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Embryology of the Human Fetal Hippocampus: MR Imaging, Anatomy, and Histology

E. Leon Kier, Jung H. Kim, Robert K. Fulbright, and Richard A. Bronen

PURPOSE: To identify changes in the embryology of the hippocampus responsible for its adult anatomy. **METHODS:** Ten human fetal specimens ranging from 13 to 24 weeks' gestational age were examined with MR imaging. Dissections and histologic sections of 10 different specimens of similar ages were compared with MR imaging findings. **RESULTS:** At 13 to 14 weeks' gestation, the unfolded hippocampus, on the medial surface of the temporal lobe, surrounds a widely open hippocampal sulcus (hippocampal fissure). At 15 to 16 weeks, the dentate gyrus and cornu ammonis have started to infold. The hippocampal sulcus remains open. The parahippocampal gyrus is larger and more medially positioned. The CA1, CA2, and CA3 fields of the cornu ammonis are arranged linearly. The dentate gyrus has a narrow U shape. By 18 to 20 weeks, the hippocampus begins to resemble the adult hippocampus. The dentate gyrus and cornu ammonis have folded into the temporal lobe. The hippocampus and subiculum approximate each other across a narrow hippocampal sulcus. The CA1–3 fields form an arc and the CA4 field has increased in size within the widened arch of the dentate gyrus. **CONCLUSION:** MR imaging of fetuses provides a developmental basis for understanding hippocampal anatomy.

Index terms: Brain, growth and development; Hippocampus; Fetus, magnetic resonance

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The advent of magnetic resonance (MR) imaging has fostered a great deal of interest in imaging the hippocampal formation. MR anatomy of the normal hippocampal formation in the coronal plane has been reported by several investigators (1–5). Abnormal hippocampal formations have been described in a number of pathologic processes, including such congenital brain anomalies as agenesis of the corpus callosum, lissencephaly, and holoprosencephaly (6, 7); temporal lobe epilepsy (8); and Alzheimer disease (9).

Development of the hippocampal formation

has been explained in the literature by diagrams showing progressive infolding of the fetal dentate gyrus, cornu ammonis, subiculum, and parahippocampal gyrus around the progressively smaller hippocampal sulcus (hippocampal fissure) (7, 10–13). These diagrammatic representations are based on the histologic study reported by Humphrey (14). Because an understanding of the imaging appearance of normal embryologic changes can elucidate anatomic relationships in the adult brain and might also help date developmental disorders seen on MR images, we decided to examine hippocampal development in normal fetal specimens using MR imaging, dissection, and histology.

Materials and Methods

Twenty human fetal specimens were examined, 10 with MR imaging and 10 with dissection. Three dissected specimens were studied histologically. Specimens had been preserved in 10% formaldehyde for over 20 years. They ranged in age from 13 to 24 weeks' gestation and were normal in external appearance. No abnormalities were found in any of the specimens examined. Fetal age was

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determined by crown-rump length and occipitofrontal diameter (15, 16). Because 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 the true gestational age. To further verify fetal age, the occipitofrontal diameter of the fetal brains was compared with the occipitofrontal diameter of photographs of fetal brains in the literature (17, 18).

Ten specimens ranging from 12 to 24 weeks' gestational age were scanned in a 1.5-T system using a wrist (10-cm-diameter) transmit/receive coil. Acquisitions in sagittal, coronal, and axial planes were obtained using a three-dimensional spoiled gradient-echo sequence that accentuates T1 weighting, and a T2-weighted fast spin-echo sequence. Parameters for the three-dimensional spoiled gradient-echo sequence were 45/7–8/2 (repetition time/echo time/excitations), 45° flip angle, 256 × 256 matrix, 8-cm field of view, and 0.7-mm section thickness. Parameters for the T2-weighted fast spin-echo sequences were 3000/100/8, echo train length of eight, 8-cm field of view, and 2-mm section thickness. Of the 10 fetuses examined with MR, the images from four were suboptimal owing to poor tissue contrast. The remaining six specimens with preserved MR anatomy had gestational ages of 13, 14, 15, 16, 18, and 24 weeks, respectively.

