., 1993), had a patchy distribution. In layer 6, labeled processes consisted of thick axon segments (up to 3.0 μm in diameter), small clusters of large boutons (also up to 3.0 μm in diameter), and (in BDA material more than biocytin) retrogradely filled neurons (Fig. 1). The large boutons in layer 6 were distinctive and distinguishable from terminations originating from pyramidal neurons in layer 3 (Fig. 2) or from lateral geniculate terminations in layer 4 (Blasdel and Lund, 1983; Freund et al., 1989). Multiple small clusters were easily observed along a single thick axon segment (Fig. 1), but unlike the terminations in the upper layers, they did not form dense patches. These terminal segments occurred as much as 8.0–10.0 mm from an injection site.

Large retrogradely filled neurons were detectable in both BDA and FB material (Figs. 3–5) at distances up to
8.0 mm from an injection site. The number of neurons ranged from 0–6 per section. More neurons were labeled within 2.0 mm of an injection site (Fig. 5), but even in this proximal zone, the density was uneven. For example, over an anterior posterior (AP) interval of 0.55 mm near one injection site (sections 79–89, Fig. 5), we counted 2, 0, 4, 0, 0, 1, 0, 5, 0, and 2 cells. Filled neurons were predominantly solitary but those near an injection site (i.e., within 2.5 mm) often were spaced as close as 0.3–0.5 mm. Further away (2.5–5.0 mm), a larger interval (≥1.0 mm) was more common. With dorsal injections, filled neurons occasionally occurred in the calcarine fissure (5 neurons in case 7). These neurons probably send their axons across the white matter to the injection sites on the lateral surface (see below, axon 7-2, Fig. 8). In the proximate injection zone, scattered small neurons in layer 6 were also retrogradely labeled.

The large retrogradely filled neurons matched the descriptions of Meynert cells on several counts (Chan-Palay et al., 1974; Lund and Boothe, 1975; Winfield et al., 1981; Valverde, 1985; Payne and Peters, 1989; Peters and Sethares, 1993): they were located in the infragranular layers, mainly at the border of layers 5 and 6; they had a large cell body (often 20 × 30 μm); they were mostly spaced widely apart; and in some instances at least, they could be seen to have large-caliber dendrites that spread over a long distance from the cell body (Fig. 4). The cell morphology was not uniform, however. As remarked in the previous studies, some neurons had triangular somas, whereas others were more oval. We noted some neurons that looked like inverted pyramids. In this instance, the axon was emitted from the pial side of the neuron (for example, axon 7-2, Fig. 8). As best we could tell, the apical dendrites seemed slender (Fig. 4; see Braak, 1982; Valverde, 1985; Peters, 1994 for discussion of dendritic variation). Many of the large neurons were densely filled, but for those that were less densely filled, there was no evidence of eccentric nuclei, such as would be expected if the neurons were basket cells (Peters and Sethares, 1993). Furthermore, the large dendritic spread is not characteristic of basket cells.

Despite the proximity of labeled cell bodies, boutons, and axon segments, we were able to establish actual continuity between cell bodies and the thick axon segments for only 10 neurons (Fig. 4). We think it likely that the difficulty in tracing segments back to Meynert somas may be attributable to technical factors, possibly related to the frequent observation of a thinning between the axon initial segment and the main axon proper (cf. Fig. 4F, I).
Axon reconstructions

Reconstructions were carried out in three brains. Of these, six reconstructions (of which four are illustrated) were relatively complete, and 12 (of which 2 are illustrated) were more partial. The consistent features were: small terminal clusters or sprigs, spaced at intervals; very large terminal specializations; and a very large spread of the collaterals. With one exception, all of the axons arborised only within layer 6.

