



Discover Generics

Cost-Effective CT & MRI Contrast Agents



WATCH VIDEO

AJNR

The normal and abnormal genu of the corpus callosum: an evolutionary, embryologic, anatomic, and MR analysis.

E L Kier and C L Truwit

AJNR Am J Neuroradiol 1996, 17 (9) 1631-1641

<http://www.ajnr.org/content/17/9/1631>

This information is current as of June 9, 2025.

The Normal and Abnormal Genu of the Corpus Callosum: An Evolutionary, Embryologic, Anatomic, and MR Analysis

E. Leon Kier and Charles L. Truwit

PURPOSE: To define the normal and abnormal genu of the corpus callosum by examining its evolution and embryology and by analyzing its normal and abnormal appearance on MR images. **METHODS:** A reference line was drawn from the mamillary body through the anterior commissure and corpus callosum—the MAC line. This line was used to evaluate the genu in adult mammal brains, in human fetal brains, on MR images of 1800 patients with normal corpora callosi, and on MR images of 113 patients with callosal anomalies. **RESULTS:** In primates, increased frontal lobe size is associated with an anteriorly shifted genu. In human fetal development, the anterior body of the corpus callosum develops before the definitive genu. The normal human genu always projects in front of the MAC line. In none of the 113 patients with callosal anomalies was there only a normal genu. **CONCLUSIONS:** The human corpus callosum develops bidirectionally, not from front to back. The MAC line is a useful frame of reference to study the evolution and embryology of the genu and to distinguish the normal from the abnormal genu of the human corpus callosum.

Index terms: Animal studies; Brain, growth and development; Corpus callosum, abnormalities and anomalies; Corpus callosum, anatomy

AJNR Am J Neuroradiol 17:1631–1641, October 1996

The normal sequence of formation of the components of the corpus callosum has a bearing on anomalous development and impacts on the examination of anomalies by magnetic resonance (MR) imaging. Knowledge of the normal developmental sequence permits distinguishing developmental from destructive lesions of the corpus callosum. Correct analysis of anomalies of the corpus callosum depends on precise identification of its components. Before the era of computed tomography (CT), the components of the corpus callosum were not identified

readily. With cross-sectional imaging, the callosal components became visible. With this came interest on the part of neuroradiologists in the embryology of the corpus callosum and, in particular, in the sequence in which its components developed. Many descriptions of the development of the corpus callosum have been published in the neuroradiologic literature since the advent of CT and MR imaging. In general, the corpus callosum has been described as developing in an anterior to posterior direction, starting with the genu, followed by the body, splenium, and finally the rostrum (1–9).

The MR imaging finding of a callosal body without a recognizable genu is not explained by the anterior-to-posterior theory of callosal development. If the genu were the first structure to develop, the body of the corpus callosum could not be present without a genu. As the genu is pivotal in the above-described developmental schema, it was decided to undertake a multiphasic investigation of the genu of the corpus callosum by using anatomic landmarks. It was hypothesized that two ancient and permanent evolutionary and embryologic structures could serve as landmarks to identify and study the

Received January 5, 1996; accepted after revision April 30.

Presented in part at the annual meeting of the Radiological Society of North America, Chicago, Ill, November 1989; at the XIV Symposium Neuroradiologicum, London, England, June 1990; at the annual meeting of the American Society of Neuroradiology, Chicago, Ill, April 1995; and at the annual meeting of the Radiological Society of North America, Chicago, Ill, November 1995.

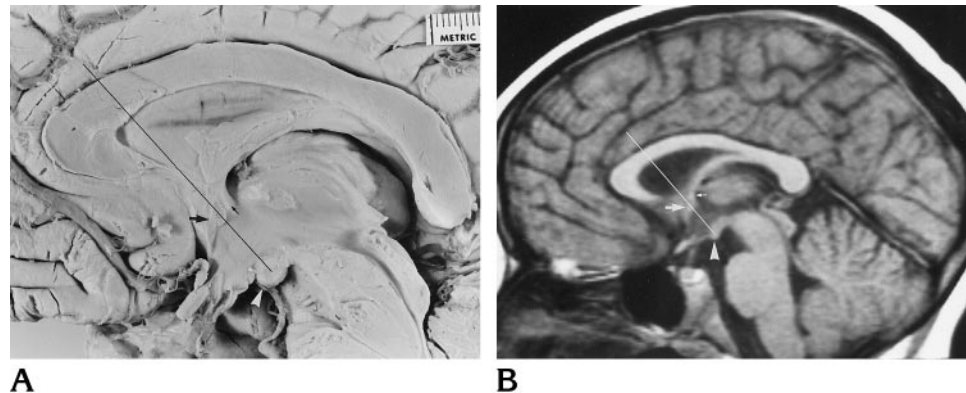
From the Department of Diagnostic Radiology, Yale University School of Medicine, New Haven, Conn (E.L.K.) and the Department of Radiology, University of Minnesota School of Medicine, Minneapolis (C.L.T.).

Address reprint requests to E. Leon Kier, MD, Section of Neuroradiology, Department of Diagnostic Radiology, Yale University School of Medicine, PO Box 208042, New Haven, CT 06520.

AJNR 17:1631–1641, Oct 1996 0195-6108/96/1709–1631

© American Society of Neuroradiology

Fig 1. Photograph of the medial surface of an adult human cerebral hemisphere (A) and T1-weighted sagittal MR image (B) show the MAC line, which is drawn from the mamillary body (arrow-head) through the anterior commissure (large arrow) and corpus callosum. The genu is in front of the MAC line, the body behind it. A small segment of the fornix (small arrow) is seen adjacent to the anterior commissure.



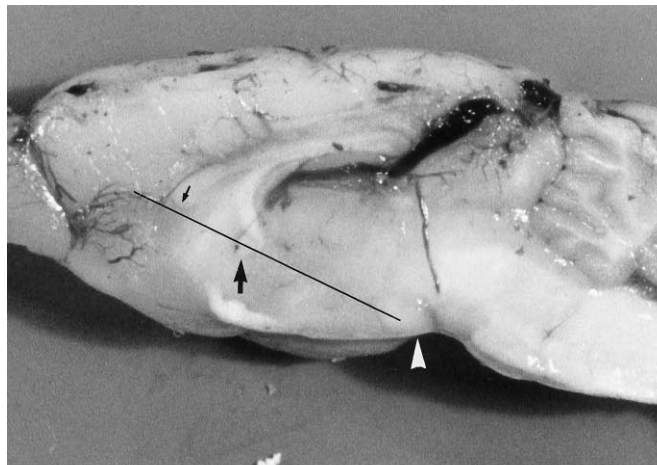
normal and abnormal genu. A line connecting the mamillary body, anterior commissure, and corpus callosum was used as a frame of reference. With the use of this line, the first phase of the investigation examined the evolutionary changes of the genu. After the presentation of the evolutionary material in 1989 (E. L. Kier, "MR Patterns of Corpus Callosum Abnormalities: Phylogenetic Clarification of Current Radiologic Concepts," presented at the annual meeting of the Radiological Society of North America, Chicago, Ill, November 1989), the next two phases of the study were done. The second phase examined the human embryology of the genu. The third phase analyzed MR images of the normal and abnormal corpus callosum.

