THE JOURNAL OF COMPARATIVE NEUROLOGY 284:567-580 (1989)

Development of the Rat Thalamus: V. The Posterior Lobule of the Thalamic Neuroepithelium and the Time and Site of Origin and Settling Pattern of Neurons of the Medial Geniculate Body

JOSEPH ALTMAN AND SHIRLEY A. BAYER
Laboratory of Developmental Neurobiology, Department of Biological Sciences, Purdue University, West Lafayette, 47907 (J.A.), Department of Biology, Indiana University-Purdue University, Indianapolis, 46223 (S.A.B.) Indiana

ABSTRACT

Long-survival, sequential, and short-survival thymidine radiograms of rat embryos, fetuses, and young pups were analyzed in order to examine the time of origin, site of origin, migratory route, and settling pattern of neurons of the medial geniculate body (MG). Quantitative evaluation of long-survival radiograms established that the bulk of MG neurons are generated between embryonic (E) days E13 and E15, with a pronounced peak on day E14. There is an overall lateral-to-medial and caudal-to-rostral chronological gradient in MG neurogenesis. On the basis of significant regional differences in the birth dates of neurons, the MG was divided into several chronoarchitectonic areas. The earliest-generated neurons (with close to 20% of the cells produced on day E13 and a negligible proportion on day E15) form the dorsal and ventral clusters far laterally. Next in sequential order are the neurons of the lateral shell, intermediate shell, and medial shell of the MG. The medial shell with it latest-generated neurons (with over 30% produced rostrally on day E15) corresponds to the medial (magnocellular) subnucleus of the MG. There were no neurogenetic differences between the traditional dorsal and ventral divisions of the MG.

Examination of sequential radiograms in rats labeled with ^{3}H-thymidine on day E14 or E15 and killed on successive days brought supportive evidence for our earlier identification, in short-survival radiograms, of a posteroventral thalamic neuroepithelial evagination as the putative source, or committed cell line, of MG neurons. Wave fronts of apparently migrating unlabeled and labeled cells could be traced from this sublobule in a posterolateral direction to the future site of the MG.

Key words: neuroembryology, thymidine autoradiography

We have previously (Altman and Bayer, '88) identified two components of the caudal lobe of the thalamic germinal neuroepithelium in day E14 rats, the intermediate lobule and the posterior lobule. In the preceding paper (Altman and Bayer, '89a) we sought to present evidence that the proliferating cells of the subsequently partitioning sublobules of the intermediate lobule produce the neurons of the ventrobasal and ventrolateral nuclei. The posterior neuroepithelial lobule, too, is divisible into sublobules, and this paper is concerned with one of them, the presumed source of neurons of the medial geniculate body (MG). In the succeeding paper of this series (Altman and Bayer, '89b), we will deal with the three other sublobules of the posterior neuroepithelial lobule and their presumed derivatives, the neurons of the dorsal and ventral lateral geniculate nuclei, and the lateral posterior nucleus.

The MG is the principal thalamic relay station in the mammalian auditory pathway. On the basis of its cytologi-

Accepted December 26, 1988.

cal organization, Ramón y Cajal ('11) divided the MG into a ventral, a dorsal, and a medial division. In the cat, these three divisions of the MG have been further divided into subnuclei on the basis of (1) characteristic patterns of cell composition and axonal architecture (Morest, '64, '65; Winer and Morest, '83a,b); (2) distinctive projections from different components of the inferior colliculus (Calford and Aitkin, '83); (3) auditory response properties of single units (Calford, '83); and (4) differential connections with the cerebral cortex (Sousa-Pinto, '73; Andersen et al., '80; Imig and Morel, '84). The organization of the rat MG has only recently begun to receive intensive scrutiny (LeDoux et al., '85, '87; Winer and Larue, '87). LeDoux et al. ('85) have identified four components, the ventral, dorsal, and medial divisions and the suprageniculate nucleus. The ventral division is composed of darkly staining, tightly packed cells, and it extends through the entire length of the medial geniculate body from caudal to rostral. The dorsal division is situated directly above the ventral nucleus and is distinguished from the latter by a lower packing density of its cells. The medial division (the magnocellular nucleus of earlier anatomists) is most prominent at caudal and intermediate levels of the MG and is located medial to the ventral division; it contains large, darkly staining cell bodies, and the packing density of its cells is lower than in the ventral division. The suprageniculate nucleus is located dorsal to the medial division and medial to the dorsal division; its cells are relatively large and are elongated in the dorsoventral plane. According to LeDoux et al. ('75), the ventral and medial divisions receive afferents from the central nucleus of the inferior colliculus, the principal relay station in the auditory pathway. The peripheral components of the inferior colliculus, the dorsal cortex, and the external nucleus project to each division of the MG. Convergent projection from the spinal cord was noted to the medial division of the MG, to parts of the dorsal division, and to adjacent areas (LeDoux et al., '87). The studies of Winer and Larue ('87) concern reciprocal connections between the MG and the cortex. The heaviest corticofugal input is indicated for the ventral division of the MG; the dorsal division is intermediate; and the medial division receives the least. These observations suggest that the fundamental organization of the rat MG is similar to that of the cat.

There are few studies currently available that have dealt with the neurogenesis of the MG. McAllister and Das ('77) found that the neurons of the rat MG are generated between days E13 and E15, and they noted a slight caudal-to-rostral and lateral-to-medial neurogenetic gradient within the structure. In our previous study of thalamic neurogenesis (Altman and Bayer, '79), we found that the peak production of MG neurons occurs on day E14 but noted that neurogenesis in the medial nucleus was still pronounced on day E15.

MATERIALS AND METHODS

The material examined in this study was identical with that described in detail in the first paper of the series (Altman and Bayer, '88). We made particular use of three collections. (1) Short-survival thymidine radiograms were used to locate the neuroepithelial site of origin of neurons of the MG. This series consists of 94 paraffin- or methacrylate-embedded embryos whose mothers were injected with a single dose of ^{3}H-thymidine on successive days extending from E12 to E21 and who were killed 2 hours after injection. The number of specimens examined in the relevant injection groups ranged from six to 12. (2) Sequential-survival radiograms were examined to trace the migratory path of MG neurons. This series consists of 254 paraffin- or methacrylate-embedded embryos or fetuses that received ^{3}H-thymidine between days E12 and E21 and were killed at daily intervals after the injection up to postnatal day 5 (P5). A minimum of six specimens were examined in every relevant survival group. (3) The long-survival series consists of 44 paraffin-embedded brains of P5 rats whose mothers were injected with two successive daily doses of ^{3}H-thymidine, with a single-day delay between the groups, on gestational days E13+E14, E14+E15 . . . and E18+E19. The data from six to eight pups in every relevant injection group were used for the quantification of the birth dates of neurons in subdivisions of the MG with special reference to intranuclear gradients. Details of the quantification procedures and statistical methods were presented in the first paper of the series (Altman and Bayer, '88), and a shorter description is provided in the preceding paper (Altman and Bayer, '89).

RESULTS

The time of origin of neurons of the medial geniculate body

Delineation of the medial geniculate body. Figure 1 illustrates the location and subdivisions of the rat MG in slightly assymetrical coronal sections stained for myelinated fibers. Although the identification of the MG poses no difficulties posteriorly (Fig. 1C, left side), its boundaries are less obvious anteriorly. We have used the brachium of the inferior colliculus (BIC on the right side at all levels, and on the left side in Fig. 1C) to delineate the MG from more medially placed brain structures, and from the ventrobasal nucleus, with which it merges imperceptibly anteriorly. The brachium of the inferior colliculus, which forms a convex curve with respect to the midline, is considered the inner boundary of the MG, whereas the more anteriorly situated medial lemniscus (ML in Fig. 1A,B on the left side), which forms a concave curve with respect to the midline, is considered the external boundary of the ventrobasal nucleus (VB in Fig. 1A,B). The dorsal and ventral divisions of the MG (MGD and MGV) are easily distinguished at caudal levels. The medial division (MGM), adjacent to and partially embedded in the brachium of the inferior colliculus, is recognizable through the entire extent of the MG.