Axon 7-1. Case 7 (Fig. 6) had a large injection (4.0 mm in diameter, sections 80–160) situated in the dorsal part of the lateral operculum. Axon 7-1 was followed from the cell body (at section 245). One thick process was followed dorsal, at the white matter/layer 6 border, for about 3.0 mm (thick arrow in Fig. 6). Because no terminations were given off, it is likely that this was the main axon and that it continued further to extrinsic targets. Ventral from the cell body, there were four collaterals, each measuring 1.25–1.75 mm in length. One branch (branch I in Fig. 6) continued mainly anterior and ventral from the cell body, but most of the collateral tree extended posterior and slightly ventral. Although the injection site seemed to be located in the lower visual field representation, terminations from this neuron extended well into the upper visual field, near the inferior occipital sulcus. In total, the full AP extent of this axon was 8.45 mm (section 163–329), and the dorsovertical (DV) extent was about 5.5 mm. Four hundred boutons were counted in total, with a range of 10–50 boutons per terminal cluster.

Each collateral branch bore 4–6 small arbors or clusters with terminations. The cluster size was usually small (<100 μm), but some judgment is involved as to whether...
closely spaced clusters should be considered as separate or as a single loosely organized cluster (up to 300 μm). The center-to-center spacing between clusters was also variable but had a tendency toward 125 μm, 250 μm or 500 μm. It is noteworthy that there were no terminations within 2.0 mm of the cell body. (The cluster at 179 appears close to the parent cell but is actually 3.25 mm posterior.)

**Axon 3-2.** This case (Fig. 7) had a large injection (3.0 mm in diameter), in the posterior dorsal part of V1. The illustrated collaterals and neuron are located in the upper bank of the calcarine fissure (CF).

From the cell body (at section 216), one thick process entered the white matter and may lead back to the injection site. One long collateral (8.0 mm) traveled ventral within the CF and bifurcated distally. Another long collateral (3.0 mm long) traveled dorsal and continued into V2. In the AP plane, the collateral field in area V1 was relatively flat (0.65 mm). The total number of boutons was 519. As for axon 7-1, there are multiple small terminal clusters, with a diameter of <100 μm (shown only schematically in Fig. 5). Along the dorsal branch, the terminal arbors have a rather regular center-to-center spacing of 500 μm; but the intervals are somewhat larger for most of the ventral branch.

The terminations in area V2 were in layer 4, about 1.5 mm anterior to the field in V1. The arbor was larger (d = 250 μm) than the intrinsic clusters and had more boutons (n = 250).

**Axon 7-2.** This axon (Fig. 8) originated from a neuron in the upper bank of the CF, situated about 1.5 mm posterior to the injected zone. Three collaterals were identified, all in layer 6. One collateral extended about 2.0 mm dorsal from the parent neuron and then terminated with four small clusters along its distalmost 0.7 mm. Another collateral descended ventrally and emitted terminal portions in the depth of the CF, at 4.0 mm and 8.0 mm from the parent neuron. In the CF, the first, smaller branch was 0.5 mm long and carried five small clusters; the second branch (1.5 mm anterior) was about 1.0 mm long, with six distinct clusters. Measured as a hollow rectangle, the full AP extent of this axon in area V1 was 2.5 mm, and the DV extent was about 6.5 mm. We counted a total of 424 boutons (105 in the dorsal focus; 102 and 207 for the two foci in the CF).

There were five additional features of interest concerning this axon. First, what seems to be the main axon (solid arrow in Fig. 8) on the basis of its caliber and proximity to the injection site followed a dorsally curved trajectory, rather than taking the shortest pathway to the injection site. Second, the main pathway of this segment was obliquely through the white matter, from the CF to the lateral surface. Third, a third collateral was identified that traveled through the white matter toward the lateral surface. This, however, was lost in a dense field of labeled axon segments. Fourth, as noted above, there were no terminations in the immediate vicinity of the cell body. Fifth, the ventral collateral, after giving off the two terminal branches in the CF, continued anterior (for another 3.0 mm) and medial. It entered the gray matter of ventromedial area V2, but by then became very fine and faint and could not be followed.