Ten specimens ranging in age from 13 to 24 weeks' gestation were dissected so that we could compare the MR findings with the anatomic material. These were different specimens from the ones that were imaged. The leptomeninges were removed and each brain specimen was examined; all appeared normal. The medial surface of the brain was examined after brain transection in the midsagittal plane. To view the temporal lobe, the cerebellum and brain stem were removed and the hypothalamus and thalamus were partially resected. Initial stages of the dissections were performed by using a 3-diopter magnifier. The medial surface of the hemispheres was examined with a dissecting microscope in the 13- to 15-week-old specimens. Photography of the specimens was performed with a 35-mm camera and a macroscopic lens. Depending on specimen size, 12-, 20-, and 36-mm extension tubes were added separately or in combination between the lens and the camera body. In identifying limbic lobe structures, we used previous studies of human embryology, anatomy, and MR imaging (1, 2, 10–12, 14, 19–24). The term hippocampus and its synonym, the hippocampal formation, includes the cornu ammonis and dentate gyrus (25). Useful dissections (those without tissue maceration or destruction) were obtained in five specimens with gestational ages of 13, 14, 15, 16, and 18 weeks, respectively.

In three dissected specimens with gestational ages of 13, 16, and 18 weeks, the temporal lobe was dissected free from the remainder of the brain. The hippocampus and adjacent parahippocampal gyrus were resected en bloc and then routinely processed for paraffin embedding. Sections 6 μ m thick were made from the paraffin blocks and stained with hematoxylin-eosin and Nissl. Adequate histologic sections were obtained in the 16- and 18-week-

old specimens but not in the 13-week-old specimen owing to tissue destruction. The final study group consisted of MR images of six specimens, dissections and photographs of five other specimens, and histologic sections of two of the five dissected specimens.

Results

MR images of 13-week-old (Fig 1A) and 14-week-old (Fig 1B) fetal specimens show an unfolded hippocampus along the medial surface of the temporal lobe bordering a widely open hippocampal sulcus. The parahippocampal gyrus region is small. The germinal matrix is prominent in the roof and lateral wall of the temporal horn. Similar findings are seen in a coronal dissection of the temporal lobe in a different 14-week-old fetal specimen (Fig 1C).

At 15 weeks, MR images reveal that an unfolded hippocampus still surrounds an open hippocampal sulcus at the medial surface of the temporal lobe (Fig 2A and B), but the hippocampal sulcus is smaller than at 13 to 14 weeks. The parahippocampal region is not much wider than the hippocampus. The germinal matrix remains prominent in the roof and lateral wall of the temporal horn. A coronal section of a dissected temporal lobe of a 16-week-old specimen (Fig 2C) shows a smaller hippocampal sulcus and the beginning of the infolding of the hippocampus. In the MR images and the dissected specimens, the parahippocampal gyrus including the subiculum projects more medially. As a result of cortical growth, the parahippocampal/subicular region is now the most medial structure of the temporal lobe. The coronal histologic section (Fig 2D) of the same specimen in Figure 2C shows the dentate gyrus, cornu ammonis, alveus, fimbria, molecular stratum, subiculum, and parahippocampal gyrus. The hippocampal sulcus is large. The CA1, CA2, and CA3 fields of the cornu ammonis have a somewhat straight course. The dentate gyrus has a narrow U-shaped configuration.

By 18 weeks, MR images show infolding of the hippocampus into the temporal lobe as the dentate gyrus and cornu ammonis change into the interlocking C shape of the adult hippocampus (Fig 3A and B). The parahippocampal gyrus including the subiculum is larger and the hippocampus is deeper within the temporal lobe. The germinal matrix is still prominent in