Qualitative observations. In day P5 rats cumulatively labeled with ^{3}H-thymidine on days E13+E14, all the cells of the MG are labeled but there are regional differences in the proportion of heavily labeled cells. Through the entire central segment (largest extent) of the MG (Fig. 2A–C), the heavily labeled cells are concentrated in two clusters (CD and CV) in the lateral aspect of the dorsal and ventral divisions (MGD, MGV). The more medially situated cells of the central segment, and those of the medial division (MGM), contain a smaller proportion of heavily labeled cells. In rats labeled on days E15+E16 (Fig. 3), the cells situated laterally are no longer labeled in the dorsal and ventral clusters, but a high proportion of heavily labeled cells are still present more medially. These observations indicate a lateral (older) to medial (younger) neurogenetic gradient within the MG. In addition, a neurogenetic gradient was also evident from the caudal to the rostral pole of the MG (not shown).

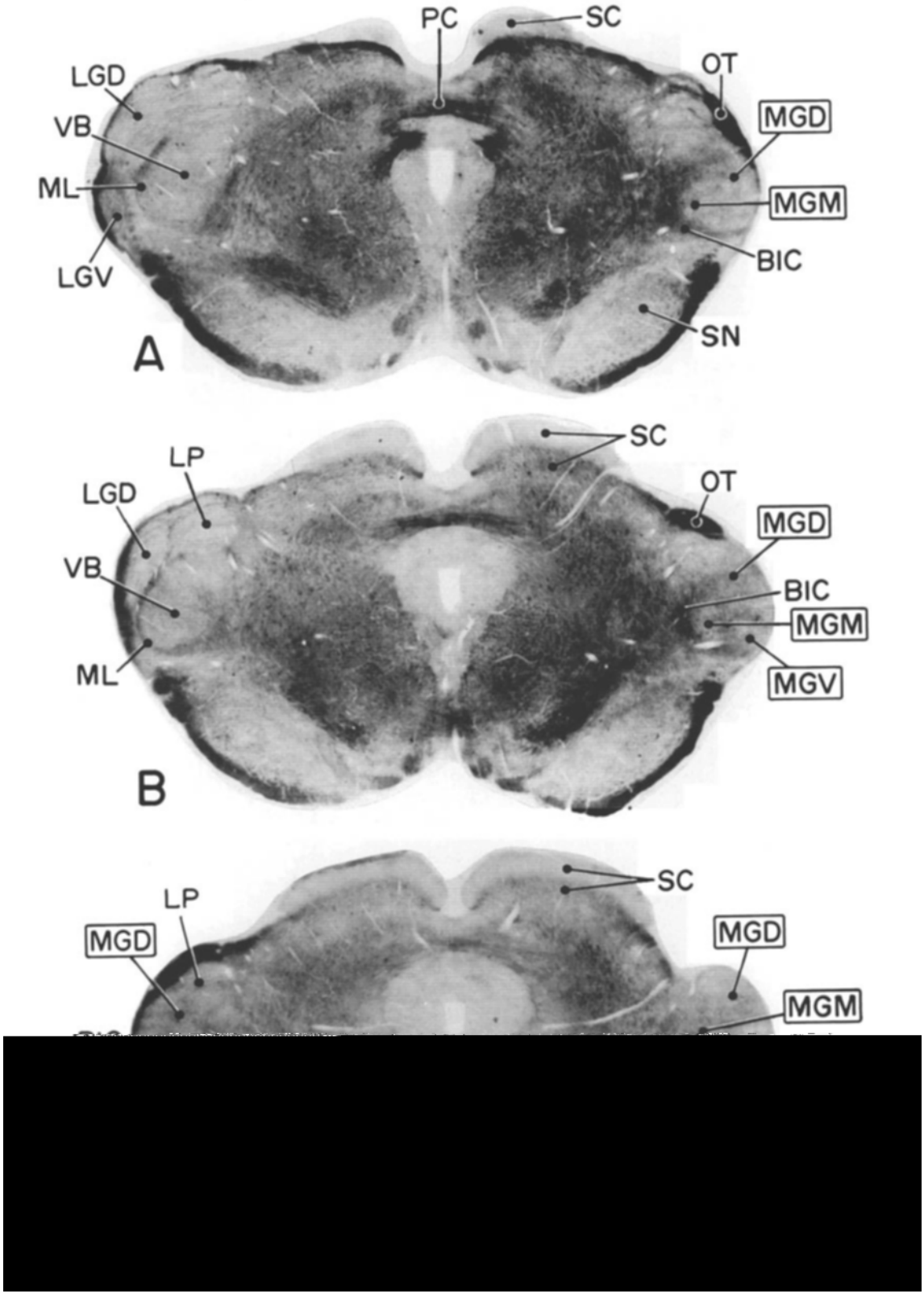

Fig. 1. Location and subdivisions of the medial geniculate body in coronal thick (50 μm) sections from rostral (A) to caudal (C) in an adult rat. Frozen section, Weigert-Pal. Scale: 1,000 μm.

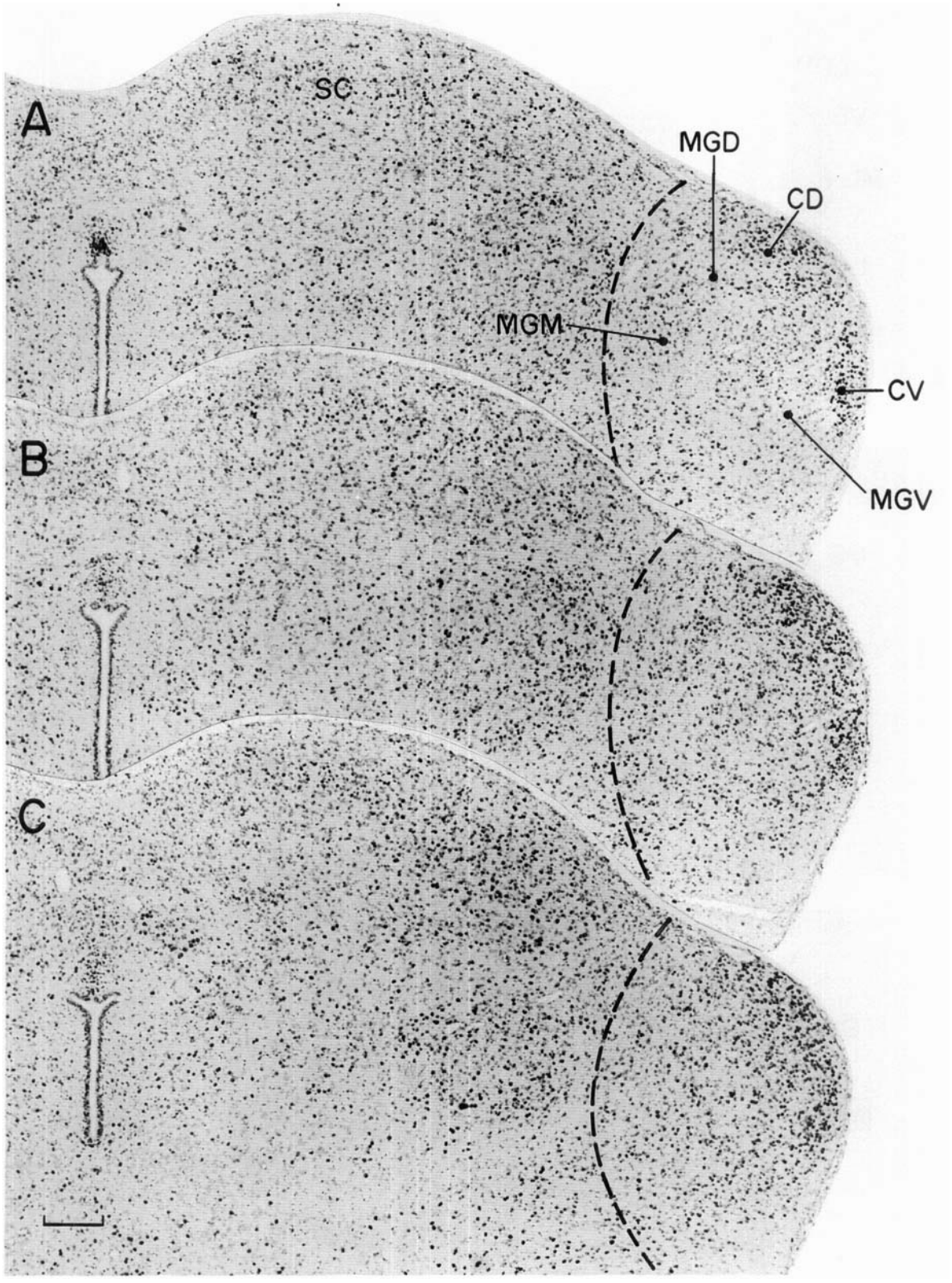

Fig. 2. Coronal radiograms of the central segment (level 2) of the MG (broken lines), from rostral (**A**) to caudal (**C**), from a P5 rat labeled with ^{3}H-thymidine on days E13+E14. Paraffin, H&E. Scale: 200 μm.