Materials and Methods

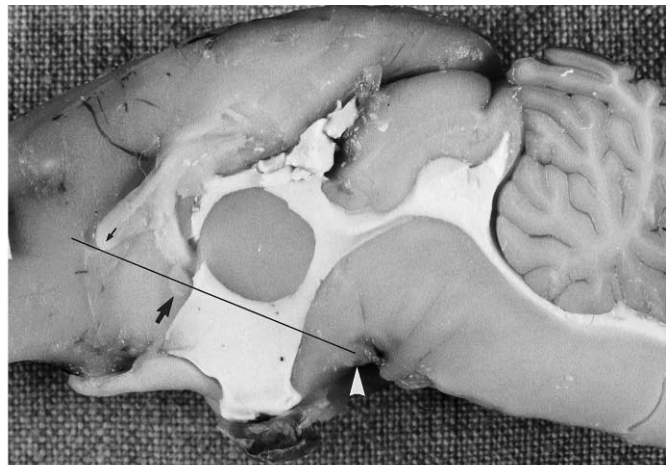
The corpus callosum of adult mammals and normal human fetuses and the normal and abnormal corpora callosi in children and adults were studied by means of dissection and MR imaging. A line connecting the mamillary body and anterior commissure was extended to the corpus callosum. This line was termed the *mamillary body–anterior commissure–corpus callosum line*, or the *MAC line* (Fig 1). The MAC line delineates the region of the genu–body interface in the normal human corpus callosum. The genu is in front of the line and the body of the corpus callosum behind it. The MAC line was established by placing a line on the photographs of the dissected brain specimens. For the MR cases, the line was drawn on the films or generated on the MR scanner console. Sagittal T1-weighted MR images of 1800 patients with a normal corpus callosum were analyzed during a 6-year period using the MAC line to establish the position of the genu of the corpus callosum. Retrospective analysis of sagittal T1-weighted MR images of 113 patients with abnormalities of the corpus callosum was also performed by using the MAC line to determine the presence or absence of a normal genu of the corpus callosum.

The anterior commissure is a compact, vertically oval bundle of myelinated fibers (10). It crosses the midsagittal plane, in the anterior wall of the third ventricle, at the upper end of the lamina terminalis, above the optic chiasm. In the region of the third ventricle, the fornix is just posterior and superior to the anterior commissure. The fornix, near the foramen of Monro, can be identified as a small dot just superior to the anterior commissure (Fig 1). The MAC line was traced through the anterior commissure whenever the fornix could be identified as a separate structure. The mamillary bodies are two rounded structures located side by side on the floor of the third ventricle behind the optic chiasm and tuber cinereum and in front of the posterior perforated substance (11). They are situated at the front end of the interpeduncular fossa.

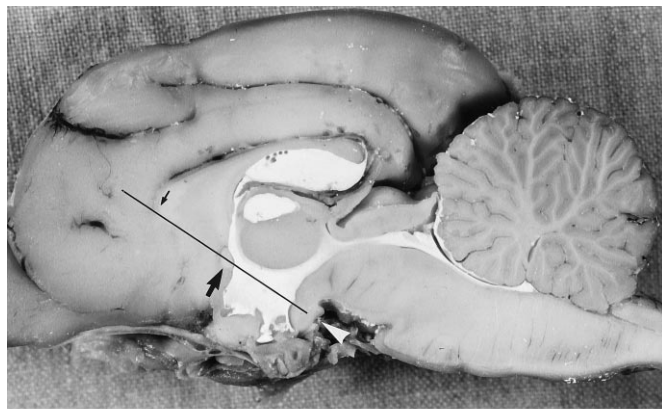
The brains of adult mammals including three rats, three rabbits, three cats, two dogs, two monkeys, and six humans were examined. In some of the adult mammals, the cerebral ventricles were injected before fixation in 10% formaldehyde with a barium gelatin mixture (12). Additionally, brains from eight human fetal specimens ranging from 10 to 30 weeks' gestational age were examined. Fetal age was determined by measuring crown-rump length and occipitofrontal diameter (13, 14). As the tables used for assessing fetal age show a 10- to 20-mm difference between the smallest and largest specimen in each age group, the ages of the specimens may vary by 1 to 2 weeks from their true gestational age. To verify fetal age further, the occipitofrontal diameter of the fetal brains was compared with the occipitofrontal diameter of photographs of fetal brains in the literature (15, 16). The specimens appeared normal and the dissected brains did not show obvious abnormalities. The midsagittal sections were obtained with the brain in situ within the calvaria. The sagittal suture was opened and the superior sagittal sinus, falx, arachnoid, and pia removed by dissection. Sagittal sectioning of the younger fetal heads, done to visualize the corpus callosum, could not be performed with the pia and arachnoid intact in the interhemispheric fissure. The extensive midline venous vasculature had to be dissected away from the interhemispheric fissure, as it was pulled while being sectioned, destroying the underlying corpus callosum. The partially myelinated fetal brain with its high water



A



B



C

Fig 2. Photographs of the medial surface of the brains of a rat (A), a rabbit (B), and a cat (C) show the relationship of the anterior edge of the corpus callosum to the MAC line. In the rat, the anterior edge of the corpus callosum (*small arrow*) is slightly behind the MAC line. In the rabbit and the cat, the anterior edge of the corpus callosum (*small arrow*) is at the MAC line. The mamilary body (*arrowhead*) and anterior commissure (*large arrow*) are also shown.

content does not fix well, even after being preserved in 10% formaldehyde for 20 years. Of the eight specimens (16 cerebral hemispheres), useful dissections were obtained from two hemispheres in fetuses less than 13 weeks old, from three hemispheres in fetuses between 14 and 18 weeks old, and from seven hemispheres in fetuses between 18 and 30 weeks old. Finally, six adult human brains, obtained from the anatomy and pathology departments and fixed in 10% formaldehyde, were examined.