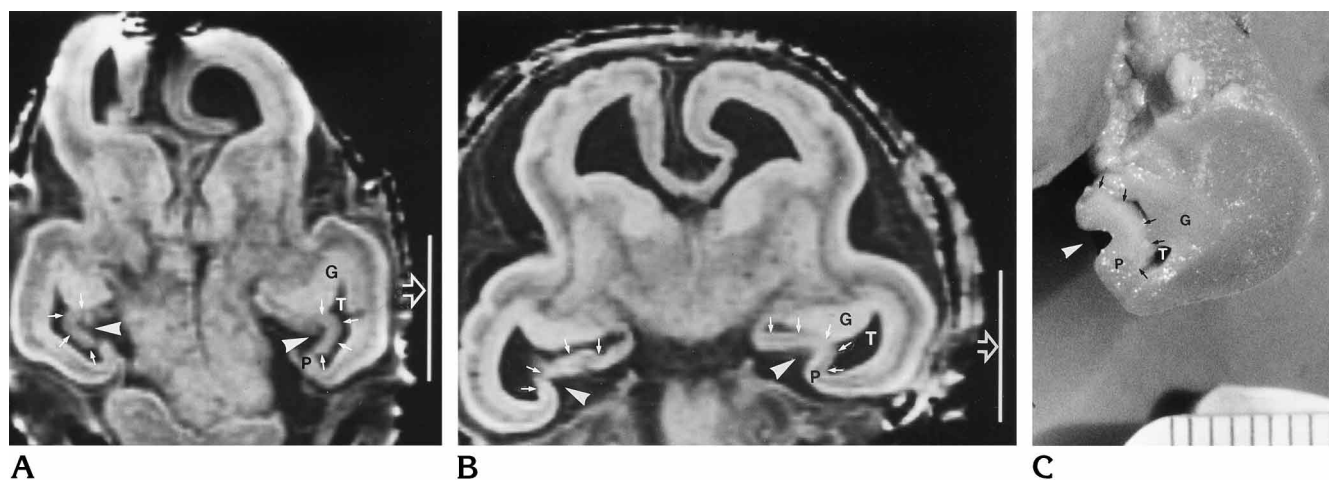


Fig 1. A and B, Coronal T1-weighted spoiled gradient-echo MR images (45/8/2; 45° flip angle) of intact 13-week-old (A) and 14-week-old (B) fetal specimens. The unfolded hippocampus (solid arrows) is on the medial surface of the temporal lobe, bordering a widely open hippocampal sulcus (arrowheads). The neocortical parahippocampal gyrus region (P) is small. The germinal matrix (G) is prominent in the roof and lateral wall of the temporal horn (T). The length of the line (open arrow) in all the fetal MR images in this article is 10 mm and illustrates the small size of the structures imaged.

C, Photograph of a coronal dissection of the left temporal lobe in a different 14-week-old fetal specimen. The anatomic structures identified on the MR images are corroborated. The unfolded hippocampus seen in the MR images and the dissected specimen is the most medial structure of the temporal lobe. The distance between two adjacent ruler lines in all the specimen photographs is 1 mm.

Key to Abbreviations and Symbols in Figures

A	alveus
C	cornu ammonis
D	dentate gyrus
F	fimbria
G	germinal matrix
M	molecular strata of the dentate gyrus
P	parahippocampal gyrus
S	subiculum
T	temporal horn
small arrows	hippocampus
small arrowheads	dentate gyrus
large arrowhead	hippocampal sulcus
1	CA1 field of cornu ammonis
2	CA2 field of cornu ammonis
3	CA3 field of cornu ammonis
4	CA4 field of cornu ammonis

the roof of the temporal horn but reduced in size along the lateral wall of the ventricle. The temporal horn is smaller. A coronal section of a dissected temporal lobe of a different 18-week specimen shows that the hippocampus is infolded deeper into the temporal lobe, bulging into the temporal horn (Fig 3C). The coronal histologic section (Fig 3D) of the specimen in Figure 3C shows that a longer segment of the dentate gyrus is facing the subiculum across the hippocampal sulcus, increasing the depth of the hippocampal sulcus. The molecular strata of

the dentate gyrus and the cornu ammonis are closer together than in the 16-week-old specimen. The dentate gyrus has a more open C configuration when compared with the tight U shape in the 16-week specimen in Figure 2C. The cornu ammonis is more arched. The stream of CA3 neurons is more prominent at the entrance of the endofolium. The CA4 field of the cornu ammonis is increased within the arch of the dentate gyrus.

In the 24-week-old specimen, the hippocampus is relatively smaller in size as compared with the parahippocampal gyrus. A collateral sulcus is now present. The position of the hippocampus within the temporal lobe is unchanged and the infolded relationship of the dentate gyrus and cornu ammonis is unchanged. The germinal matrix along the wall of the temporal horn is reduced in thickness.