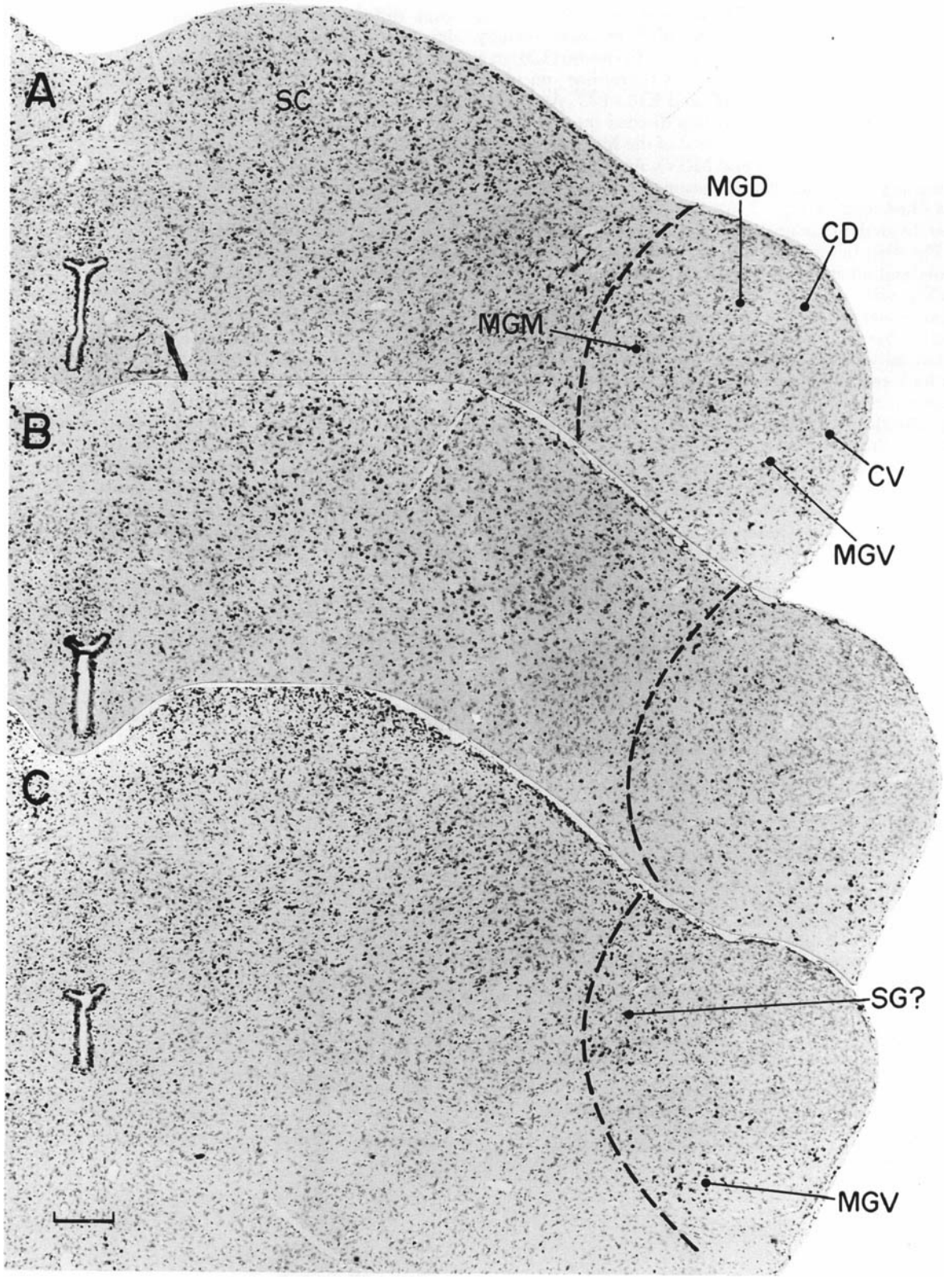

Fig. 3. Coronal thymidine radiograms of the central segment (level 2) of the MG, from rostral (A) to caudal (C), from a rat labeled on days E15+E16. Paraffin, H&E. Scale: 200 μm.

Quantitative results. The proportion of labeled and unlabeled MG neurons was quantified at three equally spaced coronal levels, from rostral (L1) to caudal (L3), in a total of 29 rats that received ^{3}H-thymidine on days E13+E14, E14+E15, E15+E16, and E16+E17. At all levels, the medial division (MGM) was divided into an upper, middle, and lower third, and the rest of the MG into a dorsal and ventral division (MGD and MGV). At level 2 (Fig. 4B), representing the large central segment of the MG (the region illustrated in Figs. 2, 3), the MGD and MGV were further divided into lateral and intermediate halves (LS and IS in Fig. 4B). In addition, the precocious dorsolateral and ventrolateral clusters were separately quantified (CD and CV in Fig. 4B).

In the presentation of the quantitative results we are combining the data of those components in which neurogenesis is statistically simultaneous and are using new descriptive terms for those parts of the MG which can be distinguished as discrete chronoarchitectonic units. There were no statistically significant differences between the upper, middle, and lower thirds of the medial division. Therefore, this region is represented as one chronoarchitectonic unit, the medial shell (MS in Fig. 5A). There were no neurogenetic differences at any level between the dorsal and ventral divisions of the MG; these data were also combined (MGD+MGV in Figs. 4A, 6A). However, at level 2 significant differences were obtained between the lateral and intermediate halves of the MGD+MGV; these are, therefore, distinguished as the lateral and intermediate shells (LS and IS in Fig. 4A). Finally, as there were no significant differences between the dorsolateral and ventrolateral clusters, the data from these two regions were also combined (CD+CV in Fig. 4A).

At L2, the neurons of the two lateral clusters (CD+CV, bottom graph in Fig. 4B) are born significantly ahead of the neurons of the rest of the lateral shell ($p < .001$). This is the only region where a fair proportion of MG neurons (19%) are generated on day E13. Second in chronological order is the lateral shell (LS, center graph), where the bulk of the neurons originate on day E14. The intermediate shell is next (IS, top graph), with 13% of its neurons generated on day E15 ($p < .001$, with respect to LS). At L1 and L3, a numerically small but highly significant ($p < .0001$) caudal-to-rostral gradient was obtained in the lateral portion of the MG (combined data of MGD+MGV in Fig. 5A). Finally, the youngest MG neurons are located throughout the MG in the medial shell (MS), with a fair proportion of them generated on day 15 (Fig. 6A). There was again a prominent caudal-to-rostral gradient. Rostrally, 33% of the medial shell neurons are generated on day E15 (L1, top graph in Fig. 6A), but caudally, only 19% (L3, bottom graph). The difference was highly significant ($p < .0001$).

Abbreviations

(Abbreviations in capital letters refer to mature structures; capital letters followed by m refer to the migratory streams of a structure; letters in lowercase refer to the putative cell lines of a particular structure in the neuroepithelium.)