To identify the developing corpus callosum on the medial surface of the cerebral hemisphere, previous studies of human embryology and anatomy were used (11, 14–25). Images of 20 fetuses that were obtained on 1.5-T scanners were compared with the dissections. The specimens that were imaged but not dissected ranged in age from 13 to 30 weeks, as determined by crown-rump length and by occipitofrontal diameter. Images in the sagittal plane were acquired with a three-dimensional spoiled gradient-echo sequence that accentuates T1 weighting. Sagittal T1-weighted MR images of 1800 patients with a normal corpus callosum were analyzed using the MAC line to establish the position of the normal genu of the corpus callosum. These patients, comprising all ages and both sexes, were studied over a 6-year period. Retrospective analysis of

sagittal T1-weighted MR images of 113 patients with abnormalities of the corpus callosum was performed using the MAC line to evaluate the genu and anterior body of the corpus callosum. Initially, 141 patients with abnormalities of the corpus callosum were included in the study; but 28 patients with total absence of the corpus callosum were excluded from the study group.

Results

In the rat, the anterior edge of the corpus callosum is slightly behind the MAC line (Fig 2A). In the rabbit and the cat, the anterior edge of the corpus callosum is at the MAC line (Fig 2B and C). In the dog, the anterior edge of the corpus callosum is slightly anterior to the MAC line (Fig 3A). The cingulate gyrus shows a slight anterior curvature before continuing toward the subcallosal area. In the monkey, the anterior edge of the corpus callosum is far in front of the MAC line and a prominent humanlike genu is present (Fig 3B). The cingulate gyrus shows a

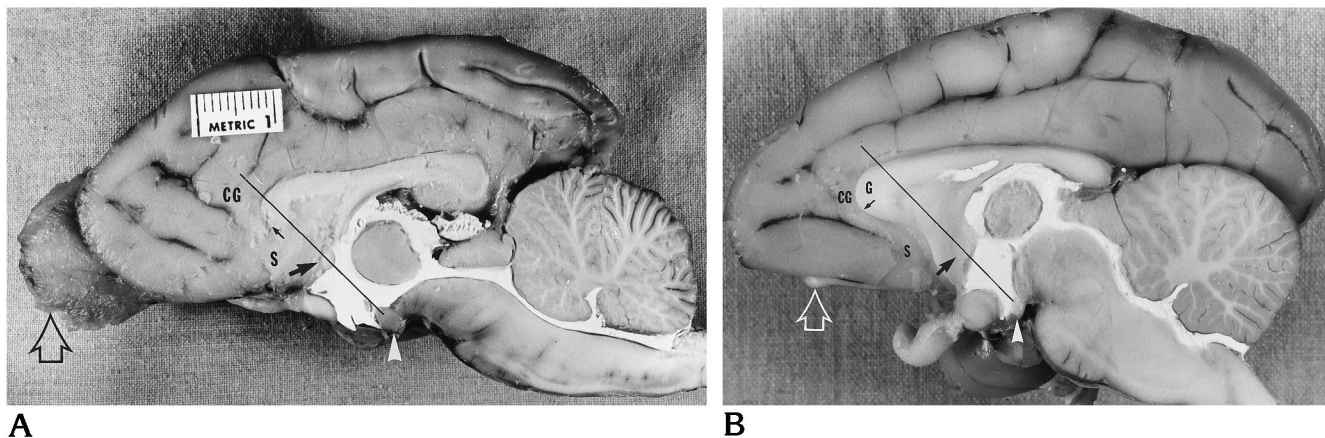


Fig 3. Photographs of the medial surface of the brains of a dog (A) and a monkey (B) show the changing relationship of the anterior edge of the corpus callosum to the MAC line. In the dog, the anterior edge of the corpus callosum (*small arrow*) is slightly in front of the MAC line. The cingulate gyrus (CG) has a slight anterior curvature before continuing toward the subcallosal area (S). In the monkey, the anterior edge of the corpus callosum (*small arrow*) is far in front of the MAC line and a prominent humanlike genu (G) is present. This is related to the marked expansion of the frontal lobes in primates associated with very significant reduction in the size of the olfactory bulb (*open arrow*). The cingulate gyrus now shows a marked anterior curvature around the genu before continuing toward the subcallosal area. The mamillary body (*arrowhead*) and anterior commissure (*large arrow*) are also shown.

significant anterior curvature around the genu before continuing toward the subcallosal area. In the 12-week-old human fetal specimen, the rudimentary corpus callosum is present below the callosal sulcus and behind the MAC line (Fig 4A). In the 16-week-old specimen, a rudimentary genu is now present in front of the MAC line; the cingulate gyrus has a minimal anterior curvature before continuing toward the future subcallosal area (Fig 4B). In the 20-week-old specimen, a prominent genu is present; the cingulate gyrus shows a marked anterior curvature around the genu before continuing into the subcallosal region (Fig 4C). In the 30-week-old specimen, the entire corpus callosum is thicker and shows increased flexion; the cingulate gyrus shows a prominent anterior curvature around the larger genu before reaching the subcallosal area (Fig 4D). An MR image of a 13-week-fetal specimen shows the presence of the corpus callosum behind the MAC line (Fig 5A). The corpus callosum is not seen in front of the MAC line. An MR image of a 14-week-old specimen shows the presence of a rudimentary genu in front of the MAC line (Fig 5B). An MR image of a 22-week-old fetal specimen shows a larger genu in front of the MAC line (Fig 5C).

Sagittal T1-weighted MR images of 1800 patients with a normal corpus callosum were analyzed using the MAC line to evaluate the position of the genu of the corpus callosum. In all 1800 cases the genu always projected anterior

to the MAC line (Fig 1). In a small number of infants less than 1 month of age, it was sometimes difficult to identify the anterior end of the corpus callosum and to determine if the genu was in front of the MAC line. MR images of 113 patients with anomalies of the corpus callosum were reviewed retrospectively. The components of the corpus callosum were analyzed as to their presence, absence, size, and relationship to the MAC line. Review of the abnormal cases revealed no cases in which only the genu was present in its expected normal position in front of the MAC line and in which the body and splenium were absent. In 18 cases, however, the entirety of the abnormal corpus callosum was behind or at the MAC line.