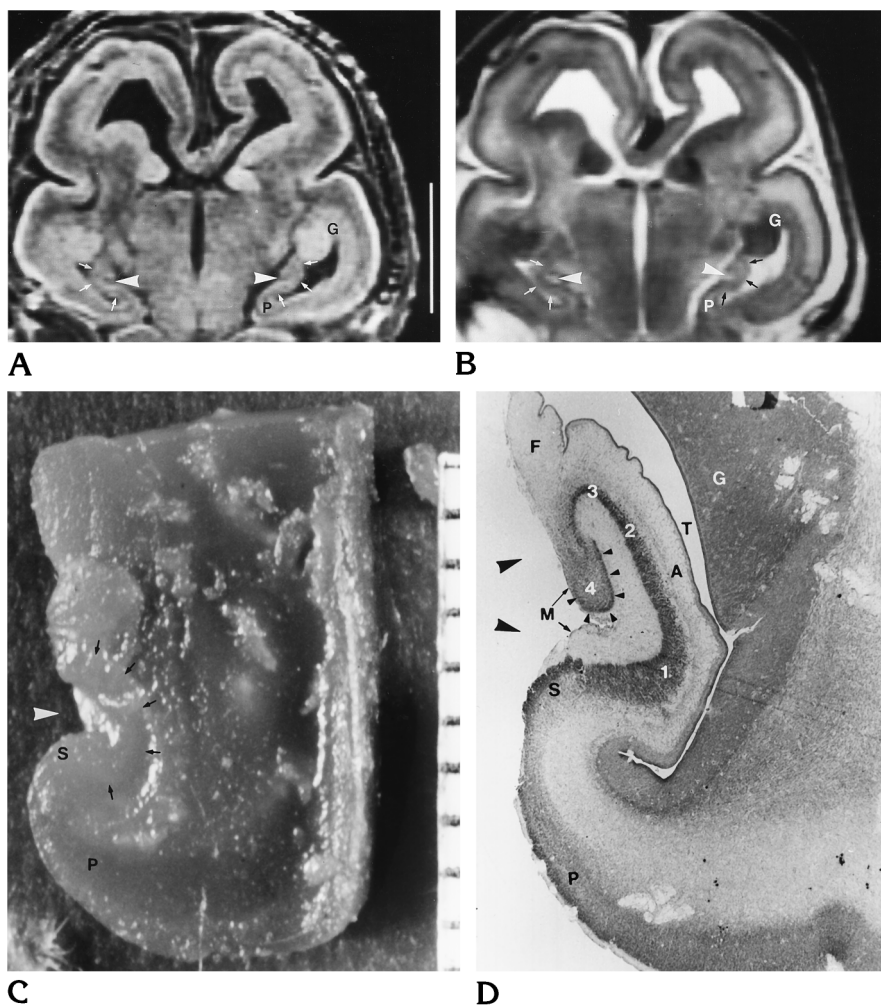
Discussion

This comparative study of normal fetal specimens using MR imaging, dissection, and histology documents transformations of the fetal human hippocampal formation (Figs 1–6). Knowledge of these transformations helps explain the complex anatomic relationships seen in the normal adult hippocampal formation and may play a role in the understanding and classification of hippocampal abnormalities.

Fig 2. A and B, Coronal T1-weighted spoiled gradient-echo (45/8/2; 45° flip angle) and T2-weighted (3000/100/8) MR images of a 15-week-old fetal specimen show a smaller hippocampal sulcus (*arrowheads*). The hippocampus (*arrows*) is still unfolded and on the medial surface of the temporal lobe. The parahippocampal gyrus (*P*) including the subicular region is now more medial than the hippocampus. The germinal matrix (*G*) is prominent in the roof and lateral wall of the temporal horn.

C, Coronal section of a dissected left temporal lobe of a 16-week-old fetal brain specimen shows the hippocampus (*arrows*) around a smaller hippocampal sulcus (*arrowhead*). The parahippocampal gyrus (*P*) including the subiculum (*S*) is larger and projects more medially. As a result of cortical growth, the parahippocampal gyrus including the subicular region is now the most medial structure of the temporal lobe, both on the MR image and the dissected specimen.