AQ	aqueduct
ar	arcuate (hypothalamic) neuroepithelium
BIC	brachium of the inferior colliculus
CD	dorsal cluster of medial geniculate body
CP	cerebral peduncle
CV	ventral cluster of medial geniculate body
HP	habenulopeduncular tract
IS	intermediate shell of medial geniculate body
lgd	dorsal lateral geniculate neuroepithelium
LGD	dorsal lateral geniculate nucleus
LGDm	dorsal lateral geniculate migratory stream
lgv	ventral lateral geniculate neuroepithelium
LGV	ventral lateral geniculate nucleus
LGVm	ventral lateral geniculate migratory stream
LP	lateral posterior nucleus
LS	lateral shell of medial geniculate body
mg	medial geniculate neuroepithelium
MG	medial geniculate body
MGD	medial geniculate body, dorsal division
MGDm	medial geniculate, dorsal division migratory stream
MGm	medial geniculate migratory stream
MGM	medial geniculate body, medial division
MGMm	medial geniculate, medial division migratory stream
MGV	medial geniculate body, ventral division
MGVm	medial geniculate, ventral division migratory stream
ML	medial lemniscus
MS	mesencephalon
OT	optic tract
PC	posterior commissure
prt	pretectal neuroepithelium
PRT	pretectum
SC	superior colliculus
SG	suprageniculate nucleus
sn	substantia nigra neuroepithelium
SN	substantia nigra
SNm	substantia nigra migratory stream
VB	ventrobasal nucleus
v3d	third ventricle, dorsal (thalamic)
v3v	third ventricle, ventral (hypothalamic)

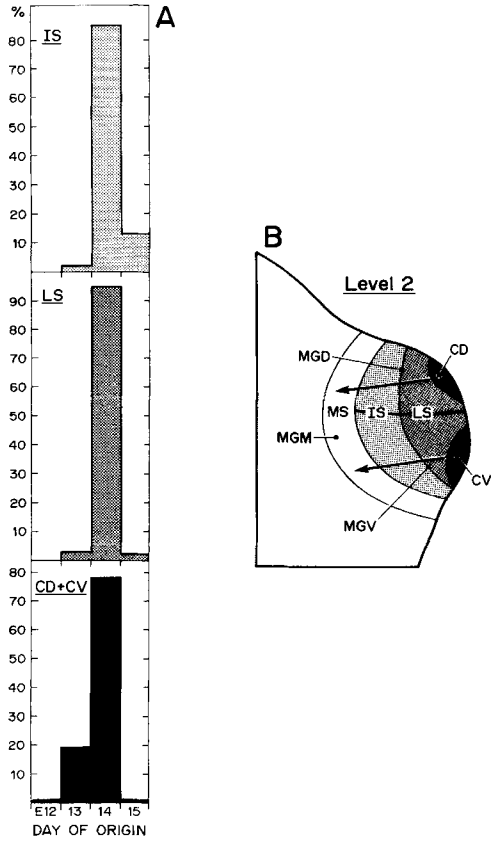

Fig. 4. **A:** Time of origin of neurons in three chronoarchitectonic divisions of the MG, the dorsolateral and ventrolateral clusters (CD+CV), the lateral shell, and the intermediate shell. **B:** Schematic illustration of the chronoarchitectonic parcellation of the MG in relation to current cytoarchitectonic divisions (MGD, MGM, MGV).

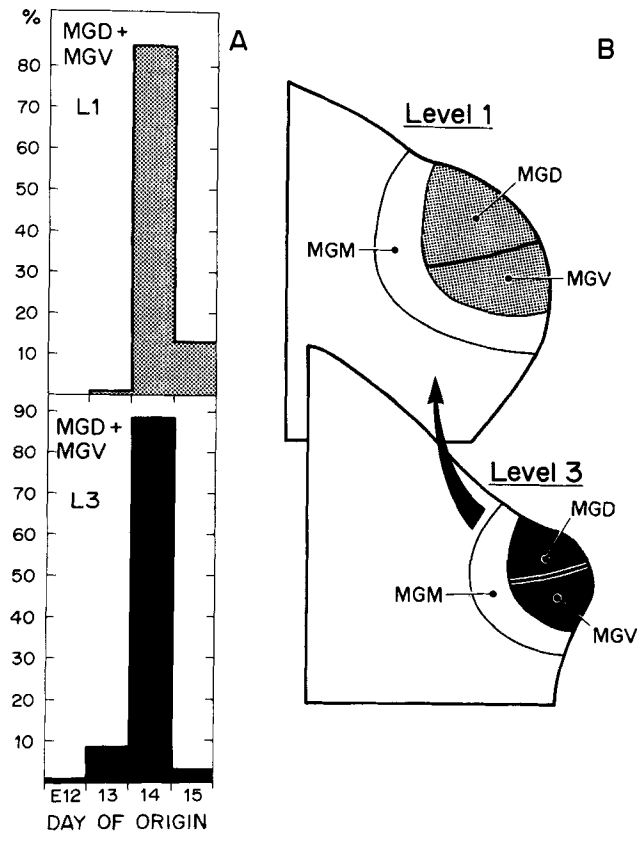

Fig. 5. **A:** Time of origin of neurons of the combined dorsal and ventral divisions (MGD + MGV) of the lateral MG at rostral (L1) and caudal (L3) levels. **B:** Schematic illustration of the two poles of MG at the levels counted; the caudal-to-rostral gradient is indicated by the arrow.

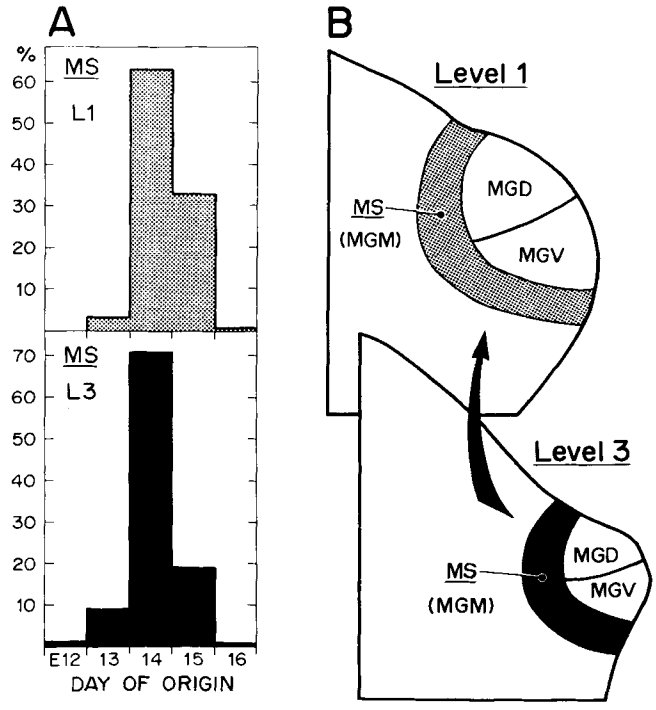

Fig. 6. **A:** Time of origin of neurons in the medial shell of the MG (MS) at rostral (L1) and caudal (L3) levels. **B:** Schematic illustration of the medial shell, or medial division (MGM), at the two levels where the counts were made; the caudal-to-rostral neurogenetic gradient is indicated by the arrow.

In summary, these results indicate that peak production of neurons throughout the MG is on day E14 but there are significant intranuclear neurogenetic gradients. In the central portion of the MG a lateral-to-medial gradient distinguishes (1) two early forming lateral clusters, (2) a lateral shell and (3) an intermediate shell, and throughout the MG, (4) the medial shell contains the youngest neurons. A caudal-to-rostral gradient was indicated both for the lateral portion of the MG and for the medial shell.

The site of origin and migration of neurons of the medial geniculate body

Sequential radiograms from rats labeled on day E14. In the introductory paper of this series we have identified in short-survival radiograms from day E15 rats a caudally situated thalamic neuroepithelial eversion as the putative source of neurons of the MG (Figs. 14C,D, 17A,B in Altman and Bayer, '88). Support for this identification is presented in this section by examining sequential radiograms from rats labeled with ^{3}H-thymidine on day E14 and killed on successive days.

The putative source of MG neurons is illustrated in serially sectioned radiograms from rostral (Fig. 7A) to caudal (Fig. 7B) in a rat labeled with thymidine on day E14 and killed on day E15. In this plane of sectioning the MG neuroepithelial eversion (mg) is situated beneath the putative ventral lateral geniculate inversion (lgv). Flanking the MG neuroepithelium are two migratory zones, one consisting mostly of labeled cells and another mostly of unlabeled cells. The labeled migratory zone adjacent to the neuroepithelium is interpreted to be composed predominantly of cells generated *after* the morning of day E14 (the time of injection); it is designated as a late wave component of the MG migration (MGm2 in Fig. 7A,B). The laterally situated, mostly unlabeled migratory zone is interpreted to be composed predominantly of cells generated *before* the morning of day E14; it is designated as the early wave component of the MG migration (MGm1). The putative MG neuroepithelium and its two migratory components (MGm1, MGm2) are illustrated at higher magnification in Figure 7C.