Discussion

The notion that the corpus callosum develops in an anterior-to-posterior direction starting with the genu and followed by the body, splenium, and finally the rostrum is now prevalent in the neuroradiologic literature. This persistent concept may have been introduced in 1967 in an important article about the corpus callosum that stated, "The extreme anterior portion of the corpus callosum develops first as a bud which grows from the upper end of the lamina terminalis and becomes the rostrum. It then grows

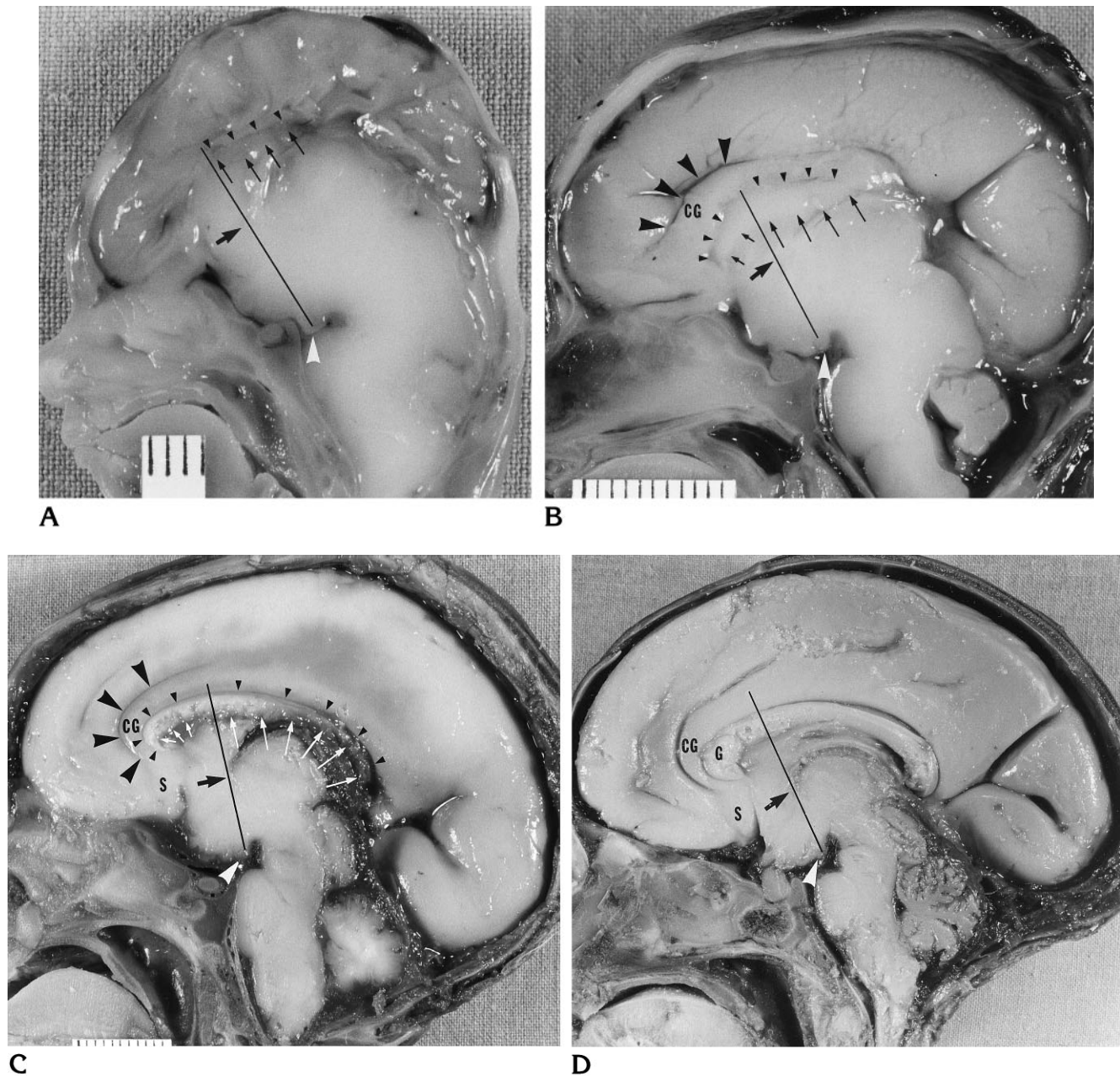


Fig 4. Photographs of the medial surface of brains of human fetal specimens show the growth of the corpus callosum.

A, In a 12-week-old specimen, a rudimentary corpus callosum (between *small arrows* and *small arrowheads*) is present below the callosal sulcus (*small arrowheads*) and behind the MAC line.

B, In a 16-week-old specimen, a rudimentary genu (between *short arrows* and *small arrowheads*) is present below the callosal sulcus (*small arrowheads*) and in front of the MAC line. The callosal body (between *long arrows* and *small arrowheads*) is behind the MAC line. The cingulate gyrus (CG), below the cingulate sulcus (*large black arrowheads*), has a minimal anterior curvature before continuing toward the future subcallosal area.

C, In a 20-week-old specimen, a prominent genu (between *small arrows* and *small arrowheads*) is present below the callosal sulcus (*small arrowheads*). The cingulate gyrus (CG) and cingulate sulcus (*large black arrowheads*) now show a prominent anterior curvature, around the larger genu, before continuing toward the subcallosal area (S). The body and splenium (between *long arrows* and *small arrowheads*) are elongated.

D, In a 30-week-old specimen, the entire corpus callosum is thicker and shows increased flexion. The cingulate gyrus (CG) shows a prominent anterior curvature, around the larger genu (G), before reaching the subcallosal area (S).

White arrowhead indicates mamillary body; *large arrow*, anterior commissure.