**Axon 7-3.** This axon (Fig. 9) was also followed from the cell body (at section 222). It is somewhat incomplete (short lines indicate two collaterals that were lost in a dense field of labeled segments near the cell body and two other collaterals that could not be followed at their distal ends). Nevertheless it had many of the same features as the previously described axons, namely, long and thick collaterals, multiple small terminal clusters, and large terminal boutons. Like axon 3-2, some terminations were discerned in area V2, but for this axon, these were comparatively few (31 in layer 4, 9 in layer 6 of V2).
Fig. 6. Camera lucida reconstruction (through 166 sections or 8.30 mm anteroposterior [AP]) of axon 7-1, labeled by a BDA injection in area V1. The parent neuron (asterisk at section 245) gives rise to four collaterals (I–IV and arrows) within layer 6 of area V1. The thick arrow points to the continuation of the main axon, which was followed dorsally, to section 179 (this part of the reconstruction is not shown to conserve space). The numbers refer to individual tissue sections, where smaller numbers are more posterior. The five coronal section outlines indicate the general location of the cell body (asterisk) and portions of the axon collaterals (X) at different AP levels. The short lines indicate the border between areas V1 and V2. The same conventions apply to Figures 7–10, except that case 6 (Fig. 10) is sectioned in the horizontal plane. The schematic brain diagram shows the location of the injection, of the cell body (asterisk), and the general position of the main collateral branches (because of space, only I, III, and IV are labeled). IOS, inferior occipital sulcus; STS, superior temporal sulcus; LS, lunate sulcus.
This axon also had a small branch in layer 4B of area V1 and an ascending collateral that traveled in layer 1 for 5.0 mm. The segment in layer 1 had four terminal clusters distributed over 2.5 mm, but no terminations were found over the further distal 2.5 mm. The total number of boutons for the reconstructed portion in area V1 was 824 (144 in layer 1, 90 in layer 4B, and 550 in layer 6).

**Segment 6-3.** Case 6 (Fig. 10A) had two smaller injections (0.75–1.0 mm in diameter) located below the ectocarinal sulcus, which produced the same pattern of label in layer 6. One axon segment was followed posterior from the injection site (section 243). It appears moderately complete, although the possibility remains that other main branches might issue from the parent neuron in other directions. The segment had five major branches, each measuring 1.25–2.75 mm long and bearing multiple small terminal clusters. The total extent of the terminal field, estimated as a bounded rectangle, was 5.0 mmDV × 6.0 mmAP. In total, we counted 1,372 boutons. Although we cannot show direct continuity with a Meynert cell soma, these features are highly consistent with those segments that were traced to Meynert neurons.

**Segment 6-4.** As seen in Fig. 10B, this is a single collateral, also followed from the vicinity of the injection site (at section 244). There were multiple terminal clusters, separated by semiregular intervals of 0.5–0.75 mm, with a total of 641 boutons. It is primarily interesting as another example of a very long collateral in layer 6 (6.5 mmAP).

**Beaded terminations in layer 4B of V1**

In scanning through individual sections, we noticed a few very large beaded terminations in layer 4B (Fig. 11), as might be expected given the occurrence in this layer of terminations from deeper Meynert cells (see axon 7-3). Since we did not attempt reconstructions in this layer, we cannot ascertain whether these boutons originate from large neurons in layer 4B or from Meynert neurons in layer 6. By contrast, inspection of intrinsic patches in layer 3 showed a mix of stalked and beaded terminations, but both were small, as is typical of most corticocortical extrinsic connections (Fig. 11).

**DISCUSSION**

In this article, we identify a system of very widespread intrinsic connections and present evidence that they originate from Meynert cells in the deeper layers of area V1 in the monkey. Distinctive features are the large spread of the collaterals, the small size of the individual terminal clusters, and the large size of the terminal specializations. Terminations are concentrated in layer 6 but can occur in layers 1 and 4B. Divergent axon projections have previously been described in layer 6 (Fig. 8 in Wiser and Callaway, 1996; Callaway, 1998), but these do not have the same set of features as those originating from Meynert cells. In cat area 17, however, an intracellularly filled neuron, characterized as Meynert, had a widespread intrinsic collateral tree, extending 2.16 mm anterior and 2.64 mm posterior to the parent soma (Gabbott et al., 1987), consistent with our results.