The migrating neurons of the MG apparently become translocated within the expanding thalamus in a caudal direction. This is illustrated in coronal radiograms from rats labeled on day E14 and killed on day E17 (Fig. 8). Whereas on day E15, the bulk of the MG migration (MGm1, MGm2) is situated rostrally at the level of the third ventricle (v3d in Fig. 7A,B), by day E17 the settling MG neurons have become translocated caudally lateral to the aqueduct (MG, AQ in Fig. 8).

Sequential radiograms from rats labeled on day E15. Day E15 is the terminal day in the generation of MG neurons. Only a negligible proportion of the cells of the dorsal and ventral clusters (CD + CV in Fig. 4A) and of the lateral shell (LS in Fig. 4A) are generated on this day. However, a fair proportion of the cells of the intermediate shell (IS in Fig. 4A) and 33% of the neurons in the rostral portion of the medial division (MS, L1 in Fig. 6A) originate on day

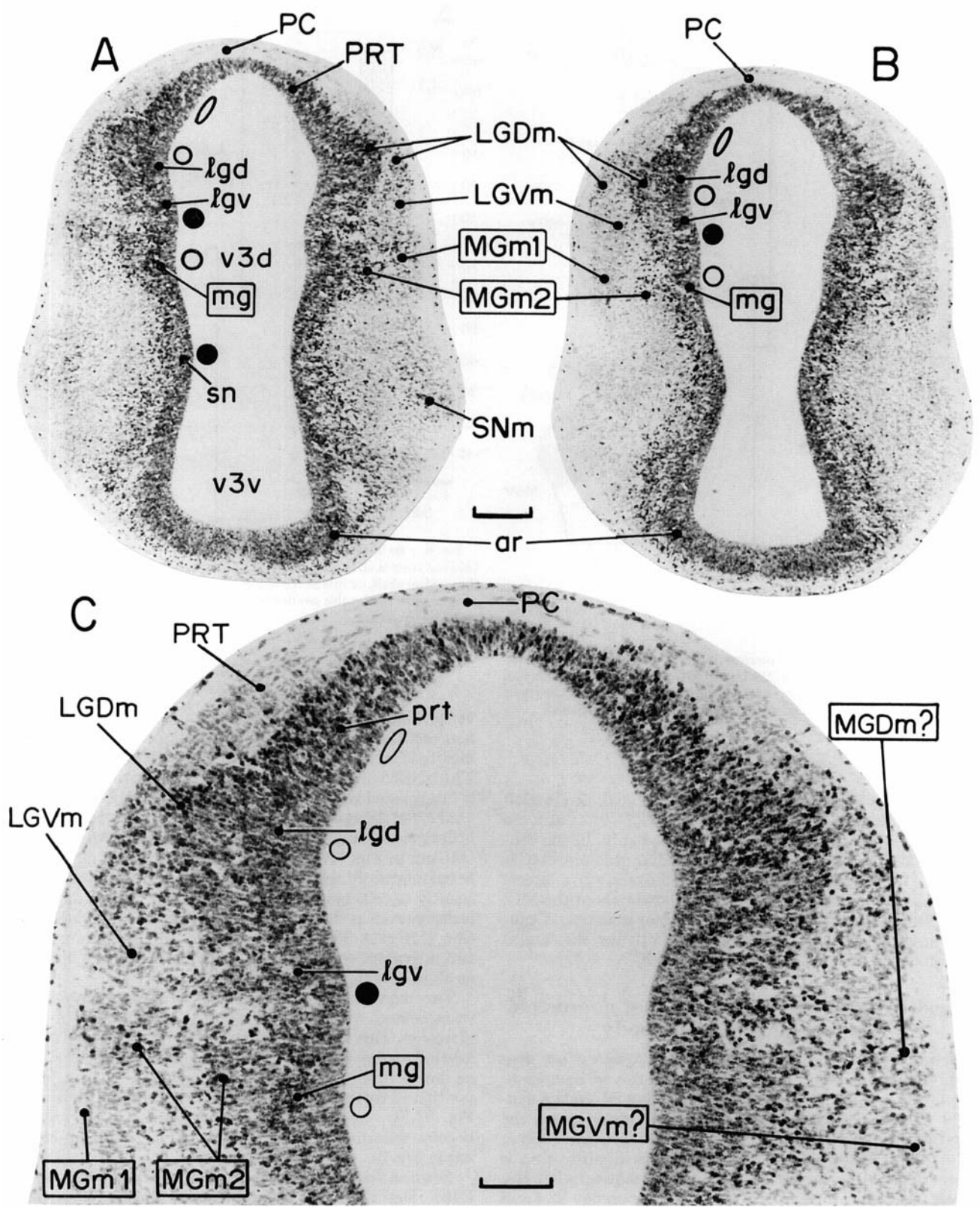

Fig. 7. Coronal radiograms, through the posterior thalamus, from rostral (A) to caudal (B), from a rat labeled on day E14 and killed 24 hours later. C: Higher magnification of A. In this and all the subsequent figures, open circles indicate neuroepithelial eversions (concavities) and solid circles indicate inversions (convexities). Paraffin, H&E. Scales: A,B, 200 μm; C, 100 μm.

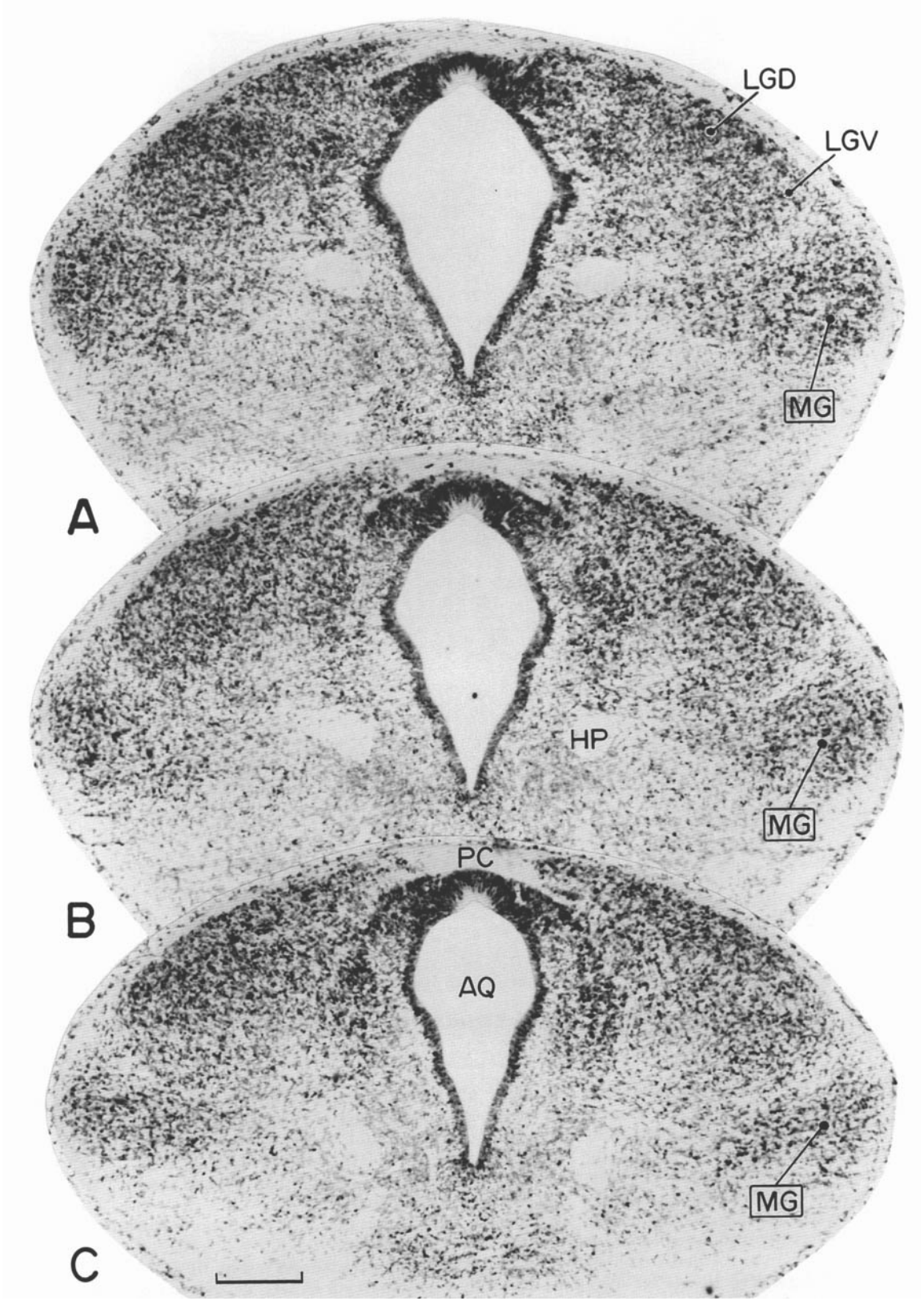

Fig. 8. Coronal radiograms, from rostral (A) to caudal (C), from a rat labeled on day E14 and killed on day E17. Paraffin. H&E. Scale: 200 μm.