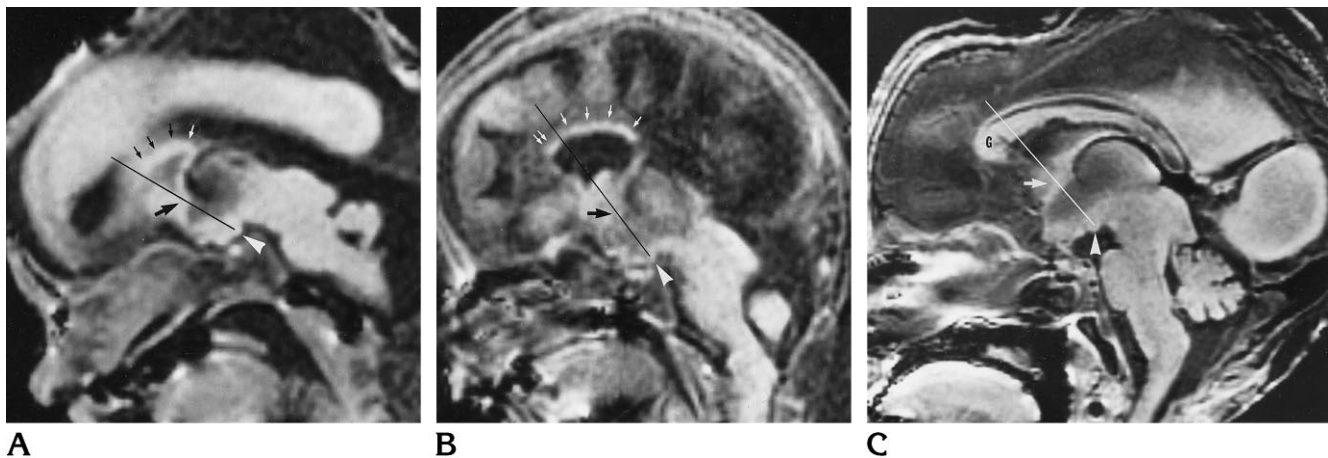


Fig 5. Sagittal T1-weighted MR images of human fetal specimens show the growth of the corpus callosum.

A, A 13-week-old fetal specimen shows the presence of a rudimentary body of the corpus callosum (*small arrows*) behind the MAC line. The genu is not present in front of the MAC line.

B, A 14-week-old fetal specimen shows the presence of a rudimentary genu (*double arrow*) in front of the MAC line.

C, A 22-week-old fetal specimen shows a much larger genu (*G*) in front of the MAC line.

Arrowhead indicates mamillary body; *large arrow*, anterior commissure.

upwards and backwards and the genu develops, followed by the body and finally the splenium" (26). This was subsequently amended to suggest that the rostrum is the final component to form (1–9). The anterior-posterior view of callosal embryology was temporarily revised to suggest that the posterior genu forms first, followed by growth in a posterior direction to fill out the body and splenium and in an anterior direction to complete the remaining genu and rostrum (27). However, the anterior-to-posterior direction of callosal growth remains the prevailing notion in the neuroradiologic literature.

As the purpose of this investigation was to evaluate the genu of the corpus callosum, an anatomic landmark to distinguish the genu from the body was needed. The mamillary body–anterior commissure–corpus callosum line, the MAC line, was selected for this investigation because the mamillary body and the anterior commissure can always be identified on an adequate sagittal MR image of the brain. The line is simple to apply, and the MAC mnemonic is an easy reminder of the structures through which the line passes. The MAC line is an appropriate landmark from evolutionary, embryologic, anatomic, and MR points of view. The mamillary body and anterior commissure are ancient and permanent evolutionary and embryologic structures (12, 28, 29). The corpus callosum develops in the hippocampal primordium, near and superior to the anterior commissure. Thus, the continuation of a line connecting

these two ancient and permanent structures is an appropriate frame of reference for evaluating developmental changes in the genu of the corpus callosum. This is especially true when comparing the corpora callosi of various mammals. The marked changes in brain size and shape require a stable frame of reference.

This investigation revealed the usefulness of assessing the normal corpus callosum by means of the MAC line. In 1800 clinical MR images that showed a normal corpus callosum that were reviewed over a 6-year period, the genu always projected anteriorly to the MAC line. The clinical images reviewed were not pre-selected and probably included patients with varying head size and shape and differing brain size. These patients most likely had different anteroposterior size of the corpus callosum, which could explain why the MAC line passed in slightly different locations in the region of the boundary of the genu and anterior body. As the genu always projected anteriorly to the MAC line, this line is a valid landmark for the position of the normal genu.

The finding in the normal corpus callosum makes sense in view of the evolutionary phase of this study, which showed that as the frontal lobes expand, the anterior edge of the corpus callosum moves progressively forward (Figs 2 and 3). The forward movement of the genu is confirmed by the increased anterior curvature of the cingulate gyrus (Fig 3). Without the MAC line, it would be difficult to compare the position

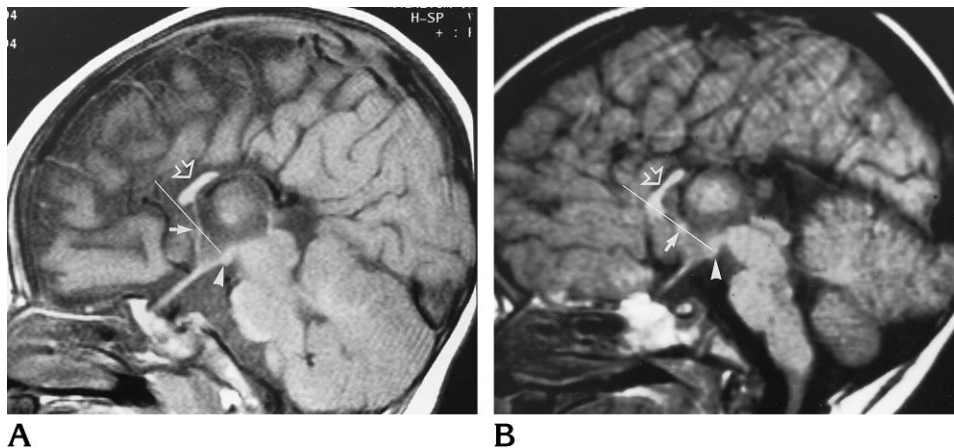


Fig 6. Sagittal T1-weighted MR images show rudimentary corpora callosi (open arrow) behind or at the MAC line. Mamillary body (arrowhead) and anterior commissure (arrow) are also shown.

of the genu in mammals with differing brain shapes and sizes. The more anterior position of the genu in the monkey and its larger size is linked to the marked expansion of the frontal lobe in primates (Fig 3). A review of the evolutionary studies of Smith (30) and Abbie (31) and the use of the MAC line on the specimens of the present study permit one to speculate that the anterior end of the corpus callosum—the genu of the rat, rabbit, and cat—is incorporated within the body of the corpus callosum in the primate.