D, On the coronal histologic section of the specimen in Figure 2C, the CA1 (*1*), CA2 (*2*), and CA3 (*3*) fields of the cornu ammonis have a somewhat straight course. The dentate gyrus (*small arrowheads*) has a tight U-shaped configuration around the CA4 (*4*) field of the cornu ammonis. The very thin molecular stratum (*M*) of the dentate gyrus is separated from the larger molecular stratum of the cornu ammonis by the very wide hippocampal sulcus (*large arrowheads*). The germinal matrix (*G*) is prominent along the lateral wall of the temporal horn (*T*) (Nissl, original magnification $\times 24$).



According to Humphrey (14), before the 10th week of development, the dentate gyrus and cornu ammonis are thin rudimentary structures positioned successively along the posterolateral aspect of the diencephalon (the posteromedial wall of the lateral ventricle). At the 10-week stage, a broad shallow hippocampal sulcus is present along the posterolateral aspect of the diencephalon. This shallow hippocampal sulcus appears when the telencephalic wall of the primordial dentate gyrus becomes thicker than that of the cornu ammonis. When first identified, the primordial hippocampal sulcus lies opposite the dentate gyrus rather than opposite the pyramidal layer of the cornu ammonis, which is seen later in development. At 10 to 11 weeks, the dentate gyrus increases in thickness, and the sulcus is deeper and shifts toward the junction of the cornu ammonis and dentate gyrus.

At 12 to 14 weeks, the increasing thickness of the dentate gyrus causes it to rotate toward the cornu ammonis, and the hippocampal sulcus becomes progressively deeper and more sharply defined (14). As the sulcus deepens it becomes oriented more toward the junction of the cornu ammonis with the subicular region. When the dentate gyrus and cornu ammonis approach each other, a diffuse zone of scattered cells appears deep to the sulcus. In the human fetus, this diffuse zone is a well-defined triangular area by 13 to 14 weeks and lies between the definitive molecular stratum of the dentate gyrus and the molecular stratum of the cornu ammonis. The growth of the dentate gyrus and cornu ammonis causes the medial wall of the hemisphere to bulge into the lateral ventricle. At 15 to 16 weeks, the hippocampal sulcus is best developed in the temporal portion of the hip-