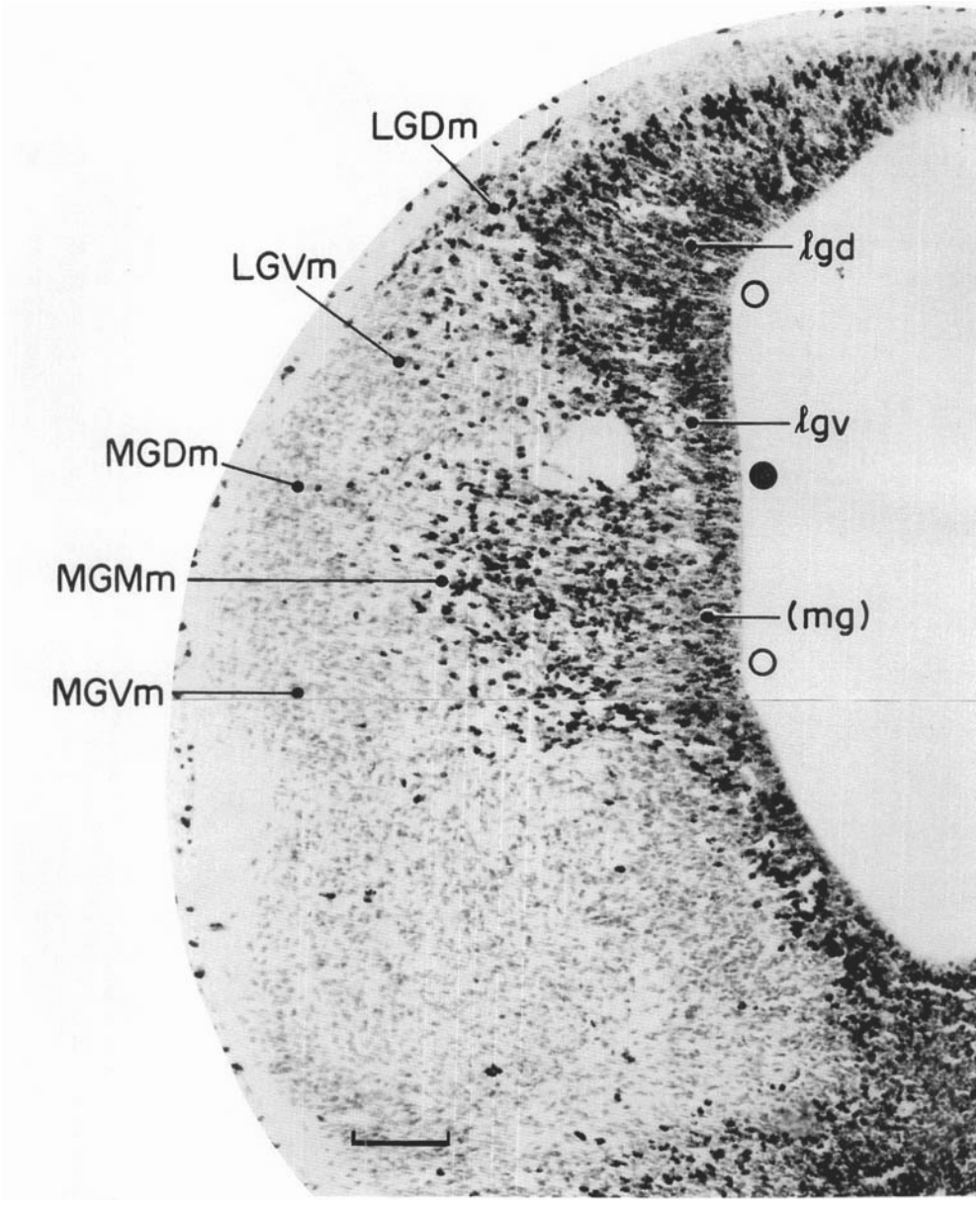

Fig. 9. Coronal radiogram from a rat labeled on day E15 and killed on day E16. Paraffin, H&E. Scale: 100 μm.

E15. The migration of MG neurons generated on day E15 (identified as the heavily labeled wave front apparently issuing from the putative MG neuroepithelium) is illustrated at high power in Figure 9. The bulk of the putative MG migration is unlabeled (MGDm, MGVm), but there is a heavily labeled wave front more medially, and this is designated as the putative migration of the medial division (MGMm). This migration is traced in sequential radiograms from rats labeled on day E15 and killed 1 day (Fig. 10A), 2 days (Fig. 10B), and 3 days (Fig. 10C) after injection. The wave of heavily labeled cells is limited to the vicinity of the neuroepithelium on day E16 (broken lines on the right in Fig. 10A) but expands in a lateral direction on days E17 (broken lines in Fig. 10B) and E18 (broken lines in Fig. 10C). On the basis of the quantitative evidence that the bulk of the neurons generated on day E15 settle in the medial shell, the leading edge of this wave is designated as the migration of the medial division of the MG (MGMm in Figs. 10B,C, 11). By day E18, the cells forming the medial division begin to form a semicircular halo around the unlabeled core of the MG (MGMm in Fig. 11).

The former putative MG neuroepithelium remains active in rats labeled on day E15 and killed on days E16, E17, and E18 (mg in parentheses in Fig. 10A–C). Because only a negligible proportion of MG neurons are produced on day E16 (MS in Fig. 6A), and none on the subsequent days, we presume that this active neuroepithelial patch occupying the site of the former MG neuroepithelium (mg in parentheses) is generating neurons for younger structures flanking the MG medially.