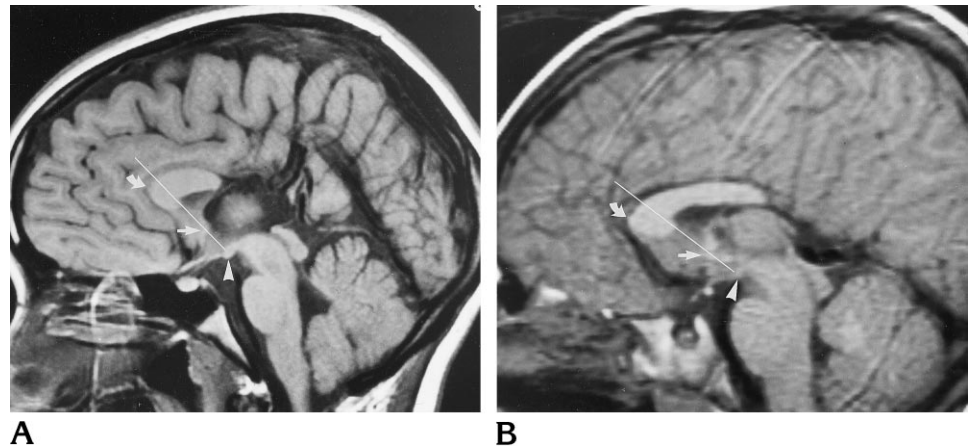
The embryologic growth of the corpus callosum is also the subject of controversy in the comparative anatomic literature. Tilney (32) states that in pig, rat, guinea pig, cat, and human embryos, the earliest fibers of the corpus callosum appear in front of the intraventricular foramen and the anterior commissure. Studies in cat embryos (33) have shown that at the 38th embryonic day only part of the body had formed. At the 53rd and 58th embryonic days, the genu, body, and splenium have formed. Experiments in mouse embryos (34, 35) found that the region of the genu forms before the splenium, in contradistinction to the study in cat embryos. Wahlsten (36) noted that in the mouse embryo, after the initial callosal fibers cross the midline, the corpus callosum undergoes rapid growth, adding fibers anterior to the existing corpus callosum and forming a distinct genu. He points out the interesting fact that the first callosal fibers in the rat embryo appear just dorsal to the hippocampal commissure in the same region in which the corpus callosum is present in adult bats, which have the smallest corpus callosum among all mammals. Ozaki and Wahlsten (35) make the important statement that the “genu and splenium are terms

most appropriate for the gross morphology of the adult.” This validates the approach taken throughout this investigation to relate the location of fetal structures to the location of the components of the corpus callosum in the adult.

The earliest fibers of the human corpus callosum appear during the 11th to 12th week of fetal development (22). In embryos aged 6 to 8 weeks, the thin rostral wall of the telencephalon, anterior to the chiasmatic plate, shows a rapid increase in the thickness of its dorsal part near the paraphysis. The anterior part near the chiasmatic ridge, the lamina terminalis, remains thin. The thicker dorsal part represents the lamina reuniens of His, a region of active cellular proliferation. The ventral part of the lamina reuniens, near the lamina terminalis, develops into the area precommissuralis. Later it will become the septal area with the anterior commissure within it. The hippocampal primordium and the future archaeocortex arise within the dorsal part of the lamina reuniens. As the hemispheric vesicles expand bilaterally, the dorsal part of the lamina reuniens begins to fold into the median groove. The banks of the median groove (sulcus medianus telencephali medii) approximate and come into juxtaposition, forming the massa commissuralis. In embryos of 11 to 12 weeks, the earliest fibers of the future corpus callosum begin to penetrate the massa commissuralis in the region of the hippocampal primordium.

This investigation showed that the rudimentary corpus callosum is only present behind the MAC line, in the region of the future anterior body, in the 12- and 13-week-old specimens (Figs 4A and 5A). In the 14-week-old specimen (Fig 5B) and the dissected 16-week-old specimen (Fig 4B), a rudimentary genu below the

Fig 7. Sagittal T1-weighted MR images of abnormal corpora callosi. In these cases, the presence of a genu (curved arrow) is always associated with the presence of the anterior body. Mamillary body (arrowhead) and anterior commissure (straight arrow) are also shown.



callosal sulcus can be seen in front of the MAC line on MR images. The development of the callosal sulcus was described previously (37). The forward movement of the human fetal genu is confirmed by the increased anterior curvature of the cingulate gyrus (Fig 4). The observation that the region of the future human genu develops after the region of the future anterior body of the corpus callosum is confirmed by superimposing the MAC lines on the figures in the studies by Retzius (19) and by Feess-Higgins and Larroche (16). The corpora callosi in some of Retzius's figures of the third month are very similar in appearance to the fetal MR images in Figs 5A and B and the clinical MR images in Fig 6 of the present study. Thus, in human embryology, the region of the anterior body develops before the region of the genu. In fact, that the human anatomic references show the anlage of the corpus callosum to be near and superior to the lamina terminalis precludes a unidirectional growth. Several publications are explicit about the bidirectional growth of the corpus callosum (14, 21, 38). Rakic and Yakovlev (22) in diagram 13 of their frequently cited article show the genu in a progressively more anterior position from the 18th to 40th week of fetal development. According to Loeser and Alvord (39), the earliest callosal fibers can be seen at the 74th gestational day, whereas the splenium and genu are recognizable at the 84th day. In their growth curve charts (39, 40), these authors list the primordial corpus callosum as developing before the genu and splenium. In addition, as recently as 1982, Sidman and Rakic (25), when discussing the formation of the cavum septi pellucidi, state that "the zone of fusion of the attendant callosal decussation extend[s] first forward, then down, and finally back again to form

the genu and rostrum of the corpus callosum." Clearly, the neuroanatomic literature has retained the concept of bidirectional callosal formation.

Another source of possible confusion is the nomenclature of the genu. In the human adult and other primates, the term *genu* is used to describe the anterosuperior segment of the corpus callosum. The fibers crossing the genu in the rhesus monkey and the human connect the prefrontal motor and association cortical regions (41–43). However, the term *genu* is also used in connection with other mammals in whom the prefrontal regions of the primate are not present (Figs 2 and 3). The genu of these vertebrates would be considered the anterior body region of the primate corpus callosum. In addition, in the older embryologic literature (17–19), the term *genu* has been used to describe the anterior-knee form-end of the human corpus callosum during in the early stages of fetal development. Retzius (19), in describing the developing corpus callosum in a 3-month-old embryo, stated, "the knee shaped (Knieförmig) anlage of the corpus callosum is visible above the lamina terminalis." However, this area is within the region of the future definitive body. Thus, the term *genu* has been used in the literature to denote three different anatomic regions: the nonprimate genu, the knee-shaped anterior end of the early human fetal corpus callosum, and the callosal genu of the developed primate.