**Origin from Meynert cells**

The origin of these connections from Meynert cells is supported by the fact that the thick-caliber collateral segments can be traced back to neurons that on the basis of their size and location can be identified as Meynert cells. We consider this strong evidence, but it is important to review other possibilities and why we have eliminated them. In particular, these segments might belong to basket cells or to geniculocortical axons, both of which terminate with large boutons in layer 6 (Blasdel and Lund,
1983; Lund et al., 1988; Freund et al., 1989). A basket cell origin, however, seems unlikely, in part because such an extensive collateral tree has not been associated with basket cells, even after intracellular filling (e.g., Lund, 1988; Lund et al., 1988; Kisvarday et al., 1996). In addition, features characteristic of basket cells, such as eccentric nuclei and pericellular terminations, have not been observed in our material. Similarly, geniculocortical axons are reported to have focused, not divergent arborizations in layer 6. Moreover, the geniculocortical terminations in layer 6 are collaterals of larger arbors in layer 4 (Blasdel and Lund, 1983; Freund et al., 1989). None of our reconstructions led to larger arbors in layer 4C.

Our results indicate some variation in the laminar termination pattern of Meynert collaterals. In our sample, five of six axons had terminations in layer 6 alone, but one had some terminations in layers 1 and 4B, as well as in 6. This variability may denote subtypes of Meynert cells. There is other evidence for subtypes, such as differences in soma shape and in the thickness and extent of apical

---

**Fig. 8.** Camera lucida reconstruction (through 106 sections or 5.30 mm AP; terminal field in V1 = 2.5 mm) of axon 7-2, labeled by a BDA injection in area V1. **A:** Higher magnification of the cell body (asterisk) and four collateral branches at their proximal portions. **B:** Lower magnification of the full reconstruction. The parent neuron (at section 48, asterisk) gives rise to four branches (hollow arrows). One proceeds dorsally and terminates, another proceeds ventrally and gives off two terminal foci in the CF, and a third heads toward the lateral surface. A fourth branch (solid arrow) is distinctly thicker and approaches near to the injection site (INJ). **C:** Three coronal section outlines indicate the position of the axon at different locations. It is shown (1) at the anterior position in area V2 (arrow in section 143); (2) in the white matter near the injection and at the ventral terminal focus in the CF (three x’s at section 80; section 80 is also used for section 78); and (3) near its origin in the posterior CF (two x’s at section 48 indicate the dorsal and middle terminal foci; section 48 is also used for 42). The position of the cell body is shown by an asterisk in section 48. CF, calcarine fissure.
Fig. 9. Camera lucida reconstruction (through 103 sections or 5.15 mm AP) of axon 7-3. From the parent neuron (at section 222), six branches are emitted. One of these (thick arrow) may be the main axon but was followed only a short distance in the white matter (to section 194). Two branches (ending in dashed lines) could not be followed beyond the immediate vicinity of the cell body. Two other branches were followed extensively in layer 6. One of these had terminations in area V2. Finally, one branch ascends from the parent neuron, gives off terminations in layer 4B, and then travels in layer 1, with four small terminal clusters. All of these three branches continued further (dashed lines). The low magnification inset provides a schematic overview of the general configuration. It shows the continuation of the layer 1 branch from the arrow in the main figure. (There were no boutons in this more distal portion in layer 1). For the sake of format, the axon has been rotated relative to axon 7-1. As shown by the section outlines, which have also been rotated, dorsal is now to the left. CF, calcarine fissure.
Fig. 10. Two axon segments within area V1, anterogradely filled by a biocytin injection in V1 (indicated by hollow arrows and by a black spot in section outline 220). One segment (A, traced through 100 sections or 5.0 mm dorsoventral) has five branches (arrows), each with multiple terminal clusters. The second segment (B, traced through 33 sections or 1.7 mm dorsoventral) appears to be simpler but has the characteristic pattern of multiple small terminal clusters. This brain was cut in the horizontal plane, and smaller numbers denote more ventral sections.
dendrites (Lund and Boothe, 1975; Braak, 1982; Valverde, 1985; Peters, 1994). Meynert cells, moreover, are reported to project to different combinations of extrinsic targets (Weisenhorn et al., 1995).