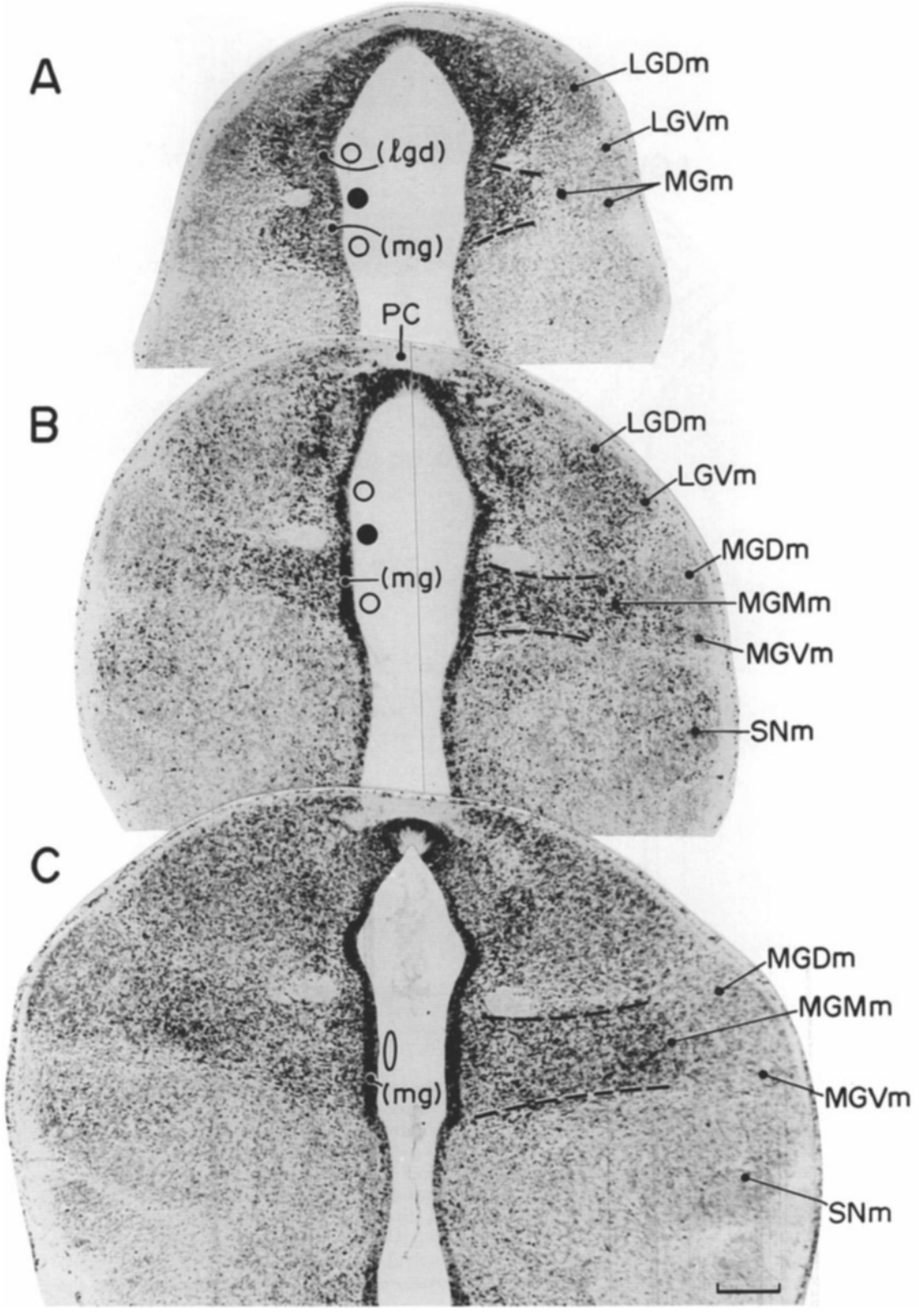

Fig. 10. Sequential coronal radiograms from rats labeled on day E15 and killed on day E16 (**A**), day E17 (**B**), and day E18 (**C**). Broken lines indicate the outflow of cells from the former site of origin of MG neurons (mg in parentheses). Paraffin, H&E. Scale: 200 μm.

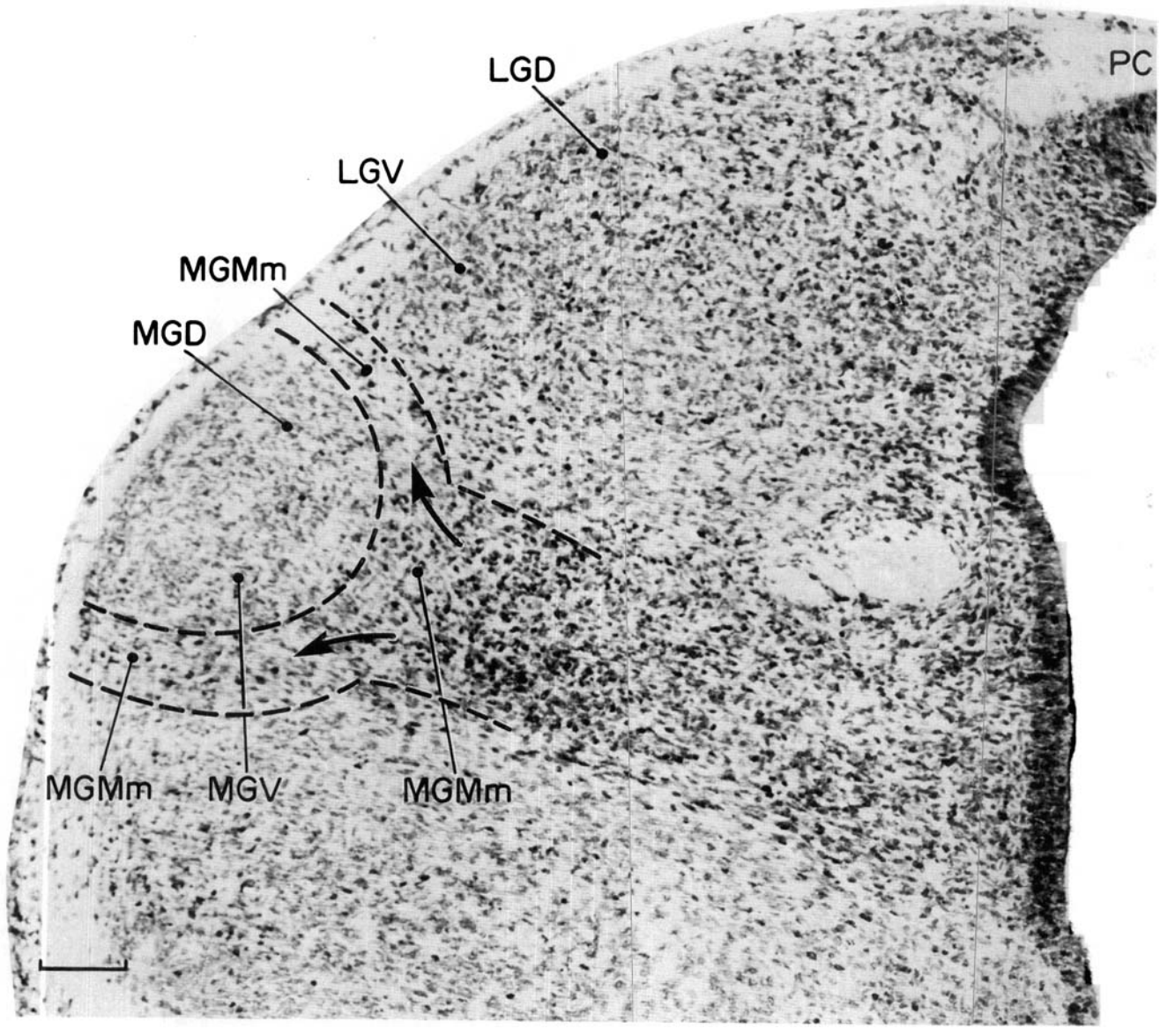

Fig. 11. Coronal radiogram from a rat labeled on day E15 and killed on day E18. Broken lines and arrows indicate the apparent migration of cells to the medial division of the MG. Paraffin, H&E. Scale: 100 μm.

DISCUSSION

Identification of the putative medial geniculate neuroepithelium

In the introductory paper of this series (Altman and Bayer, '88), we divided the caudal lobe of the thalamic neuroepithelium in day E14 rats into an intermediate and a posterior lobule and distinguished within the posterior lobule several sublobules. We proposed that these germinal sublobules constitute, from dorsal to ventral, the putative sources of neurons, or neuroepithelial mosaics, of the dorsal lateral geniculate, ventral lateral geniculate, and medial geniculate nuclei (Figs. 6, 24 in Altman and Bayer, '88). We have used two criteria for these initial identifications: (1) differences in the time of origin of neurons in these three thalamic structures, as determined quantitatively with long-survival thymidine radiography, and (2) qualitative differences in the labeling pattern of the neuroepithelial sublobules in short-survival radiograms. Quantitative examination of long-survival thymidine radiograms established that the neurons of the MG are generated first, the neurons of the ventral lateral geniculate nucleus next, and the neurons of the dorsal lateral geniculate nucleus last (Fig. 13 in Altman and Bayer, '88). This order reflects a combined ventral-to-dorsal and caudal-to-rostral internuclear neurogenetic gradient. We then recognized in short-survival radiograms of day E15 rats (e.g., Fig. 14D in Altman and Bayer, '88) a posteroventrally situated everted sublobule of the posterior neuroepithelial lobe, one that is distinguished from the other sublobules by being surrounded by the most extensive zone of unlabeled cells (that is, cells generated on day E14 or earlier). We hypothesized this sublobule as the

putative source of neurons of the early generated MG. In the present study we present supporting evidence for this identification by using sequential-survival radiograms to trace migrating neurons from the putative MG neuroepithelium to their target. The migration of neurons is indicated, in sequential-survival radiograms from a group of embryos labeled both on day E14 and day E15, by the successive displacement of unlabeled and labeled wave fronts of neurons in a lateral and caudal direction.