With the information gained by this investigation, a more precise classification of anomalies of the corpus callosum can be made. In the 113 MR studies of patients with abnormalities of the corpus callosum that were reviewed retrospectively, the MAC line was used as a landmark.

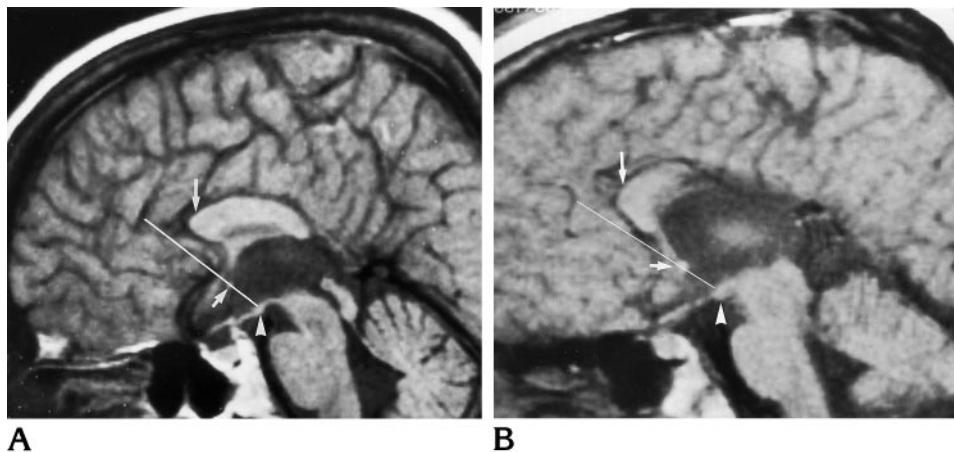


Fig 8. Sagittal T1-weighted MR images of abnormal corpora callosi. In these cases there is no corpus callosum in front of the MAC line; thus, a normal genu is not present. Only the body of the corpus callosum is present with a genulike anterior end (*long arrow*). The anterior end of the corpus callosum may represent the genu remaining in its early fetal position. Mamillary body (*arrowhead*) and anterior commissure (*short arrow*) are also shown.

Two particular findings underscore our disagreement with the concept of unidirectional, front-to-back growth of the corpus callosum. First, no abnormal cases were found that consisted of only a genu in its expected position in front of the MAC line with all the other segments of the corpus callosum absent. Second, in 18 cases, the entirety of the abnormal corpus callosum was behind or at the MAC line.

A review of the cases of hypogenesis of the corpus callosum showed that when a rudimentary corpus callosum is present, it lies at or behind the MAC line (Fig 6). In these cases, the rudimentary corpus callosum is generally in the position where it originally developed in the region of the fetal massa commissuralis, superior to the anterior commissure. In some cases it may lie anterior to the anterior commissure, but in all cases it lies at or behind the MAC line. The fetal genu may be incorporated within these rudimentary hypogenetic corpora callosi. In cases in which the genu was present, it was always associated with the presence of the anterior body (Fig 7). This study found no cases in which a normal genu was present without the anterior body.

Cases with no corpus callosum in front of the MAC line have been described as showing the presence of a genu. This study demonstrated that in cases similar to those described in the literature, the normal genu is absent (Fig 8). Only the anterior body of the corpus callosum is present with a genulike anterior end, which may represent the genu remaining in its early fetal position. Our analysis of 113 cases of callosal hypogenesis confirms that the region of the body of the corpus callosum is the first segment to develop, and that a normal genu is unlikely to

be present without a segment of the anterior body. This study also confirms the bidirectional growth of the normal corpus callosum. Rubinstein and coauthors (44) were also concerned by cases such as the ones shown in Figure 8. They stated that previous reports did not consider the position of the corpus callosum relative to the anterior commissure and fornices and that every anterior portion of the corpus callosum that was formed was called in the literature either a genu or a genu and body.

Of particular interest is the fact that the study by Rubinstein and coauthors (44) included 15 patients with the anomalous corpus callosum located posterior to the expected location of a normal genu. Their findings are similar to the results of this investigation that included 18 cases in which the entirety of the abnormal corpus callosum was behind or at the MAC line (Figs 7 and 8). Rubinstein et al stated that their 15 cases could not be explained as arrested midline growth because the prevalent theory would expect all cases of arrested growth to include the portion of the corpus callosum that develops first; that is, the genu. They suggested a different concept on the basis of a review of experimental animal studies: namely, that the abnormal cases, without the presence of a normal genu and anterior body, were explained not by arrested development but by continued and delayed development. This continued and delayed development results in cases showing a wide variety of size, shape, and location of the corpus callosum. On the basis of the results of our investigation, which analyzed the evolution, embryology, and clinical MR findings of the normal and abnormal corpus callosum, we believe that almost all cases of hypogenesis can be

explained by the phenomenon of arrested growth of the corpus callosum.

Conclusions

The contention that the corpus callosum develops normally in an anterior-to-posterior direction and that the genu is the first to form, followed by the body, splenium, and rostrum is not supported by an evolutionary, embryologic, anatomic, or MR imaging analysis. Rather, our data corroborate that the corpus callosum develops first in the region of the future anterior body and grows bidirectionally.

Acknowledgments

We thank Helmuth Gahbauer and Heinz Schlemmer for their help with the German literature, and Douglas H. Yock, Jr, for sharing his case material.