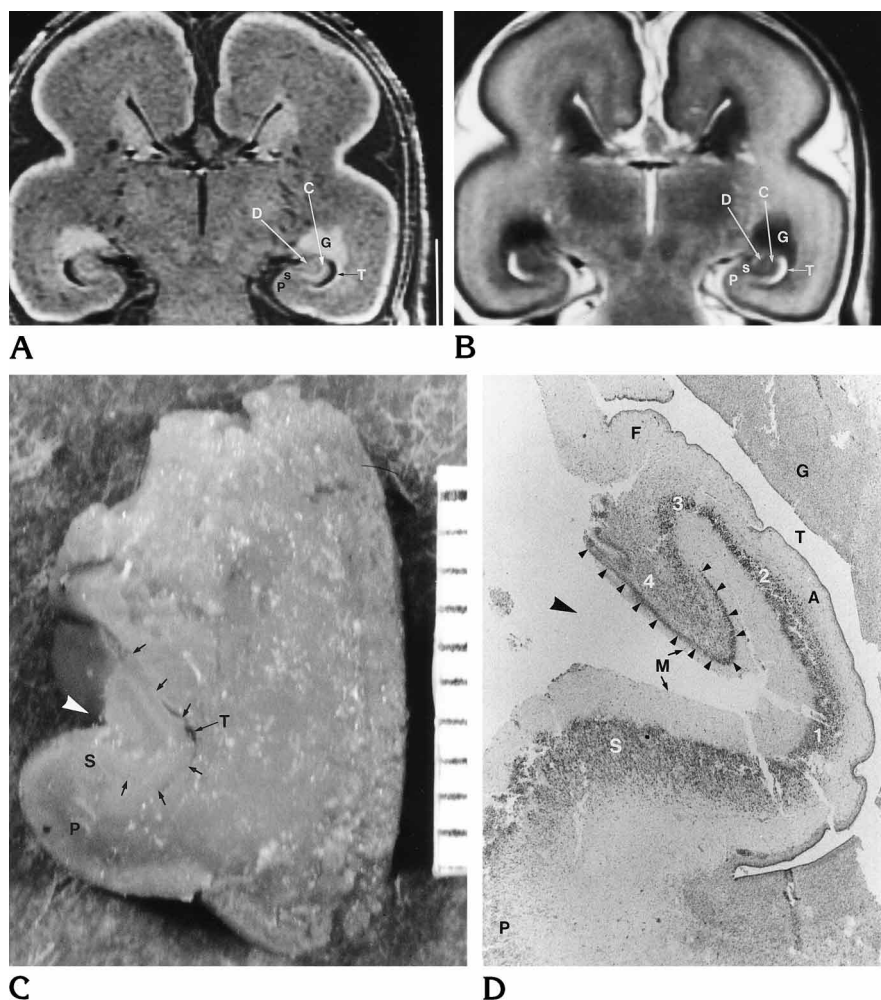


Fig 3. A and B, Coronal T1-weighted spoiled gradient-echo (45/7/2; 45° flip angle) and T2-weighted (3000/100/8) MR images of an 18-week-old fetal specimen show that the hippocampus is deeper within the temporal lobe. The hippocampus is no longer linear in arrangement and has changed into the interlocking C shape of the adult hippocampus. The cornu ammonis (C) and dentate gyrus (D) are infolded. The hippocampal sulcus is small and not visible. The parahippocampal gyrus (P) region, beyond the subicular (S) region, is wider and larger. The germinal matrix (G) is still prominent in the roof of the smaller temporal horn (T) but reduced in size along the lateral wall of the ventricle.

C, Coronal section of a dissected left temporal lobe of a different 18-week-old specimen shows that the hippocampus (arrows) is infolded deeper into the temporal lobe, bulging into the temporal horn (T). The enlarged parahippocampal (P) region projects much more medially as compared with Figure 2.

D, The coronal histologic section of the specimen in Figure 3C shows that the CA1 (1), CA2 (2), and CA3 (3) fields of the cornu ammonis are more arched. The stream of CA3 neurons is more prominent at the entrance of the endofolium. The CA4 (4) field of the cornu ammonis is increased within the arch of the dentate gyrus (small arrowheads). The dentate gyrus has a more open C-shaped configuration as compared with the narrow U shape in the 16-week specimen in Figure 2D. A longer segment of the dentate gyrus is facing the subiculum (S) across the hippocampal sulcus (large arrowhead), increasing the depth of the hippocampal sulcus. The molecular strata (M) of the dentate gyrus and the cornu ammonis are closer together than in the 16-week specimen (Nissl, original magnification $\times 31$).

pocampal formation. The sulcus both deepens and widens as the dentate gyrus enlarges and then narrows as its two walls come in contact. When the dentate gyrus is the largest and has rotated inward the farthest, the deepest portion of the diffuse zone takes on a linear character due to pressure from both the dentate gyrus and the cornu ammonis.

By 18 to 21 weeks, the relationship of the hippocampal sulcus to the surrounding structures is similar to that of the adult brain (14). The relationship of the hippocampal sulcus to the granular layer of the dentate gyrus remains constant while its position with reference to the

other parts of the limbic system changes with development (Fig 5). Anteriorly, a deep sulcus is still present. More caudally, where the dentate gyrus is infolded to a greater degree, the deep part of the sulcus is closed. Its walls are fused and there is a remaining shallow indentation between the dentate gyrus and the presubiculum, and later between the dentate gyrus and the adjacent entorhinal cortex. Both pia mater and blood vessels may be included between the walls of the hippocampal sulcus as they fuse. At times, a residual cavity of the hippocampal sulcus may remain, appearing on MR images like a cystic structure of cerebrospinal fluid signal in-