The germinal site identified as the putative MG neuroepithelium does not disappear for several days after the generation of MG neurons has come to an end. This neuroepithelial patch remains active through day E16 (Fig. 10A), to day E18 (Figs. 10C, 11). Its relation to the MG is suggested by the outflow of neurons along the same path as taken earlier by the MG neurons (Fig. 7). The identity of this system remains to be determined, but it is tempting to speculate that its neurons constitute the auditory component of the "shell" (Berkley, '80) or "lemniscal adjunct system" (Graybiel, '73) that has been postulated to surround the principal relay nuclei of the thalamus of cats and monkeys.

Chronoarchitectonics of the medial geniculate body

We have examined the differences in the birth dates of neurons within the MG with reference to its different structural and functional divisions. The quantitative results indicated statistically significant lateral-to-medial and caudal-to-rostral neurogenetic gradients. These intranuclear gradients partially overlap with the divisions based on structural and functional considerations (briefly reviewed in the beginning of this paper) but do not fully match it. The earliest neurons of the MG form two lateral cell aggregates; we have named these the dorsal (dorsolateral) and ventral (ventrolateral) clusters (Figs. 2–4). The subsequently generated neurons form crescent-shaped shells from lateral to medial, and we have referred to these as the lateral, intermediate, and medial shells. We did not obtain a neurogenetic gradient in the dorsoventral plane and thus could not distinguish, in terms of chronoarchitectonics, the ventral and dorsal divisions of the MG. The latest-generated medial shell is identical with the medial division of the MG (MGM in Figs. 3, 6). In the available material we could not examine the question of whether or not the different cell types of the MG are generated at different embryonic ages.

The temporal order of neurogenesis in the auditory pathway

In previous studies we have found pronounced differences in the birth dates of neurons in the various nuclei of the auditory pathway and consistent intranuclear neurogenetic gradients within several of these nuclei. The auditory sensory neurons of the spiral ganglion are generated between days E12 and E14, with a peak on day E13 (Altman and Bayer, '82). Neurons of the different medullary components of the auditory system are generated at different times, ranging from a peak on day E12 in the lateral trapezoid nucleus to a peak on day E16 in the lateral superior olivary nucleus (Fig. 13 in Altman and Bayer, '80; Fig. 7 in Altman and Bayer, '81). Even though the peak production time of auditory sensory neurons in the spiral ganglion (day E13) antedates the peak production of MG neurons (day E14), we must rule out an anterograde inductive influence on *neurogenesis* at successive levels of the auditory pathway because the principal relay structures between the spiral ganglion and the thalamus are generated *after* the production of MG neurons has practically ended. Peak production of neurons of the cochlear nucleus is on day E16 (Fig. 7 in Altman and Bayer, '80), and neurogenesis in different components of the inferior colliculus, which are the major source of afferents to the MG, ranges between days E16 and E19 (Fig. 5 in Altman and Bayer, '81). This evidence does not rule out possible anterograde organizing influence on the establishment of the *circuitry* of the auditory system, because the outgrowth of axons in most structures probably starts after the young neurons, following different courses, have settled in their terminal positions.

ACKNOWLEDGMENTS

This research program is supported by a grant from the National Science Foundation (to J.A.) and from the National Institutes of Health (to S.A.B.). We are grateful for the technical assistance of Julie Henderson, Mark O'Neil, Kathy Shuster, Robert Werberig, and Linda Wiesenauer.

LITERATURE CITED

Altman, J., and S.A. Bayer (1979) Development of the diencephalon in the rat: IV. Quantitative study of the time of origin of neurons and the internuclear chronological gradients in the thalamus. J. Comp. Neurol. *188*:455–472.

Altman, J., and S.A. Bayer (1980) Development of the brain stem in the rat: III. Thymidine-radiographic study of the time of origin of neurons of the vestibular and auditory nuclei of the upper medulla. J. Comp. Neurol. *194*:877–904.

Altman, J., and S.A. Bayer (1981) Time of origin of neurons of the rat inferior colliculus and the relations between cytogenesis and tonotopic order in the auditory pathway. Exp. Brain Res. *42*:411–423.

Altman, J., and S.A. Bayer (1982) Development of the Cranial Nerve Ganglia and Related Nuclei in the Rat. In Adv. Anat. Embryol. Cell Biol. Berlin: Springer, Vol. 74, pp. 1–90.

Altman, J., and S.A. Bayer (1988) Development of the rat thalamus: I. Mosaic organization of the thalamic neuroepithelium. J. Comp. Neurol. *275*:346–377.

Altman, J., and S.A. Bayer (1989a) Development of the rat thalamus: IV. The intermediate lobule of the thalamic neuroepithelium, and the time and site of origin and settling pattern of neurons of the ventral nuclear complex. J. Comp. Neurol. *284*:534–563.

Altman, J., and S.A. Bayer (1989b) Development of the rat thalamus: VI. The posterior lobule of the thalamic neuroepithelium, and the time and site of origin and settling pattern of neurons of the lateral geniculate and lateral posterior nuclei. J. Comp. Neurol. *284*:578–598.

Andersen, R.A., P.L. Knight, and M.M. Merzenich (1980) The thalamocortical and corticothalamic connections of AI, AII, and the anterior auditory field (AAF) in the cat: Evidence for two largely segregated systems of connections. J. Comp. Neurol. *194*:663–701.

Berkley, K.J. (1980) Spatial relationships between the terminations of somatic sensory and motor pathways in the rostral brainstem of cats and monkeys. I. Ascending somatic sensory inputs to lateral diencephalon. J. Comp. Neurol. *193*:283–317.

Calford, M.B. (1983) The parcellation of the medial geniculate body of the cat defined by the auditory response properties of single neurons. J. Neurosci. *3*:2350–2364.

Calford, M.B., and L.M. Aitkin (1983) Ascending projections to the medial geniculate body of the cat: Evidence for multiple, parallel auditory pathways through thalamus. J. Neurosci. *3*:2365–2380.

Graybiel, A.M. (1973) The thalamo-cortical projection of the so-called posterior nuclear group: A study with anterograde degeneration methods in the cat. Brain Res. *49*:229–244.

Imig, T.J., and A. Morel (1984) Topographic and cytoarchitectonic organization of thalamic neurons related to their targets in low-, middle-, and high-frequency representations in cat auditory cortex. J. Comp. Neurol. *227*:511–539.

LeDoux, J.E., D.A. Ruggiero, and D.J. Reis (1985) Projections to the subcorti-

cal forebrain from anatomically defined regions of the medial geniculate body in the rat. J. Comp. Neurol. *242*:182–213.

LeDoux, J.E., D.A. Ruggiero, R. Forest, R. Stornetta, and D.J. Reis (1987) Topographic organization of convergent projections to the thalamus from the inferior colliculus and spinal cord in the rat. J. Comp. Neurol. *264*:123–146.

McAllister, J.P., and G.D. Das (1977) Neurogenesis in the epithalamus, dorsal thalamus and ventral thalamus of the rat: An autoradiographic and cytological study. J. Comp. Neurol. *172*:647–686.

Morest, D.K. (1964) The neuronal architecture of the medial geniculate body of the cat. J. Anat. (Lond.) *98*:611–630.

Morest, D.K. (1965) The laminar structure of the medial geniculate body of the cat. J. Anat. (Lond.) *99*:143–160.

Ramón y Cajal, S. (1911) Histologie du Système Nerveux de l'Homme et des Vertébrés. (2 vols.) Paris: Maloine.

Sousa-Pinto, A. (1973) Cortical projections of the medial geniculate body in the cat. Adv. Anat. Embryol. Cell Biol. *48*:1–42.

Winer, J.A., and D.T. Larue (1987) Patterns of reciprocity in auditory thalamocortical and corticothalamic connections: Study with horseradish peroxidase and autoradiographic methods in the rat medial geniculate body. J. Comp. Neurol. *257*:282–315.

Winer, J.A., and D.K. Morest (1983a) The medial division of the medial geniculate body of the cat: Implications for thalamic organization. J. Neurosci. *3*:2629–2651.

Winer, J.A., and D.K. Morest (1983b) The neuronal architecture of the dorsal division of the medial geniculate body of the cat. A study with the rapid Golgi method. J. Comp. Neurol. *221*:1–30.