References

- Byrd SE, Harwood-Nash DC, Fitz CR. Absence of the corpus callosum: computed tomographic evaluation in infants and children. *J Can Assoc Radiol* 1978;29:108-112
- Davidson HD, Abraham R, Steiner RE. Agenesis of the corpus callosum: magnetic resonance imaging. *Radiology* 1985;155:371-373
- Barkovich A, Norman D. Anomalies of the corpus callosum: correlation with further anomalies of the brain. *AJNR Am J Neuroradiol* 1988;9:493-501
- Barkovich AJ, Kjos BO. Normal postnatal development of the corpus callosum as demonstrated by MR imaging. *AJNR Am J Neuroradiol* 1988;9:487-491
- Barkovich AJ. Apparent atypical callosal dysgenesis: analysis of MR findings in six cases and their relationship to holoprosencephaly. *AJNR Am J Neuroradiol* 1990;11:333-339
- Truwit CL, Barkovich AJ. Pathogenesis of intracranial lipoma: an MR study in 42 patients. *AJNR Am J Neuroradiol* 1990;11:665-674
- Georgy BA, Hesselink JR. MR imaging of the corpus callosum. *AJR Am J Roentgenol* 1993;160:949-955
- Hansen PE, Ballesteros MC, Soila K, Garcia L, Howard JM. MR imaging of the developing brain, 1: prenatal development. *Radiographics* 1993;13:21-36
- Oba H, Barkovich AJ. Holoprosencephaly: an analysis of callosal formation and its relation to development of the interhemispheric fissure. *AJNR Am J Neuroradiol* 1995;16:453-460
- Naidich TP, Daniels DL, Pech P, Houghton VM, Williams A, Pojunas K. Anterior commissure: anatomic-MR correlation and use as a landmark in three orthogonal planes. *Radiology* 1986;158:421-429
- Williams PL, Warwick R, Dyson M, Bannister LH, eds. *Gray's Anatomy*. 37th ed. London, England: Churchill Livingstone; 1989:190-194, 1063-1064
- Kier EL. The cerebral ventricles: a phylogenetic and ontogenetic study. In: Newton TH, Potts DG, eds. *Radiology of the Skull and Brain*. St Louis, Mo: Mosby; 1977:2787-2914
- Scammon RE, Calkins LA. *The Development and Growth of the External Dimensions of the Human Body in the Fetal Period*. Minneapolis, Minn: University of Minnesota Press; 1929:96-99
- Patten BM. *Human Embryology*. 3rd ed. New York, NY: McGraw-Hill; 1968:139-145, 289-294
- Barbe A. *Recherches sur L'Embryologie du Systeme Nerveux Central de L'Homme*. Paris, France: Masson; 1938:59-160
- Feess-Higgins A, Larroche JC. *Development of the Human Fetal Brain: An Anatomical Atlas*. Paris, France: Masson; 1987:88-166
- Blumenau L. Zur Entwicklungsgeschichte und Feineren Anatomie des Hirnbalkens. *Arch Mikroskop Anat* 1891;37:1-15
- Marchand F. Ueber die Entwicklung des Balkens im Menschlichen Gehirn. *Arch Mikroskop Anat* 1891;37:298-334
- Retzius G. *Das Menschenhirn*. Stockholm, Sweden: Norstedt & Son; 1896:5-7, plate 4
- Streeter GL. The development of the nervous system. In: Keibel F, Mall FP, eds. *Manual of Human Embryology*. Philadelphia, Pa: Lippincott; 1912:82-95
- Hamilton WJ, Boyd JD, Mossman HW. *Human Embryology*. 3rd ed. Baltimore, Md: Williams & Wilkins; 1962:354-357
- Rakic P, Yakovlev PI. Development of the corpus callosum and cavum septi in man. *J Comp Neurol* 1968;132:45-72
- Probst FP. Congenital defects of the corpus callosum. *Acta Radiol Suppl* 1973;331:1-152
- Probst FP. The prosencephalies. *Morphology, Neuroradiological Appearances and Differential Diagnosis*. New York, NY: Springer-Verlag; 1979:3-13
- Sidman RL, Rakic P. Development of the human nervous system. In: Haymaker W, Adams RD, eds. *Histology and Histopathology of the Nervous System*. Springfield, Ill: Charles C. Thomas; 1982:41-49
- Bull J. The corpus callosum. *Clin Radiol* 1967;18:2-18
- Barkovich AJ, Gilles L, Evrard P. Formation, maturation, and disorders of white matter. *AJNR Am J Neuroradiol* 1992;13:447-461
- Sarnat HB, Netsky MG. *Evolution of the Nervous System*. 2nd ed. New York, NY: Oxford University Press; 1981:308-309, 370-372
- Kier EL. Comparative anatomy of the third ventricular region. In: Apuzzo MLJ, ed. *Surgery of the Third Ventricle*. Baltimore, Md: Williams & Wilkins; 1987:37-91
- Smith GE. The morphology of the true "limbic lobe," corpus callosum, septum pellucidum and fornix. *J Anat Physiol* 1895;30:157-205
- Abbie AA. The origin of the corpus callosum and the fate of the structures related to it. *J Comp Neurol* 1939;70:9-44
- Tilney F. The hippocampus and its relationship to the corpus callosum. *J Nerv Ment Dis* 1939;89:433-513
- Berbel P, Innocenti GM. The development of the corpus callosum in cats: a light- and electron-microscopic study. *J Comp Neurol* 1988;276:132-156
- Silver J, Lorenz SE, Wahlsten D, Coughlin J. Axonal guidance during development of the great cerebral commissures: descriptive and experimental studies, in vivo, on the role of preformed glial pathways. *J Comp Neurol* 1982;210:10-29
- Ozaki HS, Wahlsten D. Prenatal formation of the normal mouse corpus callosum: a quantitative study with carbocyanine dyes. *J Comp Neurol* 1992;323:81-90
- Wahlsten D. Prenatal schedule of appearance of mouse brain commissures. *Dev Brain Res* 1981;1:461-473
- Kier EL, Fulbright RK, Bronen RA. Limbic lobe embryology and anatomy: dissection and MR of the medial surface of the fetal human cerebral hemisphere. *AJNR Am J Neuroradiol* 1995;16:1847-1853
- Carpenter MB, Sutin J. *Human Neuroanatomy*. 8th ed. Baltimore, Md: Williams & Wilkins; 1983:83
- Loeser JD, Alvord EC Jr. Agenesis of the corpus callosum. *Brain* 1968;91:553-570

40. Lemire RJ, Loeser JD, Leech RW, Alvord EC Jr. *Normal and Abnormal Development of the Human Nervous System*. Hagerstown, Md: Harper & Row; 1975:260–265
41. de Lacoste MC, Kirkpatrick JB, Ross ED. Topography of the human corpus callosum. *J Neuropathol Exp Neurol* 1985;44: 578–591
42. Pandya DN, Rosene DL. Some observation on trajectories and topography of commissural fibres. In: Reeves AG, ed. *Epilepsy and the Corpus Callosum*. New York, NY: Plenum Press; 1985: 21–39
43. LaMantia A-S, Rakic P. Axon overproduction and elimination in the corpus callosum of the developing rhesus monkey. *J Neurosci* 1990;10:2156–2175
44. Rubinstein D, Youngman V, Hise JH, Damiano TR. Partial development of the corpus callosum. *AJNR Am J Neuroradiol* 1994; 15:869–875

Please see the Commentary on page 1643 in this issue.