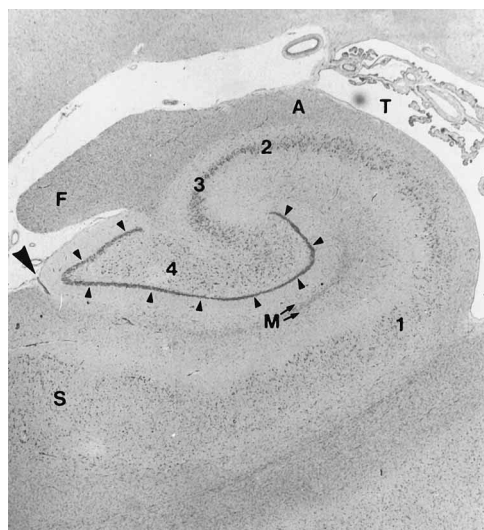


Fig 4. Coronal histologic section of a normal adult left hippocampus. Comparing the 18-week-old specimen (Fig 3D) with the adult, we find that further infolding has fused the molecular strata (*M*) of the dentate gyrus (*small arrowheads*) and subiculum (*S*), resulting in the obliteration of the hippocampal sulcus (*large arrowhead*). The CA1 (1), CA2 (2), and CA3 (3) fields of the cornu ammonis are more arched. The CA4 (4) field of the cornu ammonis is increased within the wider arch of the dentate gyrus. The alveus (*A*) and fimbria (*F*) have changed orientation from a vertical to a horizontal course (Nissl, original magnification $\times 12$).

tensity within the hippocampus (3, 13). The end result of the infolding is that the linear arrangement of the components of the hippocampus is changed so that the external surfaces of the dentate gyrus and subiculum end up in contact around an obliterated hippocampal sulcus (10). The amount of infolding varies along the length of the hippocampus. Warwick and Williams (10) and Lemire et al (11) have summarized Humphrey's findings (14) diagrammatically (Figs 5 and 6).

The complex relationships and the positions of the components of the hippocampal formation result in part from the marked evolutionary expansion of the neocortex in the temporal lobe (26). The phylogenetically older hippocampal formation is displaced inferiorly and medially and infolds internally into the temporal horn (E. L. Kier, "The Evolutionary Basis for the Complex MR Anatomy of the Temporal Lobe," presented at the annual meeting of the American Society of Neuroradiology, Los Angeles, Calif, March 1990). The infolding or "rolling in" of the hippocampal formation increases in mammals in proportion to the increase of the neocortical cerebral hemisphere (27). This is associated with a concomitant decrease in the size of the

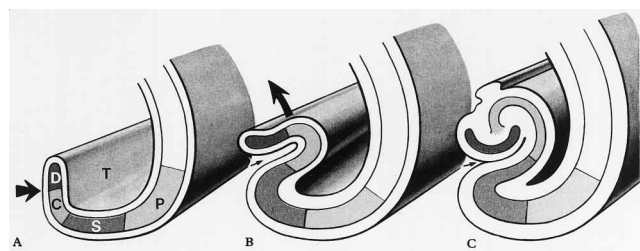


Fig 5. Diagram in the coronal plane illustrates stages of infolding of the components of the hippocampus in the left temporal lobe.

A, Early in fetal development, the dentate gyrus (*D*), cornu ammonis (*C*), subiculum (*S*), and parahippocampal gyrus (*P*) are arranged serially along the medial wall and floor of the temporal horn (*T*).

B and C, As a result of the marked expansion of the neocortex and unequal growth of the various components of the hippocampus, there is gradual infolding of the components into a progressively smaller temporal horn. The infolding occurs around the hippocampal sulcus that first forms between the dentate gyrus and cornu ammonis (*large arrow* in Figure 5A). The hippocampal sulcus (*small arrow* in Figure 5B and C) shifts later to a location between the dentate gyrus and subiculum, and eventually becomes obliterated (modified from Gray's Anatomy [23]).