Other intrinsic connections

In primate area V1, previous studies have described two systems of patchy intrinsic connections in the supragranular layers. These originate mainly from horizontal collaterals of pyramidal neurons in layer 3 or from pyramidal and stellate neurons in layer 4B (Rockland and Lund, 1983; Lund 1988; McGuire et al., 1991). Both of these differ from the Meynert system in several respects (Fig. 12). First, there are differences in overall spread. The connections in layer 3 as well as those in layer 4B are more restricted, in the range of 2.0–4.0 mm from an injection site. Second, there are differences in arbor size. In the layer 6 system, the individual terminal clusters are generally ≲100 μm in diameter, considerably smaller than the size of the supragranular patches (approximately 200 μm in diameter) or of the individual arbors revealed by intracellular injections (Gilbert and Wiesel, 1983; Martin and Whitteridge, 1984). Size differences of individual arbors and overall spread may in part be due to laminar specializations, such as have been noted in several physiological studies (Blasdel and Fitzpatrick, 1984; Tootell et al., 1988; Snodderly and Gur, 1995).

A third difference relates to the number and size of boutons. For Meynert collaterals, despite their very wide spread, the total number of boutons in layer 6 can be as small as 400 (1,372, for segment 6-3, is the largest number in our sample), but the boutons are relatively large in size. This contrasts with the supragranular connections, which have a large number of smaller boutons (section 2.7 in Rockland, 1997).

Fourth, there are differences in the density distribution of terminations. The proximal portion of Meynert collaterals, within 0.5–2.0 mm of the parent soma, seems not to
have terminations, whereas for non-Meynert pyramidal neurons, the region around the parent soma has the highest density of terminations (Ojima et al., 1992; Rockland, 1997). In addition, the bouton density of Meynert collaterals does not obviously lessen with distance from the cell body, whereas the density in non-Meynert networks does show a distal fall-off.

Fifth, there are differences in network geometry. Intrinsinc connections in layers 3 and 4B have a distinctly patchy ("latticelike") pattern, but the intrinsic connections within layer 6 do not form distinct patches. There are clusters along a single collateral, but not dense patches of neurons and convergent terminations. The actual columnar relationship between supragranular patches and Meynert collaterals is not clear, and additional work is in progress to investigate further how Meynert collaterals are aligned relative to the basic functional architecture of area V1 (Li et al., 2000).

Functional implications

The striking features of the Meynert collateral system are the large caliber of the axons, the large bouton size, and the large spread of the terminal field. The first two features suggest a fast-conducting pathway, recalling the morphological characteristics of the magnocellular geniculo-cortical pathway. All three features are consistent with the idea, based in part on Meynert projections to area MT/V5, that Meynert cells are involved in motion processing (Movshon and Newsome, 1996). In addition, convergent input from widely scattered Meynert neurons could contribute to the large receptive fields of layer 6 neurons (Gilbert and Wiesel, 1979, 1983).

Meynert cells have also been suggested to contribute to directional selectivity, in part via the asymmetrical spread of their basal dendrites (Livingstone, 1998, but see Anderson et al., 1999). Comparable asymmetry does not seem to characterize the collateral axon fields. Two axons (3-2, 7-2) in our sample did have a collateral field with a pronounced asymmetry, favoring the dorsoventral plane parallel to the depth of the calcarine fissure, but no striking asymmetry was found in the other four of the more complete reconstructions, with fields on the lateral opercular surface.

Meynert cells by definition are a specialized class confined to area V1. However, distinctively large neurons are known to occur in layer 5 of other cortical areas. For example, intracellular injections of large neurons in the deeper layers of area A1 in the cat showed a system of divergent collaterals with large, beaded terminations (Ojima et al., 1992). An interesting possibility is that these cell classes may in some ways be equivalent.

ACKNOWLEDGMENTS

We thank Peter Kaskan and Pope Yamada for their help with figures, Michiko Fujisawa for assistance with manuscript preparation, and Dr. Manabu Tanifuji for helpful discussions.

LITERATURE CITED


Fries W, Keizer K, Kuyper HS. 1985. Large layer VI cells in macaque striate cortex (Meynert cells) project to both superior colliculus and prestriate visual area V5. Exp Brain Res 58:613–616.


Rockland KS, Knutson T. 1999. A system of intrinsic connections within

DIVERGENT INTRINSIC COLLATERALS OF MEYNERT CELLS