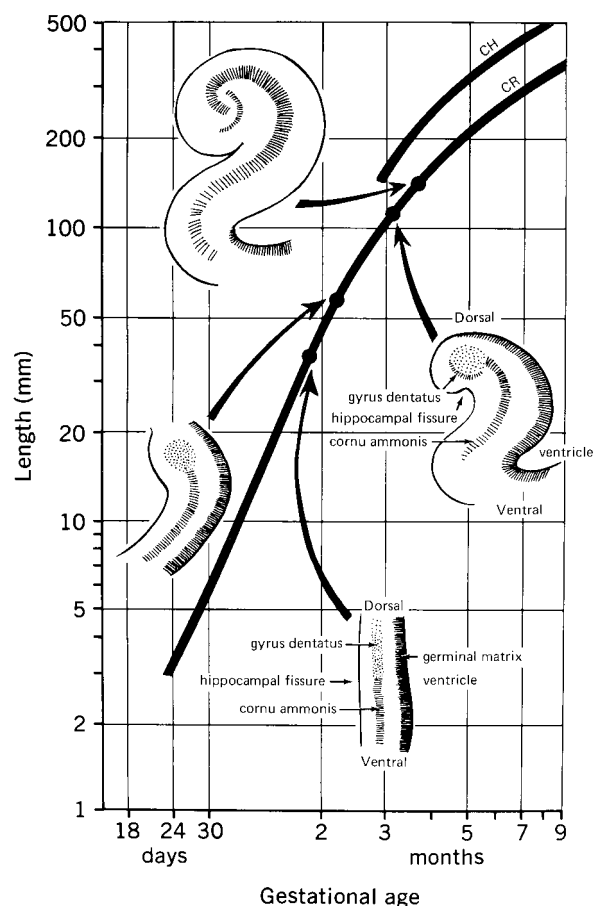
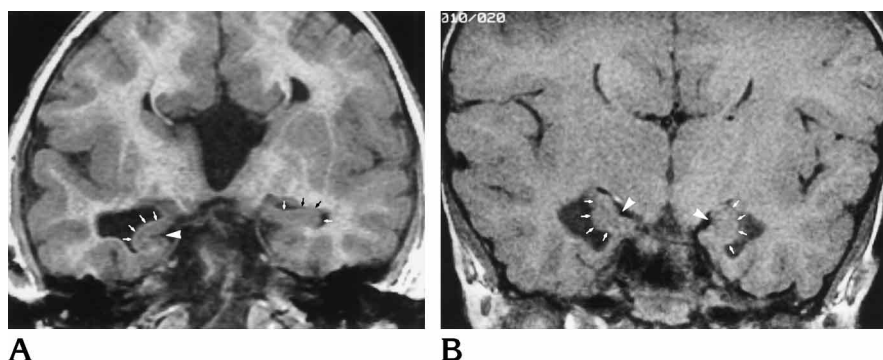


Fig 6. Diagram in the coronal plane shows the gestational age and crown-rump (*CR*) length of the stages of hippocampal infolding in the left temporal lobe (from Lemire et al [11]). *CH* indicates crown-heel length.



A **B**
 pocampi (arrows) bilaterally are located too medially and on the surface of the temporal lobe. The hippocampi are partially unfolded around the hippocampal sulcus (arrowheads). The hippocampi in this patient show a similarity to the fetal appearance in Figure 2A.

rhinencephalon. In primates, the infolding is greater than in carnivores. The infolding is most pronounced in the dolphin, which has a huge cerebral hemisphere associated with a relatively reduced hippocampus.

MR imaging of intact human fetal specimens provides a unique method for identifying developmental changes responsible for the complex anatomy of the hippocampus. Previously, these changes were illustrated only by histologic sections and diagrams. This study shows similarities between the stages depicted by MR imaging (Figs 1–3) and those portrayed in diagrammatic representations (Fig 5). However, certain relationships are seen better on our MR images and histologic sections, such as the superficial position of components of the hippocampus on the medial surface of the temporal lobe (Fig 1A and B) and the embryologic changes in the configuration of the temporal horn. The marked expansion of the cortex, placing the infolded dentate gyrus and cornu ammonis deeper within the temporal lobe, is also better appreciated on the MR images and the anatomic and histologic sections.

This investigation provides a developmental basis for the study of hippocampal abnormalities seen with MR imaging. In some cases of agenesis of the corpus callosum, lissencephaly, and holoprosencephaly, the hippocampi have been described as small, unfolded, and vertically oriented. We have seen several cases of corpus callosal agenesis in which there is a partially unfolded hippocampus and a prominent hippocampal sulcus (Fig 7A and B), resembling the fetal appearance shown in Figures 1 and 2. Although we lack histologic proof, the appearance of these hippocampi could result from arrested growth before 18 to 20 weeks' gestation.

Fig 7. Patients with agenesis of the corpus callosum and abnormalities of the hippocampi.

A, Coronal T1-weighted spoiled gradient-echo (24/5/2; 45° flip angle) MR image shows that the left hippocampus (black and white arrows) is totally unfolded. The right hippocampus (white arrows) is partially folded around the hippocampal sulcus (arrowhead). The hippocampi show a similarity to the fetal appearance in Figure 1A and B.

B, Coronal T1 weighted spin-echo (600/20/2) MR image shows that the hip-

Additional studies are needed to verify whether identification of hippocampal development can serve as a marker for dating brain insults.

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